



EXPERIMENTAL OBSERVATION DATASET AND PROCESSED DATA FOR UNSATURATED POROUS MEDIA FLOWS

ALI A.^{1*}, ALEXANDER D.V.².

¹ Lecturer, Department of Civil and Environmental Engineering, The University of the West Indies, St. Augustine Campus, Trinidad and Tobago.

² Senior Instructor, Project Management and Civil Infrastructure Systems Unit, The University of Trinidad and Tobago, San Fernando, Trinidad and Tobago

(*) anton.ali@uwi.edu

Research Article – Available at <http://larhyss.net/ojs/index.php/larhyss/index>

Received April 22, 2025, Received in revised form January 12, 2026, Accepted January 15, 2026

ABSTRACT

The realm of porous media flows comprises of many sub-divisions with the unsaturated regime being the most complex accredited to variability in media moisture content, negative suction pressures and non-linearity linked to fluid acceleration effects. We present a dataset designed to be used for further investigations into this specific flow regime. The development of further unsaturated flow models, better calibrated spatio-temporal Darcy-Forchheimer's coefficients and improvements in numerical modelling in areas such as the swash zone are foreseeable. The dataset includes both raw and processed data. Both data sets are acquired from gravity driven one-dimensional unsaturated media flow experiments on four (4) natural unconsolidated media ranging from very fine pebbles – coarse sand. A total of one hundred and twenty-two (122) varying infiltrating conditions were conducted on the four (4) initially unsaturated media. The raw data was captured by a GoPro HERO 6 recording at 1080p with screen resolution 1920x1080 at 30fps. The raw dataset provides these recordings. The processed dataset provides instantaneous readings of infiltrating velocity at the media – fluid interface, infiltrated depth and driving pressure head optically extracted from recordings. The repository containing the processed data enables researchers to contribute additional unsaturated media experiments and expand the dataset collaboratively.

Keywords: Infiltration; Natural Media; Video-Based Analysis, Non-linear regression.

INTRODUCTION

Flows in porous media can be classed into several categories based upon the moisture content of the media, linearity/non-linearity of the flows and temporal variability of the flow system (Chetti et al., 2010; Gaaloul, 2015; Ikni et al., 2017). Generally, these

subdivisions are termed saturated or unsaturated, linear or non-linear, as well as steady or unsteady flow regimes (Ali and Villaroel-Lamb, 2020). The simplest cases are within the saturated realm and are correspondingly the most well researched. The Henry Darcy (1965) model is applicable for saturated- steady- linear porous media flows where very low pore Reynolds numbers are evident outlining the dominance of viscous forces (Cimolin and Discacciati, 2013; Bear, 1979). As porous media flow velocity increases whilst remaining within the saturated-steady realm, inertial effects manifest and flows transition to the non-linear realm. For such flows the Forchheimer (1901) law is applicable via the introduction of an added quadratic velocity term for inertial effects. Both aforementioned models employ the use of empirical coefficients based on media properties; However, the coefficient introduced by the Forchheimer law is less well universally defined (Sobieski and Trykozko, 2011). For porous media flows within the saturated, unsteady realm, a phase shift between pressure gradient across the media and flow velocities can exist (Laushley and Papat, 1968). In such cases both the Darcy (1965) and Forchheimer (1901) laws are modified to include a time derivative term and accompanying coefficient. One challenge in utilizing the modified equations is the possible variability of inherent coefficients within the equations (Zhu, 2016).

Porous media flows within the unsaturated realm are complex, being unsteady- non-linear with the added complexities of variable moisture content within the media and possible manifestations of negative suction pressures (Hountondji et al., 2019; Ali and Villaroel-Lamb, 2020). Various models exist for such flows, such as the simplified infiltration model of Green-Ampt (1911) or more complex process-based models such as Richards (1931) and combined models such as the Richards-Darcy-Forchheimer relation employed in Ali and Villaroel-Lamb (2020). Although popular, many limitations surround the use of such models. For example, considering the commonly used Darcy-Forchheimer relation in unsaturated settings, constant coefficients for phase shift and inertial effects may not be applicable over the entirety of the transient flow problem (Burcharth and Andersen, 1995). Indeed, in circumstances where driving pressure gradient can vary significantly, (e.g. swash-zone flows), uncertainties in coefficient values may be further exacerbated and constant values may be insufficient as observed by Zhu (2016).

This study aims to provide much needed quantitative real-life measurements for the continued improvement of such models, as well as, general research in the unsaturated porous media realm. Noting wide accessibility and marked advances in modern camera capabilities, real-life high-quality video observations of unsaturated infiltration present a simple avenue for acquiring such datasets. The usefulness of datasets acquired from such techniques has already outlined noteworthy findings, as in the case of Ali and Villaroel-Lamb (2020), where computed parameters originating from video observations revealed the invalidity of utilizing a single combination of the Darcy-Forchheimer coefficients in the unsaturated porous media realm.

METHODOLOGY

Materials and experimental set-up

The experiments used to acquire the datasets employed four (4) grain size ranges (Fig. 1 and Table 1) classified by Wentworth (1922) and comprised of uniform sediment as noted by the coefficient of uniformity and poor gradation coefficient values under the ASTM C136/C136M-19. Each range consisted of rounded to sub-rounded grains (Table 2) under the Aggregate Imaging System (AIMS) classification as adapted from Al-Rousan et al. (2005) and depicted in Fig. 2.



Figure 1: Laboratory photo of grain size ranges used in experiments

Table 1: Properties of grain size ranges used in experiments

| Sample | Size Range (mm) | Coefficient of Uniformity (CU) | Coefficient of gradation (Cc) | 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 |

Table 2: Angularity classification of grain size ranges used in experiments

| Sample | Size range (mm) | Average angularity | Angularity classification | Average 2D form | 2D form Classification |
|--------|-----------------|--------------------|---------------------------|-----------------|------------------------|
| A | 4.75 – 2.36 | 1703.50 | rounded | 7.30 | semi-circular |
| B | 2.00 – 1.40 | 1970.90 | rounded | 7.40 | semi-circular |
| C | 1.40 – 1.00 | 2366.30 | sub-rounded | 6.20 | circular |
| D | 0.85 – 0.71 | 3454.50 | sub-rounded | 7.20 | semi-circular |

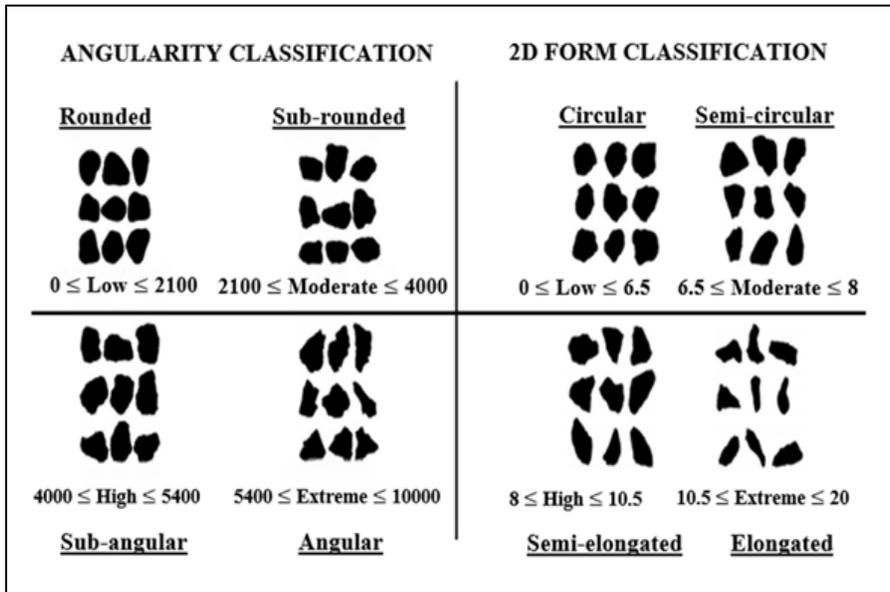


Figure 2: AIMS classification adapted from Al-Rousan et al. (2005)

The experimental set-up was similar to that of Ali and Lamb (2020). A transparent vertical square column with a side width of 0.1m and a length of 0.5m, open at one end and fitted with a wire mesh at the other (Fig. 3). The column was partitioned into two (2) sections with a removable watertight gate midway of the channel length where the lower section (section 2) was filled with the four grain size ranges and kept in place by the fitted wire mesh. The above section (section 1) was filled with clean dyed water (density 997kg/m³) to a desired depth and prevented from entering the porous media by the removable gate. Prior to placing the grain sizes into the column, each sample was washed on a #200 sieve, dried and loosely packed under the effects of gravity into the transparent hollow column. The column was then subjected to ten (10) successive saturated – unsaturated cycles via filling with water at the open-end whilst simultaneously blocking the wire mesh end until saturation of the entire column was observed. The water input was removed, and the column bottom was freed, allowing the saturated sample column to freely drain through the wire mesh. Thus, each grain size range retained their respective residual water contents.

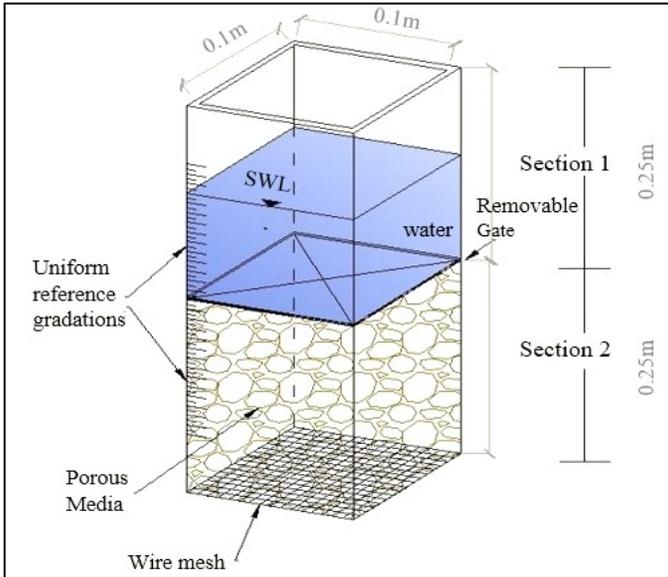


Figure 3: Experimental set-up (Ali and Villarroel-Lamb, 2020)

Experimental procedure

Section 1 was filled to a desired depth ($H_{initial}$) and prevented from entering the porous media via the removable gate. The experimental procedure involved removing the gate at high speed, permitting the above water to infiltrate into the unsaturated porous media due to gravity. Simultaneously, high frame rate videos were captured with a GoPro HERO6 recording at 1080p with screen resolution 1920x1080 at 30fps. These videos were taken along the transparent walls of the column to specifically monitor the waterfront progression within section 2 and the progressive decrease of the water depth elevation in section 1. The video observations were referenced against 0.0025m gradations in the direction of flow (zeroed at the gate location). The experiments were executed for each grain size range, for 122 initial infiltrating water depths ranging from 0.0275m to 0.18m. The results of the experiment constitute the raw data.

Raw data processing

Davinci Resolve 16 was used to extract time-referenced images from video observations. Observations (Fig. 4) of both the temporal progression of the infiltrating waterfront (D_{inf}) in section 2 and the decreasing Still Water Line (SWL) level (H) in section 1 were then used to compute the instantaneous infiltration flow velocities (U_{inf}) at the zero-referenced location. Utilizing a weighted average (equation 1) at the zero-referenced gate location resulted in the computation of U_{inf} . Figure 4 outlines the key measurements used in this process. The estimations constitute the processed data.

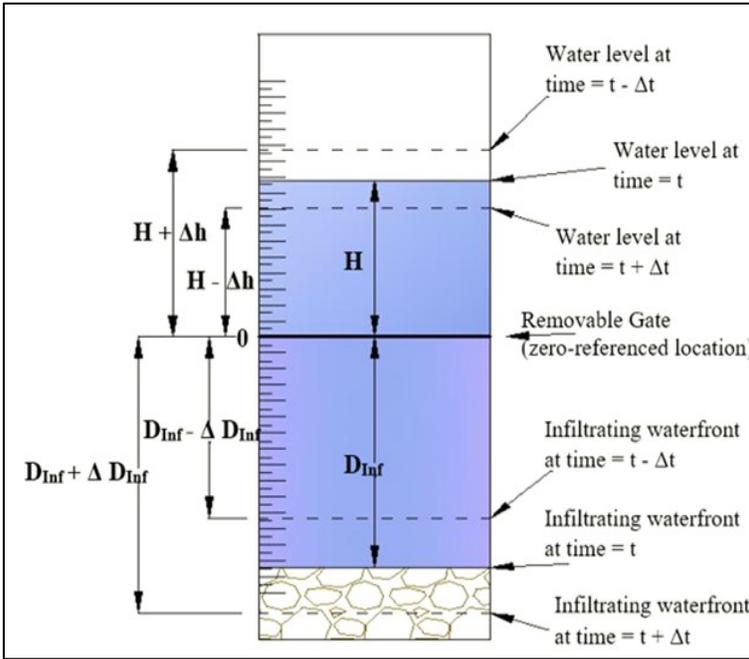


Figure 4: Measurements extracted in time-referenced images as adapted from (Ali and Villarroel-Lamb, 2020)

$$U_{\text{Inf}}(H, D_{\text{Inf}}) = \frac{1}{(D_{\text{Inf}} + H)} \left[\frac{(H + \Delta h) - (H - \Delta h)}{(t + \Delta t) - (t - \Delta t)} D_{\text{Inf}} \right] \times \left[\frac{(D_{\text{Inf}} + \Delta D_{\text{Inf}}) - (D_{\text{Inf}} - \Delta D_{\text{Inf}})}{(t + \Delta t) - (t - \Delta t)} H \right] \quad (1)$$

where: H is the water head in section 1 above the zero-referenced location, D_{Inf} is the infiltrated depth/infiltrating front in section 2 below the zero-referenced location, Δh is the change in water head (H) in section 1, ΔD_{Inf} is the change in the porous infiltrated depth/ infiltrating front (D_{Inf}) in the section below the zero-referenced location, $U_{\text{Inf}}(H, D_{\text{Inf}})$ is the instantaneous depth-averaged porous media velocity for water head (H) and infiltrated depth (D_{Inf}), both occurring at time (t). $(H + \Delta h)$ and $(D_{\text{Inf}} - \Delta D_{\text{Inf}})$ are the water heads and instantaneous depths occurring at time $(t - \Delta t)$, while $(H + \Delta h)$ and $(D_{\text{Inf}} + \Delta D_{\text{Inf}})$ are the water heads and instantaneous depths occurring at time $(t + \Delta t)$.

Limitations linked to the method were noted. Firstly, the non-instantaneous removal of the gate between sections 1 and 2 of the vertical column may have affected the uniformity of the infiltrating front across the channel. Secondly, the irregular packing of the sample material may have occurred within the column and at the gate-sample interface. Surface

tension effects between water and column walls are ignored. Minor vibrations around the time of gate removal can cause minor fluctuations in the water level (H) leading to possible errors in the observed video recordings. No account for added negative matric suction pressures that may have been present within each media at residual water content.

RESULTS AND DISCUSSION

The dataset originating from the experiments is provided on the open access online repository Ali and Alexander (2025) and detailed in Table 3. The data set is divided into three (3) main components (Fig. 5): (1) Raw data: A data repository containing four (4) folders containing the 122 experimental data video recordings from the unsaturated experiments; (2) Processed data: A repository which includes four (4) plots correlating to the four (4) media used in the experiment. The plots outline extracted instantaneous readings for interconnected infiltrating velocities, water head and infiltration depth; (3) An additional folder which provides a Readme.txt file and includes the related article by Ali and Villaroel-Lamb (2020). The Readme.txt file provides full details of the media properties used in the experiments.

Table 3: Dataset accessibility

| Repository Name | Mendeley Data |
|----------------------------------|---|
| Data type: | Raw data: Video Recordings-1080p screen resolution 1920x1080 at 30fps (.mp4). Processed data: plots (.pdf) |
| Data identification number (DOI) | 10.17632/wxk6n67252.1 |
| Direct URL to data | https://data.mendeley.com/datasets/wxk6n67252/1 |

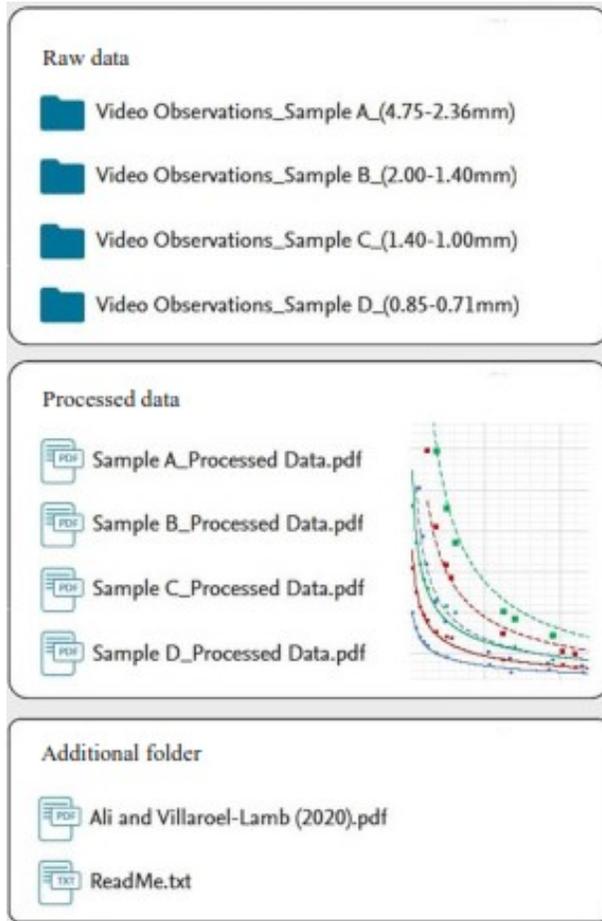


Figure 5: Illustration of the structure of the dataset

The raw data set contains 4 main folders: (1) video observations Sample A (4.75-2.36mm) which contains 29 .mp4 files; (2) video observations Sample B (2.00-1.40mm) which contains 32 .mp4 files; (3) video observations Sample C (1.40-1.00mm) which contains 32 mp4files; (4) video observations Sample D (0.85-0.71mm) which contains 29 .mp4 files. The structure of this folder is provided in Table 4. The processed data contains 4 .pdf files correlating to the 4 media types used in the experiments. These files provide visual plots of the interconnected readings taken of instantaneous water head (H), infiltrated depth (D_{Inf}) and infiltration velocity (U_{Inf}) as extracted from the raw data.

Table 4: Structure of the Raw data folder in the repository

| Folder | Sub-folder | File |
|----------|---|-------------------------|
| Raw Data | Video Observations Sample A (4.75-2.36mm) | H initial = 3.00cm.mp4 |
| | | H initial = 3.50cm.mp4 |
| | | H initial = 4.50cm.mp4 |
| | | ... |
| | Video Observations Sample B (2.00-1.40mm) | H initial = 18.00cm.mp4 |
| | | H initial = 2.75cm.mp4 |
| | | H initial = 3.00cm.mp4 |
| | | H initial = 3.50cm.mp4 |
| | Video Observations_Sample C (1.40-1.00mm) | ... |
| | | H initial = 18.00cm.mp4 |
| | | H initial = 2.75cm.mp4 |
| | | H initial = 3.00cm.mp4 |
| | Video Observations Sample D (0.85-0.71mm) | H initial = 3.50cm.mp4 |
| | | ... |
| | | H initial = 18.00cm.mp4 |
| | | H initial = 2.75cm.mp4 |
| | | H initial = 3.00cm.mp4 |
| | | H initial = 3.50cm.mp4 |
| | | ... |
| | | H initial = 18.00cm.mp4 |

The dataset provided is useful from the context that it provides video observations from the initiation of the infiltration process into an initially unsaturated media, which is an area of porous media flows less well researched. Moreover, the raw dataset was acquired across a range of coarse-grain media (very fine pebbles – coarse sand) and via a procedure that permitted a wide range of driving infiltration pressure heads. Within the field of earth sciences, the raw and processed dataset can support further investigations into unsaturated flows in coarse-grain media. Specific investigations relating to the calibration of coefficients in existing unsaturated flow models (e.g. Darcy-Forchheimer coefficients) can benefit significantly from the dataset. Further, numerical modelling of porous media flows and the development of novel empirically based-infiltration flow models are also envisioned. The raw and processed datasets are particularly valuable for investigations involving infiltration into unsaturated porous media where a highly variable infiltrating head and degree of media saturation are present such as in the upper swash-zone of the coastal zone.

Generic observations of the processed data plots outline infiltrating velocity variations which decrease as infiltration depth increases into each respective media. These observations are consistent with existing models such as Green-Ampt (1911), Phillip (1957), Darcy (1965) and Forchheimer (1901). The processed results are also consistent with unsaturated velocity profiles observed by Bitteli, Campbell and Tomei (2015). The implications of these observations outline the validity of the video method used in the study and the usefulness of the dataset acquired.

CONCLUSION

This research presents a combined raw and processed dataset from a series of unsaturated porous media flows across natural coarse-grained media. This dataset is openly available via the online repository by Ali and Alexander (2025) and contains 122 video observations and four (4) processed data plots. The results are significant from the context of documenting and detailing unsaturated media flows from the onset of infiltration onwards. Thus, the dataset provided permit for further research into many issues currently hindering existing unsaturated flow models, as well as, further development into the unsaturated flow regime of natural porous media flows. General observations from the processed data are consistent with trends from existing porous media and infiltration models; thereby confirming the relevance of the dataset and suitability of the methodology used. Future expansion of the dataset is recommended to include a wider range of media sizes, driving pressure gradients and inclusion of additional potentials such as negative suction pressures.

Acknowledgements

The authors would like to thank the University of the West Indies, St. Augustine Campus, department of Civil and Environmental Engineering staff for the assistance granted in experiment execution. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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