Title: Significance of Negative Matric Suction Pressures on Infiltration in the Swash Zone

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Abstract

The swash zone's complex hydrodynamics can be influenced by infiltration and exfiltration processes, which are not yet fully understood. This study explores the role of negative matric suction pressures in swash-zone infiltration, focusing on seven naturally occurring beach media samples. Using a combination of tensiometer and in-contact filter paper methods, we examine the prevalence of matric suction pressures for beach media ranging from fine pebbles to fine sand. The results highlight the existence of matric suction pressures within the range 0-2 kPa for the examined media samples, with maximum values observed within the grain-size range 0.85-0.71 mm. Our results reveal a previously underexamined aspect of swash-zone infiltration, highlighting the potential significance of matric suction in influencing coastal processes. The findings suggest that omitting matric suction effects is shown to be an invalid assumption under certain conditions, as these pressures can exceed gravitational potential.

Keywords: In-contact Filter Paper method, Infiltration, Matric Suction Pressure, Swash Zone, Tensiometer, Unsaturated media.

1. Introduction

The swash zone is defined as the region of the beach intermittently exposed and submerged by uprushing and backwashing resulting from induced wave action (Chen and Hulscher 2023). Amongst the many processes and phenomena evident in the zone, swash zone infiltration/exfiltration have received lesser attention in comparison to investigations into the subaerial hydrodynamics and net beach morphology in the zone. This observation may be accredited to either one of two scenarios: (1) the zone may be comprised of low permeability media such as sandy beaches, in which case infiltration effects are often ignored (Jamal 2011); (2) beaches are made up of higher permeability media (gravel beaches), in which case infiltration effects are more complex (Briganti et al. 2018) and including such effects may be a significant task.

Generally, infiltration can be complex, involving flow through saturated/ unsaturated media where steady-state saturated flow or unstable unsaturated flows are possible (Ferré and Warrick 2005). Many factors ranging across both media and fluid properties govern porous media infiltration (Ali 2010). However, of these two classes, media properties can be deemed most significant, where media porosity, which is linked to media grain size (Mishra and Singh (2003), is commonly regarded as the single most influential parameter affecting infiltration (King 1992). Correspondingly, many researchers have based the inclusion or omittance of infiltration effects in swash zone investigations on prevailing beach sediment size. In fact, Bagnold (1940), Butt, Russel and Turner (2001) and Masselink and Li (2001) outlined varying threshold grain-size values which determine which of the latter occurs.

Although less significant, hydrodynamic parameters such as intra-bed moisture content and residual moisture content along with negative suction pressures can further complicate porous media flows (Ferré and Warrick 2005). Regarding the former, an inverse relationship exists between porous media water content and infiltration (Gray and Norum 1967). Relating to the latter, negative suction pressures promote infiltration flows by imposing an additional potential at the infiltrating waterfront. This added potential is generally governed by the degree of saturation and sediment size (Okamura and Teraoka 2006). An inverse relationship exists between grain-size and negative suction pressures as outlined by Guo et al. (2020) where negative suction pressures are most prominent amongst smaller sediments within the fine sands – clays regime as opposed to medium and larger sands as noted by Yang et al. (2004).

Despite the possibility of negative suction pressures contributing an added potential to porous media flows, swash-zone investigations typically omit such inclusions. Indeed, less well researched is the prevalence/non-prevalence of negative matric suction pressure on infiltration in the zone This research is aimed at filling this gap by investigating the significance of negative matric suction pressures on infiltration in the swash zone.

2. Relevant background

2.1 Negative suction pressures

Unsaturated porous media flows such as those evident in the swash zone, are unsteady and nonlinear. In such cases, the Darcy-Forchheimer equation is applicable. However, when considering the complexities of negative suction pressures, added models are necessary to account for the potential. Generally, total negative suction pressures comprise two individual components: matric and osmotic components. Typically, the osmotic component of total negative suction is unimportant and ignored when considering media flows (Bittetelli, Campbell and Tomei 2015). Regarding the matric suction component, the Richard's equation (equation 1) is well able to account for this additional pressure along with its variation with media moisture content (Ali and Villaroel-Lamb (2020).

$$\rho \cdot \partial\theta/\partial t = \nabla \cdot \left[K_h(\psi_m)\left(\nabla\psi_m + g\hat{Z}\right)\right] \qquad \text{equation (1)}$$

Where: θ is the volumetric water content of the media, ψ_m is the matric potential (better known as the negative suction potential), $K_h(\psi_m)$ is the hydraulic conductivity of the media at matric potential ψ_m, g is acceleration due to gravity and $\hat{Z}$ is the unit vector in the vertical direction.

It is commonly known that a relationship between negative matric suction pressures and soil water content exists for each media and is typically expressed via a Soil Water Characteristic Curve (SWCC) (Figure 1) as outlined by Li et al. (2022). The SWCC can be acquired via semi-empirical relationships or more reliably via laboratory tests.

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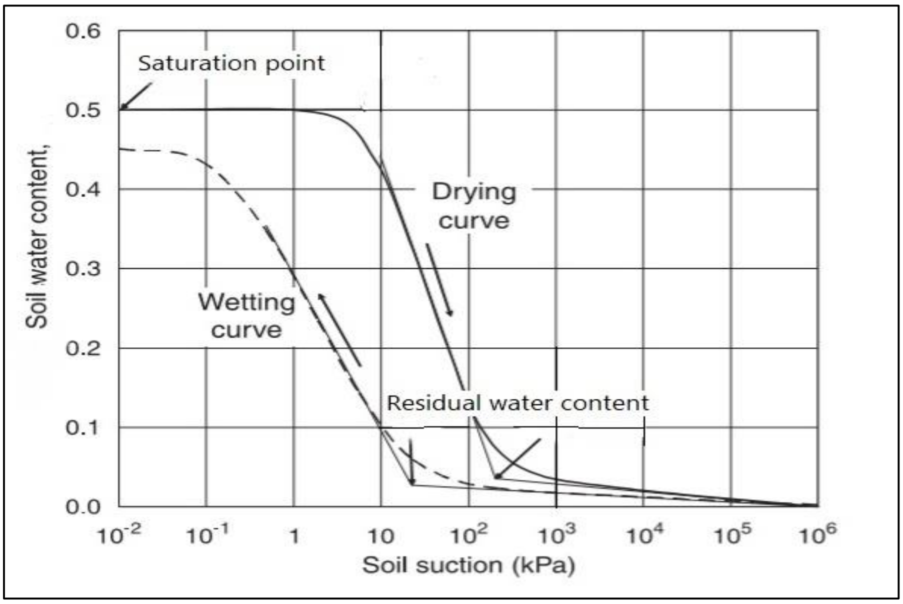

Figure 1 Typical SWCC adapted from Yang et al. (2004).

2.2 Measuring Matric Suction

A range of standardized laboratory tests, such as the filter paper method (ASTM D5298 - 16), tensiometer (ASTM D3404 - 15), pressure plate (ASTM D6836 – 16), and chilled mirror hygrometer (ASTM D6836 - 16), were developed to measure soil suction. Generally, laboratory experiments that are best suited for obtaining matric suction pressures are those using tensiometers or pressure plates. However, due to the high costs of testing and specialized equipment, semi-empirical relationships were created for simpler tests like grain size analysis and Atterberg limits, linking water content to matric suction pressures (Fredlund et al. 2002; Perera et al. 2005). Among the various laboratory tests, the tensiometer remains the most widely used method (Clark 1990), while the in-contact filter paper approach is simple and the most economical (Pan, Qing and Pei-young 2010).

The tensiometer (Figure 2) is high pressure, de-aired water-filled device comprising of a porous ceramic cup at one end connected to a pressure measuring device at the other by a small-bore tube (Fredlund and Rahardjo 1993). The device measures negative soil pressures via direct contact with the soil media and produces a matric suction reading only where a potential energy gradient between the tensiometer and the soil across the porous cup is evident. The device is best suited for lower negative pressures where - 90 kPa is the approximate upper limit (Fredlund and Rahardjo 1993).

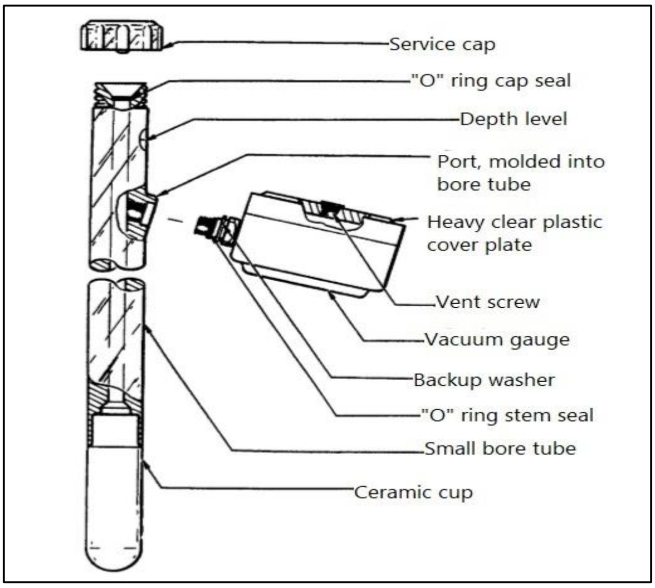

Figure 2 Typical tensiometer adapted from Fredlund and Rahardjo (1993)

The in-contact filter paper method can be dated to 1937 and is well abled to measure a wide range of suction pressures. However, the method is noted to be inaccurate for higher matric suction values (Pan, Qing and Pei-young 2010). The method works on the basis that water flows from a given media sample to an initially dry filter paper until hydraulic equilibrium between both is achieved; subsequent to which, a previously established calibration curve is used to relate between the water content and suction pressure for the specific filter paper (Kim, Prezzi and Solgado 2017). The method is the standardized as outlined by the ASTM D5298 – 16 procedure.

3. Materials and Methodology

3.1 Sample media and preparation

Seven (7) naturally occurring media (Table 1 and Figure 3) were used in the investigation. These sample media represented beaches comprised of fine pebbles to fine sand as classified by Wentworth (1922). The seven media also comprised of uniform sediment as noted by the coefficient of uniformity and poor gradation coefficient values and sub-rounded to rounded grain angularities (Table 2). The samples were initially prepared by thoroughly washing on a # 200 sieve, dried and loosely packed under the effects of gravity into respective moisture cylinders. The cylinders were gently tapped to allow for the settling of any unstable particulate arrangement and was then subjected to ten (10) successive

saturated and draining cycles. Thus, in this manner, each sample media was prepared at their respective residual water contents, representative of in-situ conditions between successive drained swash infiltration on natural beaches comprising of such homogenous media.

Table 1 Sample media ranges utilized for investigation

Sample	Size Range (mm)	Coefficient of Uniformity (C_U)	Coefficient of Gradation (C_c)	Classification (Wentworth (1922)
A	4.75 – 2.36	1.42	0.60	Fine – Very fine pebbles
B	2.00 – 1.40	1.23	0.74	Very coarse sand
C	1.40 – 1.00	1.20	0.77	Very coarse sand
D	0.85 – 0.71	1.10	0.87	Coarse sand
E	0.30 – 0.25	1.77	0.41	Medium sand
F	0.25 – 0.18	1.68	0.44	Fine sand
G	0.18 – 0.125	1.31	0.66	Very fine sand

Table 2: Angularity and angularity classification for samples A – G via Aggregate Imaging System (AIMS) adapted from Al-Rousan et al. (2005)

Sample	Size range (mm)	Average angularity	Angularity classification
A	4.75 – 2.36	1703.50	rounded
B	2.00 – 1.40	1970.90	rounded
C	1.40 – 1.00	2366.30	sub-rounded
D	0.85 – 0.71	3454.50	sub-rounded
E	0.30 – 0.25	3383.80	sub-rounded
F	0.25 – 0.18	3430.10	sub-rounded
G	0.18 – 0.125	3339.40	sub-rounded

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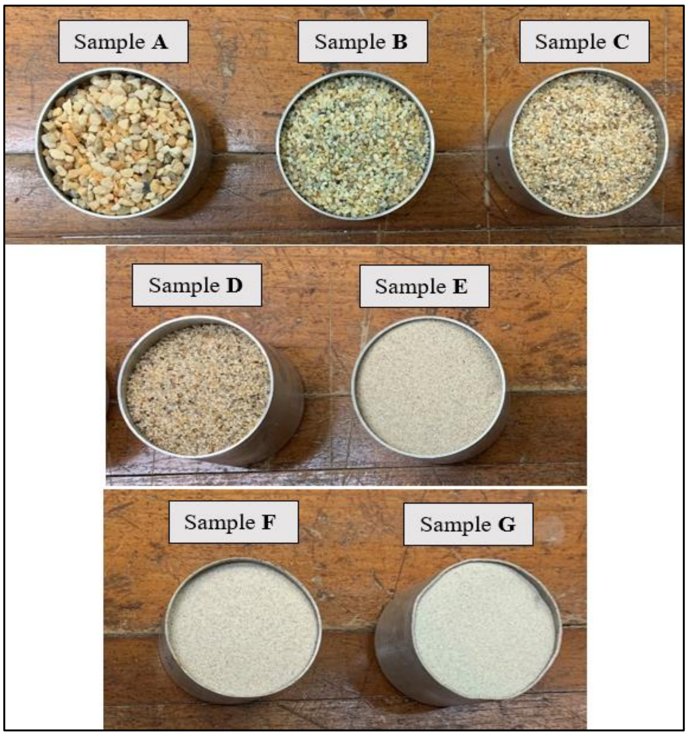

Figure 3 Sample media A – G used in experiments

3.2 Laboratory tests program

The experimental program conducted on the seven (7) sample media involved both tensiometer and in-contact filter paper test on the prepared samples. The experiments were all undertaken at the Department of Civil and Environmental Engineering Soils Laboratory, University of the West Indies, St. Augustine Campus, Trinidad and Tobago.

3.2.1 Tensiometer test

A Miniature Low Tension (MLT) IRROMETER tensiometer produced by the Irrometer Company Inc. was used due to anticipated low suction pressures from the coarse-grained samples. The device constituted the key components outlined in Figure 2. The set-up and service procedure of Fredlund and Rahardjo (1993) was adopted:

- The tensiometer was placed into the center of each prepared sample, such that, the ceramic cup tip was midway within the prepared sample.
- The open end of the cylinder with the remainder of the tensiometer protruding was then gently wrapped with clear plastic such that this end could be considered moisture sealed.

- The entire set-up was placed in a controlled environment for 24 hours, after which a gauge reading was taken.
- Another reading was taken a further 12 hours after to ascertain if equilibrium of the entire system was achieved for the initial first reading. In the event a change between readings was observed, readings were continued every 12 hours until consistency of values was observed.

Figure 4 presents the setup of the experiments for samples A – F.

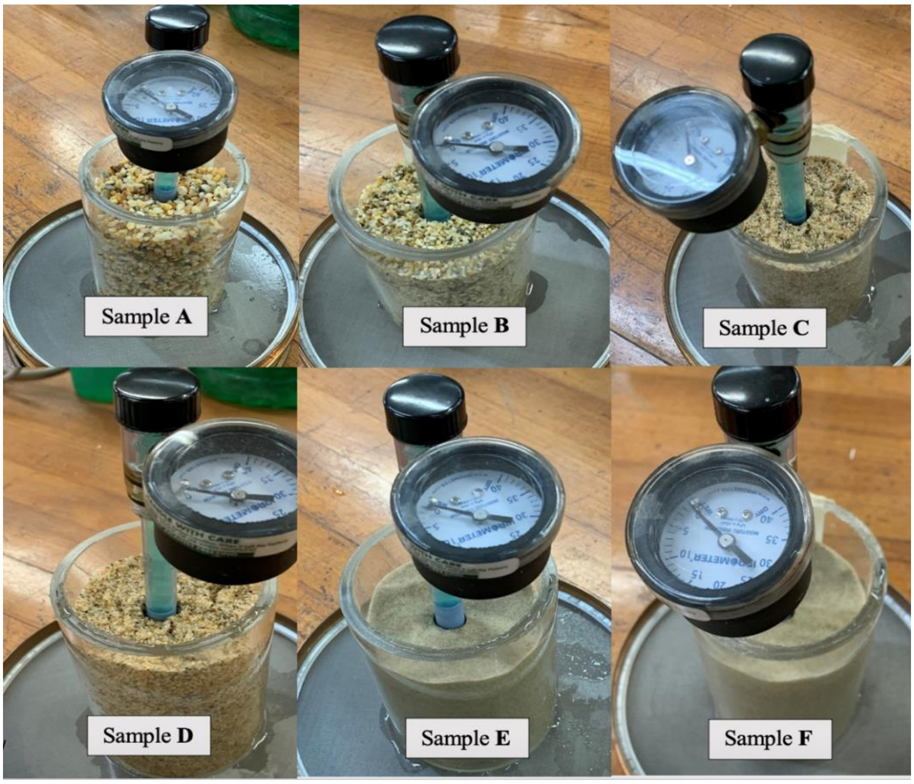

Figure 4 Matric suction experimental tensiometer set for samples A – F

3.2.2 In-contact filter paper test

The ASTM D5298 – 16 procedure was adopted for each of the seven sample media. Strict protocol was adopted to ensure: (1) full contact between the sample media and filter paper. (2) Sufficient time for hydraulic equilibrium (1 week) (Pan, Qing and Pei-young 2010). (3) Special handling of filter papers (Fredlund and Rahardjo 1993). The details of the laboratory

procedure, as adapted from Deka et al. (1995), Fredlund and Rahardjo (1993) and ASTM D5298-16:

- Two (2) types of filter paper were acquired and placed in an oven overnight to achieve full drying; quantitative ash-free Whatman No. 42 (5.5cm diameter) and qualitative Lab nerd 101 Fast (6.2 cm diameter) papers.
- The prepared samples were then placed within respective aluminum moisture cans and packed in a manner such that (a) only half of the tins were full with the respective samples and (b) samples were not significantly compacted such that it maintained a relatively close representation of in situ beach particulate arrangement.
- The filter papers were then removed from their respective jars, and seven sets of 3-stacked papers were arranged in a manner such that ash-free Whatman No. 42 papers were sandwiched between the larger diameter Lab nerd 101 fast papers.
- Respective stacks were then placed in each of the half-filled cans and then each can was topped up with their respective samples. Figure 5 outlines the set-up.

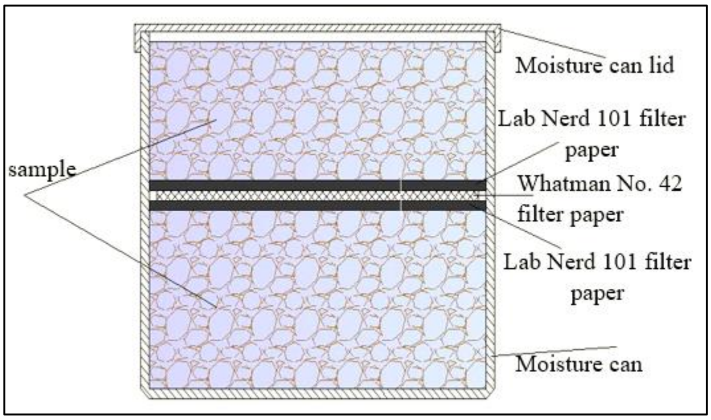

Figure 5 Generic set-up of in-contact filter paper method.

- Each can was covered with its respective lid, sealed and then placed in an insulated chest in a temperature-controlled room at 20˚C for one (1) week to achieve equilibrium. After the equilibrium period, the weight of seven (7) additional moisture cans was measured to the nearest 0.0001g and these were recorded as tare cold (TC).
- The chest was opened, sample cans opened and the central (ash-free Whatman No. 42) filter paper within each was removed and placed in the seven (7) additional moisture cans. Each can was then sealed and the weights of the filter paper and can were measured to the nearest 0.0001g. These weights were recorded as M1.

- The cans containing the filter papers were then placed in an oven to dry overnight.
- The weights of each can and dried filter paper were then measured to the nearest 0.0001g and recorded as M2 values.
- Immediately after measuring M2 values, the filter paper within each can was removed and the weights of the hot cans recorded as TH.

TC, M1, M2 and TH effectively constitute the in-contact filter paper method measurements. These values were then inputted into equations 2 – 4 to compute the equilibrium moisture content of the filter papers for each sample.

$$M_F = M_2 - T_H \qquad \text{equation (2)}$$

$$M_W = M_1 - M_2 + T_H - T_C \qquad \text{equation (3)}$$

$$WC_{fp} = 100 \cdot \left({}^{M_W}/_{M_F}\right) \qquad \text{equation (4)}$$

Where: MF is the mass of the dry filter paper, MW is the mass of the water in the filter paper and WC_{fp} is the filter paper water content in percent.

4. Results and Analysis

4.1 Tensiometer

The tensiometer test yielded results (Table 3) characterizing the matric suction pressures for the seven (7) naturally occurring media at their respective residual water content. The results for all the samples outline that the matric suction pressures measured by the IRROMETER MLT tensiometer are all ≤ 2kPa for media samples A – G. Due to limitations regarding sensitivity and accuracy of the gauge employed within the tensiometer, sufficiently precise readings were not possible.

Table 3 Equilibrium tensiometer readings for samples A – G at their respective residual water contents

Sample	Size range (mm)	Final tensiometer reading (kPa)	Photo observation
A	4.75 – 2.36	< 2	

B	2.00 – 1.40	< 2	
C	1.40 – 1.00	< 2	
D	0.85 – 0.71	< 2	
E	0.30 – 0.25	< 2	
F	0.25 – 0.18	< 2	
G	0.18 – 0.125	< 2	

4.2 In-contact filter paper

The in-contact filter paper suction method results (Table 4) all outlined filter paper water contents above 165%. Across all sample media, sample D, corresponding to grain size range 0.85 – 0.71mm, possessed the lowest water content value of 166.42 %. Whilst sample A, corresponding to size range 4.75 – 2.36mm, possessed the highest with a value of 183.75 %.

Table 4 In-contact filter paper method computations for samples A- G

Sample	Filter paper water content/WCfp (%)
A	183.71
B	178.29
C	174.20
D	166.42
E	173.20
F	175.07
G	177.62

The computed results in Table 4 were related to established Whatman No. 42 filter paper calibration curves, effectively yielding matric suction values present within each sample. A variety of calibration curves are available in literature. Figure 6 outlines the Whatman No. 42 filter paper calibration curves for Van Genuchten (1980), Greacen, Walker and Cook (1987), Fredlund and Xing (1994), Deka et al. (1995), Leong, He and Rahardjo (2002), Oliveira and Fernando (2006), ASTM D5928-10 (2010) and Kim, Prezzi and Solgado (2017). A level of uncertainty/division amongst researchers persists as to whether calibration curves relate to matric suction, total suction, or both. This division within the filter paper method is subject to on-going investigation.

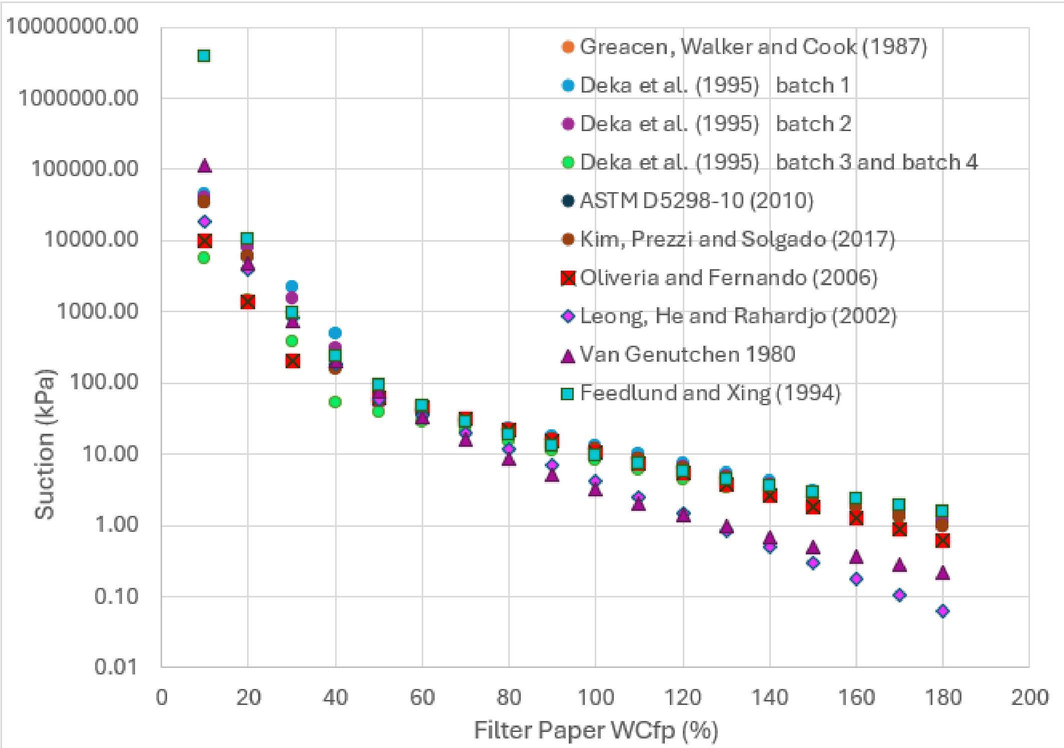

Figure 6 Whatman No. 42 filter paper calibration curves adapted from Kim, Prezzi and Solgado (2017) and Power, Vanapalli and Garga (2008)

Utilizing the computed results in Table 4 and calibration curves of Figure 6, matric suction pressures for each of the samples are presented in Figure 7. Noting these results, all samples fell within the range 0 – 2 kPa. However, suction values obtained within the grain size range 0.85mm- 0.71mm was notably higher ranging from 0.12kPa to 2.00 kPa.

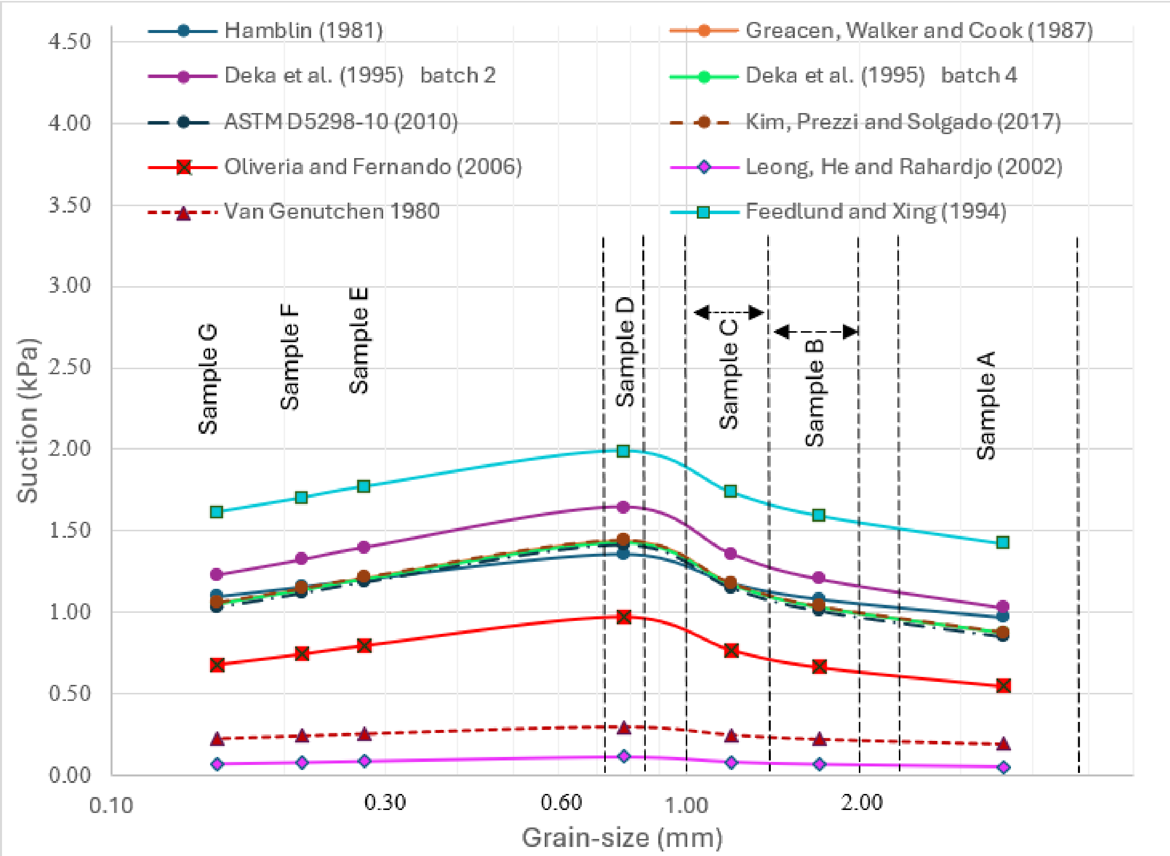

Figure 7 Matric suction variation across samples A – G for various Whatman No. 42 filter paper calibration curves

5. Discussion

The results of the tensiometer and in-contact filter paper method corroborate the existence of negative matric suction pressures within the range 0 – 2kPa for beach media ranging from fine pebbles to fine sand at their respective residual water contents. Although the tensiometer results were limited to solely outlining the beforementioned range, the in-contact filter paper method outlined more exact values for each respective media, permitting more detailed observations.

Firstly, across all the outlined Whatman no.42 calibration curves, it is easily seen that matric suction is a maximum within the grain-size range 0.85 – 0.71mm (Sample D). Grain-sizes above and below this range corresponds to incremental decreases from this value. Thus, it can be stated that within the threshold grain-size range (0.85-0.71) the influence of negative matric potentials (at residual pore-water content) within the swash zone is at a maximum.

Secondly, regarding the justification for omitting matric suction effects, consideration is given to: (1) the maximum suction values and, (2) the minimum suction values. Considerations (1) and (2) correspond to the worst-case and best-case scenarios of matric suction effects in the zone. Specifically, the minimum matric values (Leong, He and Rahardjo (2002): 0.05 – 0.12 kPa) corresponds to the best-case scenario which support the assumption of negligible matric suction contributions; whilst the latter is the worst-case scenario (Fredlund and Xing (1994): 1.42 – 1.99 kPa) which contradicts the assumption.

For the worst-case scenario, the matric suction pressures (as expressed by accelerations per infiltration depth) can range from 14200 – 19900 cm^2s^{-2}/cm. In such cases, the lower end of the range (14200 cm^2s^{-2}/cm) exceeds the gravitational potential for all infiltration depths < 15cm. Whilst, the upper limit (19900 cm^2s^{-2}/cm) exceeds the gravitational potential for all infiltrated depths < 20cm. These worst-case values outline the invalidity of assuming matric potentials are negligible when modelling unsaturated swash infiltration flows. For the best-case scenario, matric suction pressures can range from 500 – 1200 cm^2s^{-2}/cm (accelerations per infiltration depth). In this case, the lower end of the matric suction range never exceeds the gravitational potential, though it is worth mentioning that the matric potential values remain above 100 cms^{-2} (expressed as an acceleration) for all infiltration depths < 5cm. The upper range exceeds the gravitational potential only for infiltration depths < 1.5cm, though this upper range matric potential value remains above cms^{-2} (expressed as an acceleration) for infiltration depths < 12cm.

Via these observations, it is clear, even from a best-case scenario, noteworthy matric potentials are prevalent for unsaturated swash infiltration flows. The full extent ultimately depends on the exact suction value of the media, residual water content and the depth of infiltration. Thus, it appears invalid to fully neglect negative matric suction pressures when modelling swash infiltration flows, at least for grain-sizes within the range 4.75 – 0.125mm and particularly within the sub-range of 0.85mm – 0.71mm.

Admittedly, the differences between various researcher calibration curves prevent the establishment of an exact mathematical relationship between grain-size and in-bed matric suction values for coarse-grained media within the swash zone. Nonetheless, Figure 7 highlights undeniable trends and provides clear answers as to whether the omission of matric suction pressures is a reasonable assumption for swash-zone infiltration. It is

recommended that the investigation be expanded to include alternative matric suction test, the inclusion of osmotic suction and grain sizes beyond the range investigated.

6. Conclusion

The study demonstrates the significance of negative matric suction pressures in swash-zone infiltration flows for beach media ranging from fine pebbles to fine sand. The results outline that matric suction pressures can range from 0-2 kPa for the investigated range, with maximum values observed within the subrange of 0.85-0.71 mm. The findings suggest that omitting matric suction effects may not be justified, especially for worst-case scenarios where matric suction pressures can exceed gravitational potential. Even in best-case scenarios, noteworthy matric potentials are prevalent for unsaturated swash infiltration flows. The study highlights the need for careful consideration of matric suction pressures in modeling swash-zone infiltration flows. Further research is recommended to expand the investigation to include alternative matric suction tests, osmotic suction, and grain sizes outside the range investigated.

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Ethics Statement

The dataset presented in the research did not involve human subjects, animal experiments, or data collected from social media platforms. Therefore, Ethics approvals are not required.

Credit Author Statement

Anton Ali: Conceptualization, Methodology, Visualization, Investigation, Formal Analysis, Resources, Writing-Original Draft. **Damian Alexander**: Investigation, Methodology, Resources, Writing-Review and Editing

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