Particle size effects on the water retention properties of colluvial sediments

Rodrigo Osses i,ii,iii), Jubert A. Pineda iv), Carlos Ovalle v), Sandra Linero vi) and Stephen Fityus vii)

i) PhD Visiting Researcher, School of Engineering, The University of Newcastle, Callaghan Campus, Newcastle, NSW 2308, Australia.
ii) PhD Candidate, Department of Structural and Geotechnical Engineering, Pontificia Universidad Católica de Chile, Avda. Vicuña Mackenna 4860, Santiago, 7820436, Chile.
iii) Assistant Professor, Department of Civil Engineering, Universidad de La Frontera, Avda. Francisco Salazar 01145, Temuco, 4780000, Chile.
iv) Senior Lecturer, Priority Research Centre for Geotechnical Science and Engineering, School of Engineering, The University of Newcastle, Callaghan Campus, Newcastle, NSW 2308, Australia.
v) Assistant Professor, Research Institute of Mining and Environment (RIME UQAT-Polytechnique), Department of Civil, Geological and Mining Engineering, École Polytechnique de Montréal, Montreal, Canada.
vi) PhD Candidate, Priority Research Centre for Geotechnical Science and Engineering, School of Engineering, The University of Newcastle, Callaghan Campus, Newcastle, NSW, 2308, Australia.

vii) Professor, Priority Research Centre for Geotechnical Science and Engineering, School of Engineering, The University of Newcastle, Callaghan Campus, Newcastle, NSW, 2308, Australia.

ABSTRACT

This paper explores the influence of the particle size on the water retention properties of a colluvial deposit derived from banded iron formations in the Pilbara region in Western Australia. A small-scale experimental program aimed at evaluating the water retention curve of 4 particle fractions (1.18 - 2.36 mm, 0.60 - 1.18 mm, 75 - 600 µm and < 75 µm) is described. Water retention curves, defined in terms of the gravimetric water content vs total suction, were obtained by exposing the specimens to a controlled wetting path using the vapour transfer technique. Total suction was measured using a dew-point psychrometer. The experimental results show an important increase in the maximum water retention capacity with decreasing the particle size. Finally, the influence of the water storage of each particle fraction on the water retention curve of mixed specimens, i.e. those composed by several fractions, is discussed.

Keywords: water retention curve, colluvium deposit, particle size, total suction, relative humidity, vapour transfer.

1 INTRODUCTION

Proper characterization of the water retention properties of rockfill-type geomaterials is fundamental for predicting the performance of civil infrastructure. Rockfill dams and excavations for mining exploitation are typical examples where the estimation of the water retention properties for the construction material is essential to assess settlement and stability problems caused by moisture content changes. In situ and laboratory data have demonstrated that wetting induced settlement is a common phenomenon in rockfills (e.g., Marsal, 1973; Naylor et al., 1997; Oldecop & Alonso, 2001). This behaviour is explained by breakage of particles caused by rock weakening due to wetting. Such a weakening effect is controlled by the water sensitivity of the rockfill.

The water retention curve (WRC) is commonly used to evaluate the water sensitivity of geomaterials. It provides information about the water storage capacity of soils and rocks which is controlled by two main mechanisms (e.g., Romero & Vaunat, 2000; Olivella & Gens, 2000): (i) the flow of free water through the ‘macro’ pores, (ii) the water adsorption at ‘micro’ porosity level (e.g. intra-aggregate). Whereas the storage of water in the macro pores is highly influenced by changes in void ratio (or dry density), water adsorption at micro level does not depend on macrostructure. Two sets of voids can be considered in rockfill materials (Oldecop & Alonso, 2001): macro voids formed by inter-particle spaces and micro voids contained within single particles. Rockfills are typically composed by more than one particle size. From an experimental point of view, large particles are problematic as they exceed the dimensions of typical devices employed to measure suction in the laboratory. The alternative in these cases is to estimate the WRC by using small specimens, assuming that scale effects are negligible.

This paper describes preliminary results of an...
experimental study aimed at evaluating the effects of the particle size on the water retention properties of colluvial deposits from Western Australia. Water retention curves estimated for four particle fractions are presented in the following sections. Emphasis is given to the contribution of each particle fraction to the water retention capacity of specimens composed by mixed fractions.

2 MATERIAL TESTED

The material tested comprised the eroded and transported particles (colluvium) derived from sedimentary Precambrian-aged Banded Iron Formation (BIF) found at the Pilbara region (Western Australia). These deposits, which consist of alternating beds and laminae of hematite or magnetite and chert, comprise BIF fragments up to 150 mm. Figure 1 shows the particle size distribution of a ‘natural’ sample reported by Linero et al. (2017). Inspection of Figure 1 shows that particles larger than 50 mm correspond to less than 3% of the mass in the natural specimen.

![Particle size distribution](image)

Fig. 1. Particle size distribution for the colluvial sediments from the Pilbara region (Linero et al., 2017).

Four particle fractions are analyzed in this study: 1.18 - 2.36 mm, 0.60 - 1.18 mm, 75 – 600 µm and < 75 µm. These fractions are shown in Figure 2. The fine fraction (<75 mm) has a liquid limit varying between 19 - 27% whereas the plasticity index falls consistently around 6%. This material classifies as a low plasticity clay/silt (CL-ML). Particle fractions tested here have a predominant sub-equant block shape, in contrast to larger particles which tend to be more platy (less elongated and flatter) (Linero et al., 2017). Mean values for elongation ratio (breadth to length: I/L), flatness ratio (thickness to breadth: S/I) and roundness coefficient established by Linero et al. (2017) are shown in Table 1.

![Particle fractions](image)

Table 1. Shape descriptors (Linero et al., 2017).

| Shape descriptor | Size fraction |
|-----------------|---------------|
|                 | 1.18–2.36 mm | 0.60–1.18 mm | 75 – 600 µm |
| Mean I / L      | 0.79          | 0.76          | 0.79         |
| Mean S / I      | 0.54          | 0.54          | 0.50         |
| Mean roundness coefficient | 0.34 | 0.27 | 0.30 |

3 EXPERIMENTAL PROGRAM

The WRC, defined in terms of the gravimetric water content \( w \) vs total suction \( \psi \), was obtained by exposing the tested specimens to controlled hydraulic paths using the vapour transfer technique (e.g. Blatz et al., 2008). This is achieved by means of a closed system (constant vapour mass) in which water vapour could be absorbed by rock particles (see Figure 3). The thermodynamic relationship between relative humidity \( RH \) and total suction \( \psi \) (which considers the contribution of capillary \( s \) and osmotic \( \pi \) effects: \( \psi = s + \pi \)) is given by Kelvin’s law:

\[
\psi = -\frac{RT\rho_w}{M_w}\ln(RH)
\]

where \( R \) is the gas constant (8.314 J/(mol K)), \( T \) is the absolute temperature, \( M_w \) is the molecular mass of water (18.016 kg/kmol) and \( \rho_w \) is the density of pure water (998 kg/m³ at 293 K).

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Only the wetting branch of the WRC is presented in this paper. The estimation of the WRC followed a multi-stage approach. Different suctions were achieved by exposing samples to water vapour for different lengths of time. When target values of water content change are reached, the samples were extracted, sealed and stored at controlled conditions.
for at least 48 h to allow them to reach suction equilibrium prior measuring the total suction using the WP4C dew-point psychrometer (see Figure 4). This process was repeated until measured suction was close to the upper (300 MPa) and lower (0.05 MPa) limits of the psychrometer.

The WP4C measures the temperature at which condensation first appears (dew-point temperature) when a sample reaches equilibrium with the surrounding air within the housing chamber. The chamber contains a mirror and also a condensation detector (on the mirror), where a photoelectric cell measures the mirror reflection. A reduction in reflection indicates the condensation point. The relative humidity RH is obtained from the difference between the dew-point temperature of the air and the temperature of the soil sample, which is measured with an infrared thermometer. It is assumed that since both dew-point and sample surface temperatures are simultaneously measured, the need for complete thermal equilibrium is eliminated. With this process, each measurement on the WRC takes around 15 minutes. More details about the technique and apparatus employed might be found in Decagon Devices (2018).

3 RESULTS

Figure 5 shows the wetting branch of the WRC obtained for the four particle fractions evaluated in this paper. The initial suction, i.e. the “air dry” suction at laboratory conditions, is around 75 MPa irrespective of the particle size. The fact that initial total suction is not affected by particle size confirms the proper equalization of the RH within all the specimens prior testing. Nevertheless, particle size seems to have a small influence on the initial water content. It varies from 1.20 % (1.18 - 2.36 mm) to 1.60 % (< 75 µm).

The results obtained during the wetting path show a consistent increase in the water retention capacity with decreasing the particle size. The maximum water content measured at the end of the wetting path (ψ ≈ 1 MPa) for the lowest (< 75 mm) and largest (1.18 – 2.36 mm) particle fractions are equal to 6% and 3.25%, respectively. Fractions between 0.60 – 1.18 mm and 75 – 600 µm display values around 3.6 % and 4.5%, respectively. The increase in the water retention capacity may be due to differences in the mineralogical composition between fractions but also by an increase in the specific surface with reducing the particle size. Additional tests are currently underway to confirm these two hypothesis.

Experimental results presented in Figure 5 have been fitted with the modified van Genuchten model proposed by Jacinto et al. (2009), defined as:

\[
w = w_{sat} \left[ 1 + \left( \frac{\psi}{P_0} \right)^{\frac{1}{\lambda}} \right]^{-\lambda}
\]

where \(w_{sat}\) is the gravimetric water content at saturated conditions and \(P_0\) and \(\lambda\) are parameters obtained by fitting.

Figure 6 compares the experimental data and the simulated wetting paths via Eq. 2. Values of \(P_0\) and \(w_{sat}\) are reported in this figure for completeness. A fixed value of \(\lambda\) is used to simulate the experimental data for all particle fractions, so that only parameter \(P_0\) (in addition to \(w_{sat}\)) controls the WRC for the colluvial sediment fractions tested in this study. \(P_0\) increases with the particle size, from 1.6 MPa (< 75 µm) to 3.7 MPa (0.60 – 1.18 mm and 1.18 – 2.36 mm). Although not directly associated with it, the
increase in $P_0$ suggests the increase of the air entry value (AEV) with particle size. This behaviour is consistent with the fact that water storage capacity in rockfill materials is mainly controlled by micro pores of single particles as discussed by Oldecop & Alonso (2001). Particle fractions between 0.60 – 1.18 mm as well as 1.18 – 2.36 mm are expected to have lower porosity (void ratio) than smaller particles, since the smaller particles are likely to be mineralogically different, as is evident from the plasticity of the fines. This, in turn, implies they would have larger AEVs.

The WRCs described above show that lower values of gravimetric water content are obtained in fractions of larger sized particles when exposed to the same relative humidity (total suction). As rockfills typically include several particle sizes it is important to evaluate what is the contribution of each fraction to the WRC of mixed specimens.

The WRC (wetting branch) of a new specimen composed by the four fractions described earlier was estimated and compared against the WRCs presented in Figure 6. Figure 7 shows the PSD adopted for the preparation of the mixed specimen. Particle sizes between 0.60 – 1.18 mm dominate with 59.1 % followed by largest particles (1.18 – 2.36 mm) with 16.9%. The contribution of the smallest fraction (< 75 mm) is 10%. The same experimental protocol described above was followed in the estimation of the WRC for the mixed specimen.

Figure 8 shows values of total suction and water content estimated for the mixed sample during wetting. The fitted curves obtained via Eq. 2 are also included in this figure as reference. At the initial “air dry” water content, the results are closer to the WRC of the largest particle fraction (1.18 – 2.36 mm). As wetting proceeds, there is an increase in the water retention capacity of the mixed sample which eventually falls above the WRC of the dominant particle fraction (0.60 – 1.18 mm). A maximum water content of 4.5% is observed at the lowest suction applied during the wetting path. These results show that larger particle sizes, which are the main contributors to the PSD, control the water storage capacity at high suctions. On the other hand, the smaller fraction seems to play an important role on the water absorption at low suctions even if this is not a major contributor to the PSD.

The possibility for combining the WRC of single particle fractions to ‘predict’ the WRC of mixed specimens is currently under study by the Authors.

Fig. 6. Fitted WRCs using Eq. 2.

4 DISCUSSION

Fig. 7. PSD for the mixed specimen.

Fig. 8. Comparison between WRC for single particle fractions and mixed fractions.
5 CONCLUDING REMARKS

The influence of the particle size on the water retention properties of colluvial sediments derived from BIF has been evaluated in this paper. It has been shown that the maximum water retention capacity increases with decreasing the particle size. The comparison between the water retention curve of a mixed specimen and those obtained for single particle fractions shows that larger particle sizes (the main contributors to the PSD) control the water storage capacity at high suctions. However, smaller particle sizes seem to control the maximum water storage of the mixed specimen. Experimental results described in this paper suggest that it would be possible to predict the water retention curve for specimens composed by a wide variety of particle fractions by combining the curves obtained experimentally on single fractions. This aspect is currently under study by the Authors.

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