This study tested the relationship between infiltration data collected using all tension settings of the Mini Disk Infiltrometer (MDI), against infiltration data collected using a 100mm Single Ring Infiltrometer (SRI). Three soil textures, sand, silt and clay were used for infiltration sampling. The results show that the MDI tension setting of 0cm most closely replicated the findings of the SRI across all soils, which was supported through applying the Nash and Sutcliffe Efficiency analysis.

Quantification of the influence of different Mini Disk Infiltrometer (MDI) suction settings when measuring infiltration across various soil types

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Abstract

Defining the infiltration characteristics of an area is beneficial for understanding soil compaction, determining soil health, and measuring the rate of surface water infiltration, which is needed for hydrological modelling. Single and double ring infiltrometers (SRI, DRI) are commonly used to determine infiltration characteristics in the field, however these are frequently impractical due to the required water volume, the weight and the intrusiveness of measurement, hindering the ease of replication. The Mini Disk Infiltrometer (MDI) offers a lightweight, portable and non-intrusive method of measuring infiltration, however no previous research has explained the influence of changing the tension settings on the collected infiltration data. To address this gap, this novel study tested the relationship between infiltration data collected using all tension settings of the Mini Disk Infiltrometer (MDI), against infiltration data collected using a 100mm Single Ring Infiltrometer (SRI). Three soil textures (sand, silt and clay) were collected from different geographical areas of the UK and deposited within the experimental facility designed for this study. Controlled infiltration measurements were taken with both the MDI and the SRI for each soil type, to further define the impact of MDI tension settings on derived infiltration, in comparison to the SRI. For the first time, the results show that the MDI tension setting of 0cm most closely replicated the findings of the SRI across all soils, which was supported through applying the Nash and Sutcliffe Efficiency (NSE) analysis. The accuracy with which the MDI replicated the infiltration of the SRI reduced as tension increased. Consequently, the previously assumed ideal tension setting of 2 cm, as defined by the MDI handbook and used in previous research, does not offer an accurate representation of derived infiltration.

Keywords: Mini Disk Infiltrometer, Single Ring Infiltrometer, Infiltration, Tension Setting, Soil Texture, Nash and Sutcliffe Efficiency, Laboratory Sampling, Soil Sampling

1. INTRODUCTION

Determining the infiltration characteristics of an area is beneficial for various hydrological and geotechnical applications (Vand *et al.*, 2018). For example, characterising infiltration rates aids in determining the speed of pollutant leaching, understanding and estimating soil compaction and soil health, and determining the rate of surface water infiltration and subsequent overland flow, which is of particular use for hydrological modelling (Marshall *et al.*, 2014; Nestingen *et al.*, 2018; Umar Farid *et al.*, 2019). To make such a determination, numerous approaches have been developed to better understand infiltration rates, with the most popular being the single and double ring infiltrometers (Nestingen *et al.*, 2018; Di Prima *et al.*, 2019).

Single ring infiltrometers (SRIs) use a cylindrical metal or plastic tube, inserted in to the sample soil to a depth of 5-10 cm (Carroll *et al.*, 2004; Bagarello *et al.*, 2014; Chandler *et al.*, 2018). Water is added to the tube and the level is recorded at consistent time intervals, defined by the user (Bátková *et al.*, 2020). Measurement continues until the water level remains the same for (commonly) three-time intervals, at which point the total and average (per minute) infiltration and of the area can be calculated (Bagarello and Sgroi, 2004; Chandler *et al.*, 2018). Total infiltration is the sum amount of water that enters the soil over the measurement period, and the infiltration per minute is a division of the total sum by the measurement duration. Use of the SRI suffers from lateral leakage (seepage), whereby infiltrating water travels laterally instead of vertically, leading to an overestimation of the infiltration rate (Muneer *et al.*, 2020).

Double ring infiltrometers (DRI) consist of two cylindrical tubes, one larger than the other inserted 5-10 cm into the sample soil (Fatehnia *et al.*, 2016; Folorunso and Aribisala, 2018). Whilst there is no guidance regarding the ratio of DRI ring sizes, it is common to use an outer ring with double the diameter of the inner (Lai and Ren, 2007; Zhang *et al.*, 2017; Nestingen *et al.*, 2018). The outer ring of the DRI is filled and kept at a constant head throughout measurement, forming a 'bulb' around the infiltrating water from the inner-ring (Hornberger *et al.*, 2014). This encourages the vertical infiltration of inner-ring water and minimises lateral seepage and measurement inaccuracy, which is often inherent with SRI measurement (Folorunso and Aribisala, 2018; Rönnqvist, 2018; Zhang *et al.*, 2019; Muneer *et al.*, 2020). The infiltration process of the SRI and the DRI are shown in figure 1.

[Insert figure 1]

The method of recording and deriving infiltration rate and saturated hydraulic conductivity using the DRI is the same as the SRI. It is agreed within the literature that the size of SRI's and DRI's should be as large as possible to minimise lateral seepage and provide the most accurate representation of sample soil infiltration characteristics (Bagarello and Sgroi, 2004; Lai and Ren, 2007; Khodaverdiloo *et al.*, 2017; Nestingen *et al.*, 2018).

One significant limitation associated with both the SRI and DRI is that they disrupt the soil (Zhang *et al.*, 2019). The intrusive insertion of the rings in to the soil can create macropores, leakage passages and distort the natural homogeneity of the soil making replication difficult and increasing measurement error (Bagarello and Sgroi, 2004; Zhang *et al.*, 2017). Whilst both devices are common methods of measuring in-situ infiltration characteristics, they can become rapidly impractical in the field if transportation, personnel and water availability is limited (Milla and Kish, 2006; Chen and Hsu, 2012; Kirkham, 2014; Nestingen *et al.*, 2018). Additionally, measurement of infiltration can be a time consuming process time (in some cases up to six hours Johnson, 1963) dependent on desired result and soil type, making multiple site sampling challenging (Alagna *et al.*, 2016).

To address and alleviate the issues discussed above with regard to the SRI and DRI methods (METER® Group Inc., 2018)**, t**he Minidisk Infiltrometer (MDI) developed by METER® Environment (2019) was designed. The MDI it is a portable infiltrometer that is capable of measuring the infiltration characteristics of a soil under a user-specified tension setting (see Figure 2) (Burguet *et al.*, 2016; METER® Group Inc., 2018; Nestingen *et al.*, 2018; Bátková *et al.*, 2020).

[Insert figure 2]

The MDI has a measuring (soil contact) diameter of 4.5 cm and holds a total of 135 ml of water; 95 ml of which is for infiltration (the bubble chamber accounts for the additional 40 ml), 500% less than what is required by small SRI's or DRI's. Furthermore, the method is non-intrusive - meaning measurements are taken from the soil surface which aids in measurement replication over time. However vegetation cover does have to be removed from the soil surface around the area of measurement before the MDI can be used, as full contact with the soil is required (Robichaud *et al.*, 2008; METER® Group Inc., 2018; Nestingen *et al.*, 2018; Naik *et al.*, 2019). The force that must be exerted on the base of the MDI by the soil to break the surface tension is controlled using the tension regulation tube. The user can select a desired tension, ranging from 0.5 cm (0.5 kPa) to 7 cm (7 kPa), in increments of 0.5 cm. The user manual suggests applying a higher tension when sampling more permeable soils and a lower tension when the soil is more compact (Fatehnia *et al.*, 2016; METER® Group Inc., 2018; Nestingen *et al.*, 2018; Naik *et al.*, 2019). Despite these indications, there is limited guidance on the influence that different suction settings have on deriving infiltration, and therefore the impact of selecting dissimilar settings for various soil textures when calculating the infiltration rate and saturated hydraulic conductivity. Furthermore, these values are typically not considered in studies that have used the MDI (Robichaud *et al.*, 2008; Fatehnia *et al.*, 2014; Matula *et al.*, 2015; Nestingen *et al.*, 2018; Naik *et al.*, 2019). The MDI user manual suggests a suction setting of 2 cm will sufficiently derive the infiltration characteristics of most geology textures (METER® Group Inc., 2018).

Therefore, this study aims to evaluate the accuracy and feasibility of using the MDI to measure soil infiltration characteristics as an alternative to traditional SRI methods across different soil textures. The infiltration characteristics measured with both the MDI and the SRI that are used to assess their performance and compared are the infiltration rate and infiltration capacity.

2. MATERIALS AND METHODS

To test the relationship between the MDI and SRI effectively, soil was collected from three different locations in England (Figure 3): The Heart of England (HofE) Forest site at Spernal, Five Acre Community Farm at Ryton and Woodlands Farm at Kirton. A soil texture testing kit was used to confirm the exact texture of each of the collected soils (LaMotte, 2020).

[Insert figure 3]

As this study was focussed primarily on testing the MDI and its suction settings against the SRI, the replication of processes was critical. For this reason, large rocks, roots, or soil conglomerates present in the soil samples were removed using a coarse sieve (3 cm x 3 cm). This allowed infiltration with both the MDI and the SRI to be comparable, as there would be no geological characteristics (such as rocks, roots or conglomerates) influencing results. This process maintained enough of the main soil matrix represent the in-situ soil type, which is the aim of this study (Di Prima *et al.*, 2018; Cui *et al.*, 2019).

The soil samples were established in wooden boxes measuring 120 cm x 70 cm x 20 cm (0.168m^3). Twelve holes (⌀10 cm) were drilled in the bottom of the boxes to allow the soil to drain between measurements, ensuring replicable measurements (Alfredo *et al.*, 2010; Sande and Chu, 2012; Hu *et al.*, 2017; Morbidelli *et al.*, 2017; Di Prima *et al.*, 2018). Figure 4a shows a schematic of the sample boxes, and figure 4b shows one of the boxes filled with the sandy soil, attained from Five Acre Community Farm.

[Insert figure 4]

The dimensions of the sample boxes reflected the space that would be required to fit the maximum soil volume that could reasonably be transported from each site to the laboratory, whilst also considering the surface area required to conduct all measurements without the influence of lateral seepage or edge effects. Edge effect is the phenomena of an external factor, or change in sampling consistency, influencing the process of consistent data collection or replication (Woo, 2004; Dai *et al.*, 2017). For this study, a higher infiltration value closer to the edges of the wooden sample box, caused by infiltrating water being able to leak down, would be considered an edge effect. Taking this in to consideration, the depth of the boxes was an important parameter to select. The SRI would be inserted 10 cm into the surface, so enough soil needed to still remain under the inserted SRI to reduce any edge effect caused by infiltrating water interacting with the bottom of the box (Alfredo *et al.*, 2010; Hu *et al.*, 2017; Di Prima *et al.*, 2018). This decision was made considering that this study was conducted to verify the ability of the MDI to represent the measurements derived from the SRI over different tension settings.

Once each testing box had been filled with soil, they were left for 14 days. This process aimed to settle the soil, somewhat re-instating it represent its original homogeny before the disruption caused by both the removal from site and the sieving processes (Bryan and Luk, 1981; Phi *et al.*, 2013; Lawrence *et al.*, 2016; Thomsen *et al.*, 2019). The boxes were kept outside under plastic sheeting during the setting period, and when not being used for sampling. This was decided to avoid rainfall events interfering with the antecedent conditions of the soil when not in use, and to prevent weed growth.

2.1 Data Collection Method

MDI measurements were conducted on each soil sample using every suction setting of the MDI from 0 (where the suction tube was removed) to 7 cm (the strongest suction setting), in increments of 0.5 cm. Each measurement was taken three times (Marshall *et al.*, 2014) in a horizontal line across half of the box, 10 cm away from the previous location to reduce lateral seepage from one area to the next (Folorunso and Aribisala, 2018; Rönnqvist, 2018). Each measurement row of was staggered slightly from the row above to utilise space and distance the rows far enough apart to further avoid lateral seepage. SRI measurements were taken three times from a vertical line through the middle of the box, 15 cm apart. The distance between replicas of the SRI was greater than that of the MDI due to the larger size of the SRI and greater water requirement – which would increase the chance of lateral seepage (Zhang *et al.*, 2019; Muneer *et al.*, 2020). No measurements were taken from within 5 cm of the side walls of the box to further reduce edge effects caused by the presence of the box wall. It is noted in the literature that the larger the ring size, the more accurate the collected data (Bagarello and Sgroi, 2004; Khodaverdiloo *et al.*, 2017; Nestingen *et al.*, 2018). Therefore, a 100 mm ring was used to compare the MDI measurements too, due to availability and cost. The reason for using the SRI and not a DRI is due to the desired outcome of this project and similarity in nature of the measurements taken with the MDI. In measurements taken with both the SRI and the MDI, lateral seepage is inherent. The DRI is designed to minimise this phenomenon through the presence of the second ring; so, comparing data collected using the MDI to a DRI would not be accurate. Additionally, the SRI is more commonly used to determine infiltration variables in field studies due to the lower cost, lower water requirements and the portability of the device in comparison to a DRI (Asleson *et al.*, 2009; Nestingen *et al.*, 2018), so by using a SRI, the study is more applicable to the real-world uses of the MDI. Figure 5 shows the sampling method with both the MDI and SRI.

[Insert figure 5]

Sampling of each soil type began in the top-left corner with the MDI set to the lowest suction setting for that sample day; measurements were taken in rows of three, with the MDI suction increasing by 0.5 kPa at a time, until the last measurement (bottom-right corner) had been taken on the highest setting. Measurements were replicated in a cycle over the duration of the sample day in order to be inclusive of any changes in soil characteristics due to varying weather conditions. For example, measurements with suction settings 0 kPa through 7 kPa were taken one at a time in sequence, followed by the SRI measurement, then the cycle was repeated until each measurement had been taken 3 times. Infiltration measurements were carried out until three consecutive volumes were recorded (~10 minutes), in line with Chandler et al. (2018) and Bagarello and Sgroi (2004). Literature suggests that three consecutive volumes indicate a soils infiltration capacity, and most boxes reached this value within 10 minutes (Bagarello and Sgroi, 2004; Chandler *et al.*, 2018). A total of 144 infiltration measurements were taken for this study.

2.2 Soil Conditions and Variability

Initial soil conditions affect infiltration characteristics (Beven, 2004; Hornberger *et al.*, 2014). A higher temperature can increase infiltration, whereas a lower temperature can reduce it (Jaynes, 1990; Prunty and Bell, 2005); and a high initial soil moisture decreases infiltration creating more tortuous flow paths for infiltrating water (Hornberger *et al.*, 2014; Ruggenthaler *et al.*, 2016). In order to account for all these varying soil conditions at the time and location of each infiltration measurement, values of soil temperature and soil moisture content were taken regularly using a WET KIT and WET-2 Sensor (Delta-T, 2020). Six measurements were taken with the WET sensor from each soil box throughout the course of a sample day to account for changes due to changing weather. The WET sensor was calibrated to each soil type to be tested prior to use, and recorded temperature to an accuracy of ± 1.5°C, and volumetric water content to and accuracy of ± 10%.

3. RESULTS

3.1 Soil Moisture and Temperature

The initial soil moisture and temperature were sampled using the WET sensor, these results are shown in table I.

[Insert table I]

The temperatures of both the clay and sand samples are similar with the clay being only 0.38°C warmer than the sand, the silt is warmer than both the clay and the sand by 7.5°C and 7.88°C respectively. The silt sample shows the lowest moisture content, being 0.97% lower than the sand, and 6.06% lower than the clay sample. As discussed in section 2.2, antecedent soil moisture and temperature conditions can influence the infiltration rate (Prunty and Bell, 2005; Ruggenthaler *et al.*, 2016), so consideration should be given to the variations in the initial soil conditions when interpreting results.

3.2 Infiltration Data

Table II shows the total infiltration (in mm) of all replicated MDI and SRI measurements, along with the mean total for each soil type. Figure 6 shows the cumulative infiltration of each MDI tension setting and the SRI over the 10-minute measurement duration across the three sample soils.

[Insert table II]

[Insert figure 6]

Table II and figure 6 show that derived infiltration values decrease as the tension of the MDI is increased. As the MDI tension setting is increased from 0 kPa through to 7 kPa, the derived total infiltration in comparison to the total infiltration determined using the 100 mm SRI.

3.3 Statistical Analysis

To investigate the correlation between the MDI tension settings and the SRI and determine which MDI tension setting best represents that of the 100 mm SRI, the Nash-Sutcliffe Efficiency (NSE) index was used. The NSE is a widely used method of assessing the goodness-of-fit of two time stepping datasets (McCuen *et al.*, 2006; Schaefli and Gupta, 2007; Criss and Winston, 2008; Ritter and Muñoz-Carpena, 2013), and has been used in infiltration studies (de Almeida *et al.*, 2018; Mahapatra *et al.*, 2020). The NSE index is common in computer modelling, however is applicable to the datasets collected throughout this study due to the time-stepping nature, and the goal of aiming to find the MDI tension setting of best-fit to the SRI (Ritter and Muñoz-Carpena, 2013; Mahapatra *et al.*, 2020). The NSE equation shows;

$$NSE = 1-¿ \quad (1)$$

Where Y_i^{obs} is the observed discharge, $Y_i^{¿}$ is the simulated discharge and Y^{mean} is the mean of observed discharge.

In this study, the mean SRI value for each time step was used as the constant observed value, and each tension setting was inputted as the simulated value. This allowed for the NSE values to be derived for each MDI tension setting in order to define the tension setting that most closely correlates with the SRI, over the measurement period, for all three sample soils. Results related to the calculated NSE are shown in figure 7.

[Insert figure 7]

Figure 7 shows that an MDI tension setting of 0 derives the closest total infiltration to the 100 mm SRI in all soils, with a 0.95 NSE in sand, 0.54 NSE in silt, and 0.51 NSE in clay. In both sand and clay, the 0 cm tension setting underestimated the SRI (however was still the closest tension setting) by 0.67 and 3.33 respectively, however in the silt soil, the MDI infiltrated 3 mm more water than the SRI. The volume of infiltrated water mostly decreases in uniform with each 0.5 cm of tension applied across all soils, as is seen in the silt soil, however there are anomalies to this; tension setting 1 and 1.5 in the sandy soil and settings 2.5 and 3 in the clay soil. Infiltration slows significantly compared to the SRI when using the higher tension settings, settings 6 cm to 7 cm show 0 mm infiltration across the sandy soil, and settings 5.5 cm to 7 cm show 0 mm of infiltration across both silt and clay soils.

4. DISCUSSION

The results of this study have shown that the different tension settings of the MDI influence the derived total infiltration value over the measurement duration, resulting in a new set of values that suggest alternative tension settings to use to replicate the infiltration characteristics derived from the SRI. It is determined that a tension setting of 0 cm (where the tension control tube is completely removed from the MDI), most closely represents the infiltration rate derived from the 100 mm SRI across sand (NSE 0.95), silt (NSE 0.54) and clay (NSE 0.51). These findings vary from the suggestion of a tension of 2 cm across all soil types as suggested by the MDI user manual (METER® Group Inc., 2018). For infiltration measurements taken with the MDI across sand, silt and clay-textured soils to be comparable to that of a 100 cm SRI, the tension tube should be removed, this has been demonstrated through the results collected and displayed throughout section 3. It is discussed in section 3.1 that initial soil moisture and temperature differ slightly between sand, silt and clay. Through analysing the presented data in figure 6 and table II the variation in these parameters cannot be seen to influence the collected infiltration data, therefore, the sampling of the soils can be deemed uniform, with all of the boxes being as comparable as possible for the duration of the sample period.

This paper has provided evidence for the use of this MDI tension setting across the sample soils through undertaking 144 controlled infiltration experiments, whereas there is no justification for the use of 2 cm published in the user manual or in the wider literature. It should be noted when interpreting these results that the texture, structure and porosity of soils vary greatly over space, therefore infiltration characteristics of a soil cannot be summarised under one specific value without further justification, such as that recommended in the MDI user's manual (Chesworth *et al.*, 2008; Archer *et al.*, 2013; Hornberger *et al.*, 2014; Kirkham, 2014; Gee and Or, 2018). If the recommended tension setting of 2 cm was to be used across all soil types, total infiltration volume would be underestimated by 4.67 mm in sand, 8 mm in silt, and 7.66 mm in clay when compared to the 100 mm SRI.

This demonstrates the importance of this study, which forms a foundation for the development of results derived from the MDI, which provides a lightweight, portable alternative to a typical SRI (Burguet *et al.*, 2016; METER® Group Inc., 2018; Nestingen *et al.*, 2018; Bátková *et al.*, 2020). This study has provided validity to the results collected by the MDI, showing that replicable infiltration values to that of a SRI can be derived through adjusting the tension of the MDI to suit the soil texture. This offers greater opportunity for soil science research, as the SRI no longer needs to be a limitation in studies that require multiple replications over large study sites, and infiltration testing can be carried out in otherwise difficult to reach places, leading to further data collection and greater addition to the soil-infiltration literature base.

Whilst a 100 mm SRI was used for comparison in this study due to availability and cost, it is also worth considering the implications that using different SRI sizes may have on results. If a larger ring was used in this study, the infiltration measurements may become greater due to the increased surface area, and increase amount of area available for infiltration in comparison to the MDI (Bagarello and Sgroi, 2004; Khodaverdiloo *et al.*, 2017; Nestingen *et al.*, 2018). This signifies that further research needs to be conducted regarding the influence of ring size on infiltration data collection, particularly when comparing SRI data to MDI data. This could indicate that as SRI size changes, so does the most suitable MDI tension setting. Additionally, whilst this research has demonstrated the accuracy with which the MDI can calculate infiltration in a laboratory setting, further research is required to better understand the applicability in a field environment. Such a setting would further consider roots, compaction and stones that are likely to be present, but were sieved out as part of this project.

5. CONCLUSIONS

Overall, this study has provided a calibration of the infiltration data derived from the tension settings of the MDI, forming a basis for further studies into the influence of MDI tension settings across even more soil types, in addition to the ones tested here. The tension settings of the MDI have been tested against a 10 cm SRI, and the most appropriate tensions, selected by statistical correlation have determined for use to replicate that of the SRI across the tested soil types. This study acts as a framework for determining the MDI tension settings to use in the field to replicate that of a SRI, and add validity to the results derived from the MDI.

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DATA AVAILABILITY

To access the data collected and analysed in this study, please contact the corresponding author Nathaniel Revell (revelln@uni.coventry.ac.uk).

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TABLES

Table I. Data recorded using the WET Sensor

Sample Soil	Temperature (°C)	Moisture (%)
Clay Sample	6.93	20.07
Sand Sample	6.55	14.05
Silt Sample	14.43	13.08

Table II. The total infiltration of each MDI and SRI (in mm), with the mean average, across all three sample soils. R=replicate.

	Sand				Silt				Clay			
MDI tension setting	R1	R2	R3	Mean total infiltration	R1	R2	R3	Mean total infiltration	R1	R2	R3	Mean total infiltration
0	9	9	9	9.00	13	13	12	12.67	7	5	6	6.00
0.5	8	7	7	7.33	7	8	7	7.33	4	5	5	4.67
1	6	6	6	6.00	3	3	4	3.33	4	4	4	4.00
1.5	6	6	7	6.33	3	2	3	2.67	3	2	3	2.67
2	5	5	5	5.00	2	2	1	1.67	1	2	2	1.67
2.5	4	6	4	4.67	2	2	1	1.67	1	1	1	1.00
3	3	4	4	3.67	1	2	1	1.33	1	1	1	1.00
3.5	2	3	3	2.67	0	1	1	0.67	1	0	0	0.33
4	3	2	2	2.33	1	1	0	0.67	1	0	0	0.33

4.5	1	1	1	1.00	0	0	1	0.33	0	1	0	0.33
5	0	1	0	0.33	0	1	0	0.33	0	0	1	0.33
5.5	0	0	1	0.33	0	0	0	0.00	0	0	0	0.00
6	0	0	0	0.00	0	0	0	0.00	0	0	0	0.00
6.5	0	0	0	0.00	0	0	0	0.00	0	0	0	0.00
7	0	0	0	0.00	0	0	0	0.00	0	0	0	0.00
SRI	10	9	10	9.67	8	9	12	9.67	9	10	9	9.33