Dispersion and re-deposition of colloidal particles and their effects on hydraulic conductivity in sandy soils

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Abstract

Measurements of saturated hydraulic conductivity (K) have been used to determine the factors controlling the rates of structural breakdown and pore clogging which occurred during leaching of two sandy soils, one of agricultural origin and the other a mining residue. Soil columns were leached with solutions of different electrolyte concentrations under saturated conditions using a Marriotte constant-head device. A reference hydraulic conductivity (Ko) was considered to be that measured initially at the highest concentration of 500 mmol/L sodium chloride (NaCl) solution. Subsequently measurements were made with either abrupt change of concentration to 1 mmol/L or gradual decreasing concentration from 500, 100, 50, 10 to 1 mmol/L NaCl followed by deionised water. The relative hydraulic conductivity (K/Ko) decreased substantially with time and with decrease in electrolyte concentrations for both soils. The decrease in K/Ko was attributed to decreases of pore radii as a result of detachment followed by re-deposition of the clay fraction during leaching. There was little difference in ultimate K/Ko reduction between the abrupt and gradual changes of concentration from 500 to 1 mmol/L for both soils. The mining residue was substantially more prone to structural collapse than the agricultural soil with absolute K reductions from 61 to 0.2 mm/h and from 15 to 1.4 mm/h respectively with change in solution concentration from 500 to 1 mmol/L.

Key Words

Hydraulic conductivity, soil structural breakdown, dispersion, leaching, colloidal particles, electrolyte concentration.

Introduction

Structural instability and subsoil structural deterioration (Aylmore and Cochrane 1995) are common physical problems known to affect land productivity. Several studies simulating aggregate breakdown and stability have been carried out (Le Bissonnais 1995; Loch 1994 and Quirk 2001). Aggregate breakdown is important in the production and release of fine or colloidal particles. The release of colloidal particles is favoured by high pH, irrigation with Na-rich water of low ionic strength and high intensity rainfall events. The effects of electrolyte concentration on swelling, dispersion and permeability have been extensively studied (Schofield and Quirk 1955 and Abu-Sharar and Salameh 1995). During dispersion colloidal particles are mobilized and these can then be re-deposited within the soil matrix thereby resulting in changes in pore size and geometry.

We have used measurements of hydraulic conductivity (K) to examine and contrast the factors controlling the rates of structural breakdown and pore clogging which occur during leaching of two sandy soils, one of agricultural origin and the other a mining residue. This study was carried out to elucidate and compare the influence of solutions of various electrolyte concentrations on dispersion and re-deposition of colloidal particles during leaching and hence on hydraulic conductivity.

Materials and Methods

A sample of the Balkuling sandy loam soil, a soil extensively used in Western Australian agriculture, was collected from “Yalanbee” CSIRO Research station farm near Bakers Hill, Western Australia. The mining residue, a loamy sand consisting of waste products (>63 µm tailings sands and <63µm fines) was collected from the Cable Sands (WA) Pty. Ltd. Sandalwood Mine site, 5 km north of Brunswick Junction, Western Australia. The clay-sized fractions of the two soils were determined using a Malvern Mastersizer analyzer [Mastersizer Microplus Ver.2.18, c/o Malvern Instruments Ltd.1995]. A clay refractive-index (RI) of 1.59 was used in the analysis and a particle density of 2.6 g/cm^3 were assumed. Water was used as dispersant (RI = 1.33). The remaining fractions, comprising of sand sized particles, were determined using a mechanical wet-sieving method (Day 1965). Samples were allowed to pass

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through the sieve sizes of 1, 0.5, 0.25, 0.125, and 0.045, mm and the various sand fractions were collected and their proportions by weight calculated.

Air-dry soil aggregates (< 2 mm) were uniformly packed into 3cm long and 5cm diameter columns to a packing density of approximately 1.65 g/cm^3. Samples within the columns were confined between coarse sintered-glass plates to enhance hydraulic contact, while a 50 micron nylon mesh was placed as a filter in both ends of the soil columns. The samples were first flushed with carbon dioxide (CO_2) to remove entrapped air and then saturated overnight in a tray filled with the desired solution prepared using de-aired water.

Pore-size distributions of the soil columns were estimated from water-retention versus water-potential curves determined using sintered glass funnels and the Haines method over the low pressure ranges (measured at 5 cm suction interval) and pressure-plate, ceramic-membrane apparatus for the higher pressure range (10 to 800 KPa). The column samples were pre-wetted with 0.1*M* $CaCl_2$ solution to avoid swelling. The soils were predominately kaolinitic in nature and therefore have low swelling potential. The water-retention data was transformed to pore-size distribution using the form of Kelvin equation:

$$\Delta P = (2\sigma / r_p) \qquad (1)$$

where ΔP is the pressure difference (Pa) across an air-water interface, σ is the surface tension of water(Jm^{-2}) and r_p is the radius of a circular capillary tube (m).

The soil columns were leached with solutions of different electrolyte concentrations adjusted to pH 8.5. The hydraulic flow was under saturated conditions using a Marriotte constant-head device. Table 1 present column characteristics before leaching, and after leaching with 1 mmol/L NaCl. The hydraulic conductivity was measured during these flows.

Table 1. Column characteristics during measurement of hydraulic conductivity.

	Before leaching		**After leaching**	
Property	**Balkuling sand**	**Mining Residue**	**Balkuling**	**Mining Residue**
Packing density (g/cm^3)	1.69	1.60	1.69	1.60
Pore volume (cm^3)	21.7	22.9	19.8	22.1
Weight of soil (g) used	95.0	84.7	95.4	85.2
Column volume (cm^3)	56	53	56	53
Void ratio or Porosity (-)	0.387	0.431	0.354	0.417

We define a reference conductivity hydraulic conductivity (*K*o) as being that measured initially at the highest electrolyte concentration of 500 mmol/L sodium chloride (NaCl) solution. Subsequently, measurements of *K* were made during flow following either an abrupt change of concentration to 1 mmol/L or a gradual decreasing concentrations from 500, 100, 50, 10 to 1 mmol/L NaCl followed by deionised water. The saturated hydraulic conductivity during these steady-state flows were estimated using Darcy's law for one-dimensional vertical flow:

$$K = (4VL)/(\pi d^2 \Delta t \Delta H) \qquad (2)$$

where V (L^3) is the volume of water collected during time interval Δt (T), L (L) is the length of soil sample, d (L) is the inner diameter of the column and ΔH (L) is the change in hydraulic head across the soil sample.

The sizes of any particles found in the effluents from the leaching columns were also examined using the Malvern Master Sizer.

Results and discussion

Particle size distributions

The particle-size distributions obtained by wet sieving for the sand fractions of the Balkuling soil and the Cable Sands Mining Residue, together with those for the clay fractions and for effluent particles obtained from the columns at the lowest electrolyte concentration are shown in Figure 1.

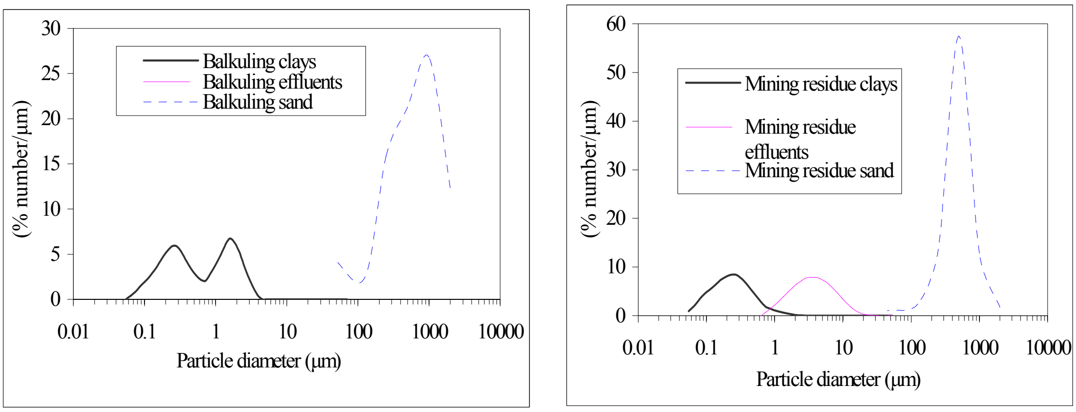

Figure 1. Particle size distributions for clay, sand and effluent particles (at 1 mmol/L NaCl) (left -Balkuling and right- Cable mining residue).

The Balkuling clay fraction exhibits a bimodal distribution of particle sizes ranging from 0.08 to 5 microns. The peaks are at approximately 0.3 microns and 2 microns. The mining residue has a single peak ranging from 0.05 to 2 microns. The sand distributions for both materials range from approximately 45 to 2000 microns, with a somewhat narrower distribution for the mining residue

Pore Size Distribution of Soil Columns

The pore-size distributions were obtained from water retention data and presented as (dθ/dr) where θ is volumetric water content and r is pore radius. The pore-size distributions for the columns packed with Balkuling soil and Cable Mining residue are shown in Figure 2.

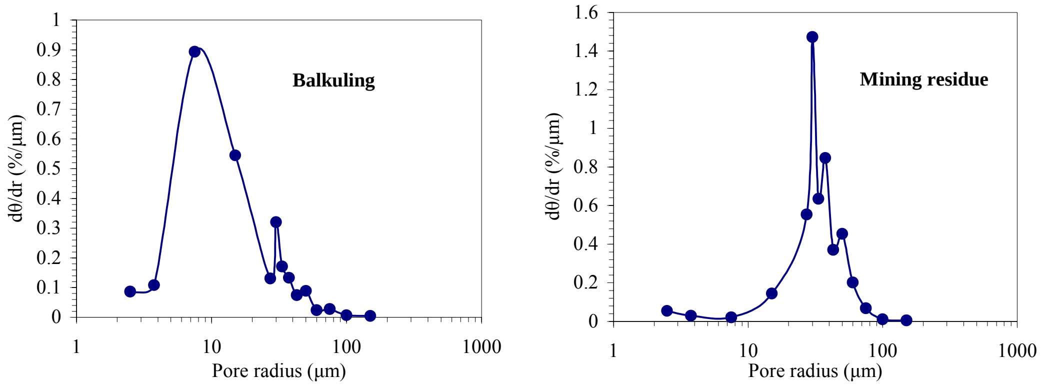

Figure 2. Pore size distribution of porous medium (left- Balkuling and right-Cable Mining residue).

The pore size distribution for the Balkuling soil columns were broader with the peak occurring at approximately 8 microns while those for the Cable residue were much narrower with a peak at approximately 12 microns.

Electrolyte concentration effects on aggregate breakdown and hydraulic conductivity with time

Figures 3a and 3b show that the relative hydraulic conductivity (K/Ko) of both materials decreased with decreasing concentration, and with time during leaching. The decrease of K/Ko at higher electrolyte solution was attributed to aggregate slaking during the initial wetting of the mixture (Keren and Ben-Hur 2003) while at lower concentrations K/Ko decreased as a result of swelling and dispersion. The reference saturated hydraulic conductivity (Ko) for the mining residue, and the Balkuling sand for both abrupt and gradual concentration changes during leaching with 500 mmol/L, were 61 and 15 mm/h respectively decreasing to minimums of 0.2 and 1.4 mm/h respectively during leaching with 1mmol/L NaCl solution. There was little difference in hydraulic conductivity between the abrupt and gradual changes of concentration when the columns were finally leached with 1 mmol/L solution for both soils (Figs. 3a and 3b). However K/Ko decreased by 1 and 3 - 4 orders of magnitude in the agricultural soil and mining residue, respectively. No clay was observed in the effluents from either material until the electrolyte concentration was reduced to 1 mmol/L.

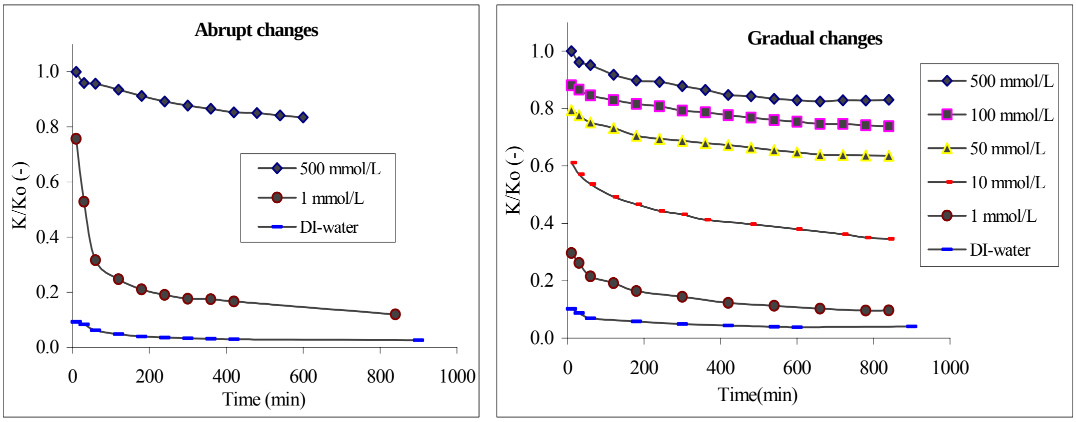

Figure 3a. Relative hydraulic conductivity as a function of electrolyte concentration (left-abrupt and right-gradual changes) in Balkuling sandy soil.

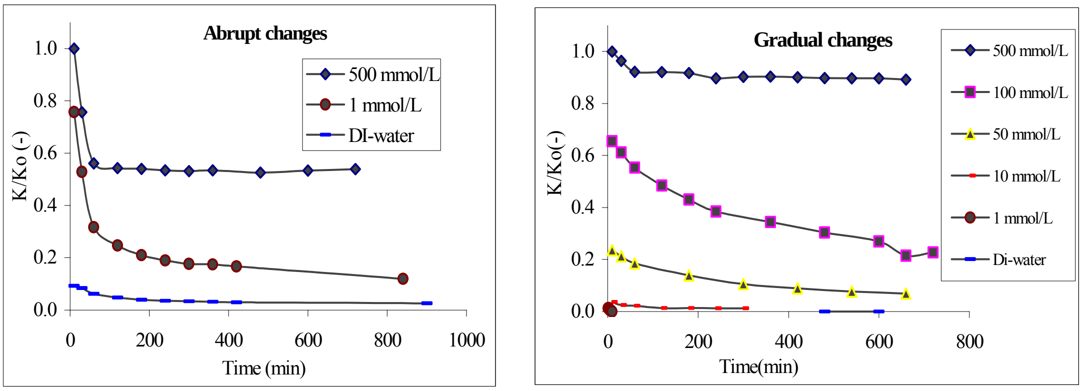

Figure 3b. Relative hydraulic conductivity as a function of electrolyte concentration (left-abrupt and right-gradual changes) in Cable mining residue sandy soil.

Some internal swelling is likely to have occurred within the rigid sand matrix of the columns to an extent determined by the ionic concentration of the leaching solution. With the observation of material in the effluent, once the very lowest concentration had been reached the decreases in permeability would seem to be significantly enhanced by the detachment, re-deposition and entrapment of clay particles within the sand matrix. This would likely result in pore radii decreases. However no effluent particles were observed until the lowest concentrations had been reached when dispersion would have greatly enhanced particle mobility.

The mining residue soil was more vulnerable to structural collapse than the Balkuling soil with absolute K reductions from 61 to 0.2 mm/h and from 15 to 1.4 mm/h respectively with a change in solution concentration from 500 to 1 mmol/L. This relative difference is likely to be related to the nature of the different clay constituents. The Balkuling soil is predominately kaolinite while the mining residue contains an equal amount of smectite clay particles which are more readily mobilized. The narrower and smaller pore size distribution of the mining residue columns (Figure 2) may also facilitate the re-deposition of detached clay particles.

Similar results were obtained by Keren and Singer (1988) for sand-clay mixture who reported that during gradual reduction in leaching concentration, a steady decrease of K was observed with no clay in the leachate. With their abrupt change to leaching with a lower concentration, and then deionised water, there was a sharp drop in K and dispersed clay was observed in the leachate. Similarly decreases of orders of magnitude in the hydraulic conductivity (up to 3 - 4) were reported by Keren and Singer (1988) for a clay-sand mixture leached with 5 mmol/L solution with sodium adsorption ratios (SAR) 10.

Effluent particles and particle sizes of migrating clays

The particle size distribution of the effluent particles from the columns at the lowest electrolyte concentrations are shown in Figure 1. The results reveal that the particles in the effluent leaving the soil systems were relatively larger than the clay sized fraction, indicating that detached particles probably included larger aggregations of clay plates, as well as the finer fractions.

Conclusions

Our relative hydraulic conductivity (K/Ko) defined on the basis of electrolyte concentration, for both the agricultural soil and the mining residue, decreased with decreasing concentration and with time during leaching. The extent of the drop was presumably determined by the effects of swelling and dispersion and decreases in pore radii as a result of detachment followed by re-deposition of the clay fraction. The mining residue soil was substantially more vulnerable to structural collapse than the Balkuling soil. This is likely related to the different pore-size distribution of the residue columns and the nature of their clay constituents. The Balkuling soil is predominately kaolinite while the mining residue contains an equal amount of smectic clay particles. These are likely more readily mobilized, and available to re-deposit and occlude downstream pores.

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