Decrease in hydraulic conductivity and particle release associated with self-filtration in saturated soil columns

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ABSTRACT

The dynamics of the process of self-filtration in soil columns have been evaluated for two soils with different structural cohesion (Balkuling agricultural soil and a mining residue) by carrying out experiments focusing on microscopic particle behaviour during filtration. Soil column experiments were set up to simultaneously measure changes in hydraulic gradients ($\Delta H/\Delta L$) along the columns and outflow particle sizes and concentrations during pressure leaching with solutions of 100, 10 and 1 mmol/L NaCl and deionised water. The lowest ionic strength has resulted in more reduced hydraulic conductivity and relatively more release of colloids associated with hydrodynamic shear and dispersion. Steady increases in hydraulic gradient ($\Delta H/\Delta L$) and corresponding decreases in relative saturated hydraulic conductivity (K/K_o) with time were observed for both soils and follow similar trends at all column depths. The most severe increases in $\Delta H/\Delta L$ and decreases in K/K_o always occurred near the inlet to the columns and the decline gradually decreased along the column. The decrease in K/K_o and increase in $\Delta H/\Delta L$ were clearly influenced by the size as well as the concentration of migrating particles in the porous medium. The finer mobile particles in the mining residue were clearly more readily self-filtered at the lower concentration than the larger Balkuling soil particles producing more rapid increases in $\Delta H/\Delta L$ and decreases in K/K_o. This was attributable to more effective self-filtration and more pore clogging probably due to increased development of the diffuse double layer, swelling and dispersion within the soil matrix at these concentrations.

Keywords:
Saturated hydraulic conductivity
Self-filtration
Pore clogging
Particle migration
Particle release
Deposition

1. Introduction

The migration and rearrangement of particles and removal of particles within the porous medium (or self-filtration) has profound effects on the stability of soils (Reddi et al., 2000; Tomlinson and Vaid, 2000). These processes are central to the understanding of soil formation, colloid facilitated contaminant transport, pore clogging and filter design. For example, soil formation processes result in coarsening of the near-surface horizon (e.g A and E) leading to accumulation of fine particles in the deeper horizons (Birkeland, 1974). This eventual entrapment of colloid-size particle in a filter is sensitive to the physico-chemical environment of the porous media (Reddi and Bonala, 1997). Further, the processes of particle generation and accumulation in natural subsurface soils as influenced by soil structural stability, solution chemistry (Felhendler et al., 1974; Frenkel et al., 1978; Pupisky and Shainberg, 1979; Grolimund et al., 1998), and the size of the particles (<10 μm, Kretzschmar et al., 1999), are still poorly understood (Ryan and Elimelech, 1996; Ryan et al., 1998). This is particularly true for sodic soils for which hardsetting, crust formation and densification are serious factors contributing to soil degradation.

To explain how particle rearrangement contributes to soil degradation, we need to develop a better understanding on the dynamics of how particles are mobilized, moved and redeposit which in turn adversely affects hydraulic properties. While a number of studies have looked at how hydraulic conductivity changes due to changes of soil chemistry, very few studies have looked at the rate at which hydraulic conductivity decreases (Quirk and Schofield, 1955; Felhendler et al., 1974; Pupisky and Shainberg, 1979; Reddi et al., 2005; Bagarello et al., 2006), at what depth pore clogging occurs and the amount and particle size of fines being released from soil. These are dynamic aspects of self-filtration that will be the main focus of this paper.

Pore clogging following the entrapment of fine particles is a major cause of reduced soil hydraulic conductivity for surface soils particularly when irrigated with sodic waters of low electrolyte concentration (Felhendler et al., 1974; Frenkel et al., 1978; Hajra et al., 2002). Self-filtration and the continuous accumulation of fine micron-sized particles can seriously limit the infiltration capacity and drainage properties of the whole soil profile (Reddi et al., 2000; Moghadasi et al., 2004) and low hydraulic conductivity in the subsoil can also create surface runoff (Russo and Bresler, 1981; Russo, 1983). Further geochemical transformation and deposition processes (Elimelech et al., 1995; Song and Elimelech, 1995) enhance particle release from filters

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Table 1
Selected physico-chemical properties of Balkuling soil and mining residue soil

Property	Balkuling soil	Mining residue
Texture	Sandy loam	Loamy sand
Sand (%)	83.3	89.0
Silt (%)	6.6	1.9
Clay (%)	10.1	9.1
Packing density (g/cm^3)	1.61	1.58
Electrical conductivity (μS/cm)	42	380
pH (water)	6.1	8.7
CEC (cmol/kg)	3.4	8.1
ESP (%)	2.5	27
Organic carbon (%)	0.3	0.55
Clay mineralogy	Kaolinite, vermiculite with traces of gybsite	Kaolinite-smectite with traces of quartz

CEC—cation exchange capacity, ESP—exchangeable sodium percentage.

(Grolimund and Borkovec, 1999). For example particles moving along the flow path may be retained in porous media as a result of changes in chemical properties such pH or salinity of the fluid medium (Moghadasi et al., 2004). Similarly, Roy and Dzombak (1997), in their study of colloid transport found that pH changes are unlikely to have significantly influenced sorption or desorption of colloids.

All these studies reveal that the processes contributing to particle detachment, transport and retention are very complex in soils and that to this date no comprehensive modeling approaches have been developed to cope in particular reduction of hydraulic conductivity associated with clogging of pores. Moreover, developments of filtration theory and modeling of colloid transport have focused largely on homogenous porous media involving studies on very well defined porous media such as glass beads. These theories do not perform well when applied to natural porous media which are generally characterized by wide particle size distributions and complex pore geometry (Kretzschmar et al., 1999). Similarly, researches on transport of natural colloidal particles within the context of the dynamic changes of hydraulic conductivity appear scarce (Kretzschmar et al., 1997).

The present study was designed to experimentally examine the dynamics of the progressive particle mobilization and re-deposition and removal of particles within the porous medium, here referred to as self-filtration, during the flow of solutions of decreasing electrolyte concentration through two soil materials of differing structural cohesion. We used the temporal changes of hydraulic conductivity and hydraulic gradient at different soil depths and the outflow particle size and concentrations as means to quantify self-filtration process in microscopically complex porous material.

2. Materials and methods

2.1. Soil materials

Laboratory investigations into the dynamics of particle mobilization and its effects on saturated hydraulic conductivity were carried out using an agricultural soil commonly used in Western Australia (Balkuling soil) and a mining spoil (mining residue) with significantly different physical and chemical properties (Table 1 and Fig. 1). Balkuling soil is a duplex soil classified as brown loamy earth (WA soil group, McArthur, 1991), or sodic manganesic brown Kandosol (Australian Soil Classification, Isbell, 2002) and is also classified as Vertic Ferralsol (World Reference Base for soil classification, FAO, 1998). Although structurally fragile, Balkuling soil possesses micro-aggregation and when carefully managed has been extensively and successfully used for both pasture and crop production in Western Australia. In contrast, in the mining residue or spoil, consisting of waste products (>63 μm tailings sands and <63 μm fines) was collected from the Cable Sands (WA) Pty.(Ltd). Sandalwood mine site, 5 km north of Brunswick Junction, Western Australia. Any previous structural cohesion in the mining residue has been essentially disrupted by the mining treatment and such spoils pose significant problems in terms of rehabilitation. Selected physico-chemical and mineralogical properties (Table 1 and Fig. 2) were determined using standard procedures (Klute, 1986).

2.2. Column experiment: pressure measurement using pressure transducers

Experiments were carried out using soil columns as shown schematically in Fig. 2. Soil samples (<2 mm) were initially mixed with 0.9–1 mm acid-washed sand to provide a rigid skeletal structure to facilitate flow and colloidal mobility. Basing on their structural cohesiveness, the proportions of mixtures were 50% soil–50% sand and 30% soil–70% sand, for the mining residue and Balkuling soil, respectively. The mixtures were uniformly wet packed into acrylic soil columns (400 mm long, 25 mm diameter, 2 mm wall thickness, cross-sectional area 4.91 cm^2, volume 196 cm^3) and saturated with the desired electrolyte concentrations. To avoid mechanical dispersion, samples were moistened by dripping about 5 mL solution onto the soil which was packed in 10 g increments. The column size chosen is in same range of column dimensions that were used in comparable studies of colloid mobility (Grolimund et al., 1998, Moghadasi et al., 2004). Pressure sensors (P_1, P_2 and P_3) were inserted on holes bored at various column depths (D_1 = 50 mm, D_2 = 150 mm and D_3 = 250 mm), along the column from the inlet (Fig. 2). Miniature pressure transducer with tensiometers (1.5 m

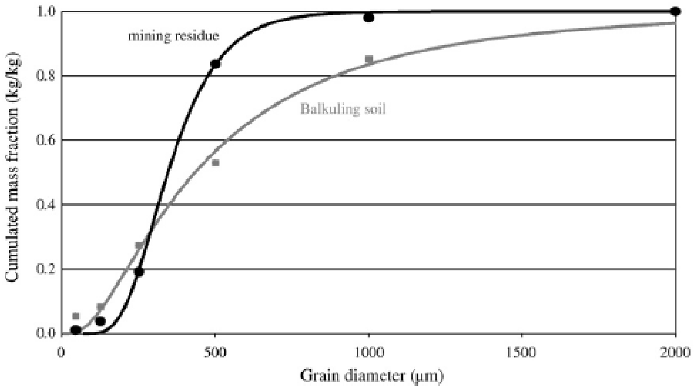

Fig. 1. Particle size distribution of the Balkuling soil and mining residue.

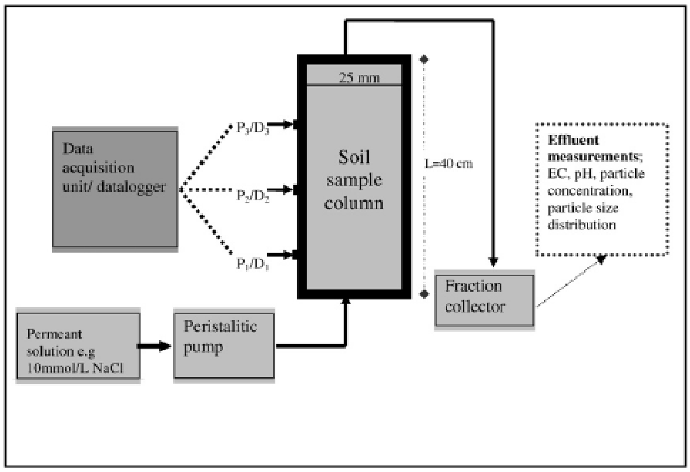

Fig. 2. Schematic diagram of laboratory column-pressure head measurements during leaching with solutions of various electrolyte concentrations. P_1, P_2, and P_3, and D_1, D_2, and D_3 represent positions of pressure transducers and depths, respectively.

cable long, 5 cm shaft long and 20 mm diameter) T5–7/5 model (UMS, 2000) were connected to the system for online pressure–time monitoring to yield information about hydraulic head changes and saturated hydraulic conductivity reductions with time. The pressure transducers with tensiometer-T5 cups were installed horizontally into the soil columns. These T5 tensiometers have special ceramic cups, and, are known to offer minimal soil disturbance, punctual measurements and fast response times suitable for highly sensitive wet water regime phase.

A peristaltic pump (designed with a system maximum discharge pressure of 300 kPa at 0–40 °C), was used to pump solutions of ionic strengths: 100, 10 and 1 mmol/L NaCl into the soil columns in a continuous vertical upward flow. During experimental runs, pressures were measured at designated points along the columns under predetermined constant flow rate . Pressure (P) was measured as a function of time (t) and axial distance along the soil columns (L). For continuous online pressure measurements, an Agilent 34970A model data logger-PC system (Agilent Technologies, 2003) was used as a data acquisition system. To ensure equilibration of the system and to enable particle-hydrodynamic settling, the columns were saturated with the desired solution overnight (for at least 12 h). Prior to experimental runs, a steady state was attained by measuring outflow rates until a constant value was achieved at the various times as presented in Table 2 for each experimental set up.

Table 2
Column characteristics and experimental conditions of packing material

Property	Electrolyte concentration (mmol/L)			
	100	10	1	Di-water
Balkuling soil				
Porosity or void ratio (cm^3/cm^3)[a]	0.21	0.21	0.21	0.21
Constant flow rate achieved (cm^3/min)	0.96	0.95	0.98	0.96
Time required (min)	20	25	20	20
Pore velocity (cm/h)[b]	11.7	11.6	12.0	11.7
Mining residue				
Porosity or void ratio (cm^3/cm^3)[a]	0.17	0.17	0.17	0.17
Constant flow rate achieved (cm^3/min)	1.88	1.84	1.78	1.76
Time required (min)	15	20	20	25
Pore velocity (cm/h)[b]	23.2	22.5	21.7	21.5

Time required is the time to reach steady state following start of leaching.

[a] Estimated by amount of water saturating soil column.

[b] Computed by dividing pore flow rate by column cross-sectional area.

The characteristics of the columns and experimental conditions are presented in Table 2. The porosity or void ratio was estimated by determining the amount of solution required to saturate the soil column (313 g for the Balkuling soil and 330 g, for the mining residue) while the pore velocity was estimated from the pore flow rate divided by column cross-sectional area. In accordance with their structural cohesiveness, for Balkuling soil, the column was pumped at a relatively low constant pore velocity of 12 cm/h for a pressure range of 20–300 kPa while the mining residue was maintained at constant pore velocity of 22 cm/h for a pressure range of 0.5 to 10 kPa during leaching dilution from 100 mmol/L to deionised water.

2.3. Particle release

Mobile effluent particles were obtained simultaneously by collecting suspensions from the outflow fraction collector during leaching (Fig. 2). A fraction collector was set up with pre-weighed 10 mL vials to collect effluents during leaching. The effluent colloidal size distributions and their specific surface areas were determined using a Malvern Mastersizer (Malvern Instruments, UK, 1995). The pH {$\text{pH}=-\log[\text{H}^+]$, where [ ] denote activity} and electrical conductivity (EC) in mS/cm were measured on each effluent using Eutech Cybernetics instrument (model Cyberscan con 10), to assess the temporal changes during particle release. Collected fractions of known volume were oven dried at 100 °C for 24 h and weighed to determine the actual particle concentration. Corrections for salt accumulation in the leachates collected were also measured and were 1.3, 0.4 and 0.1 mg for 100, 10 and 1 mmol/L solutions, respectively.

3. Results and discussions

3.1. Effect of Darcian flow regime on transport properties of porous medium

The extent of particle release and hydraulic conductivity changes using saturated columns (Fig. 3 through to Fig. 6) were evaluated by measuring hydraulic gradient ($\Delta H/\Delta L$) increase along the soil columns. During fluid flow through a porous medium, pressure increases develop along the soil matrix in the direction of flow. The increase in pressure head is a function of the system geometry (void

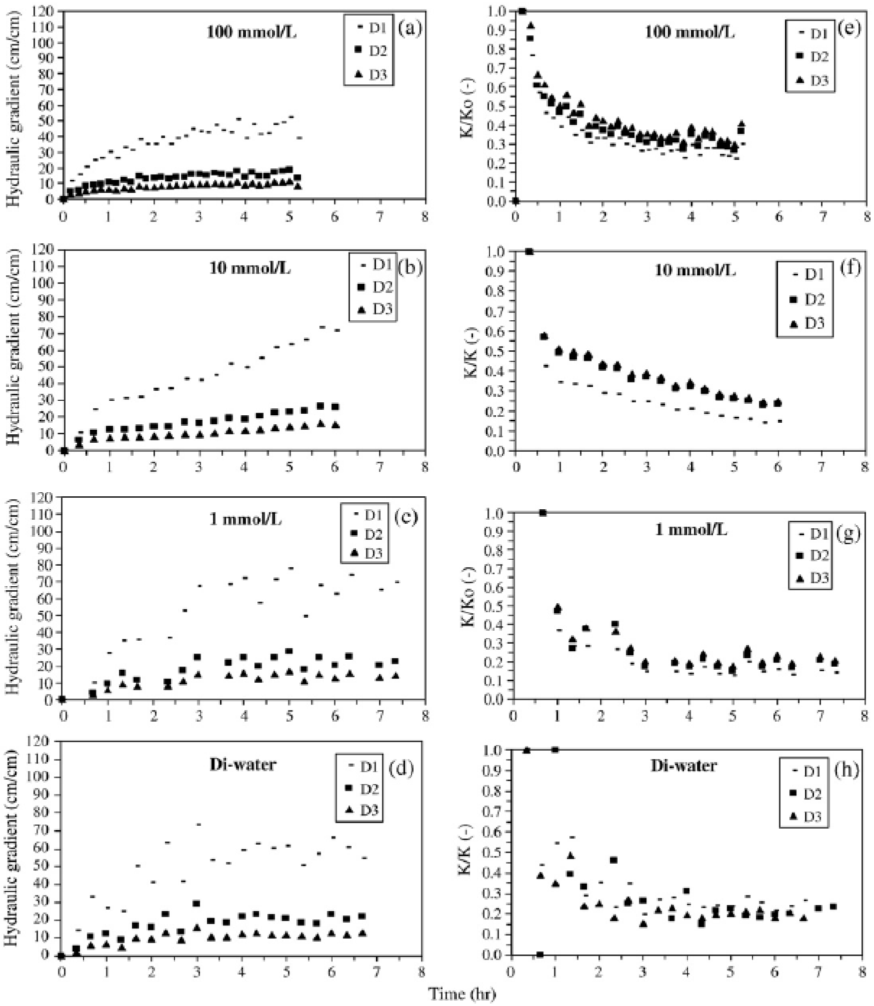

Fig. 3. Hydraulic gradients (a–d) and relative saturated hydraulic conductivities (e–h) during particle deposition for Balkuling soil leached with different electrolyte concentrations and symbols D_1, D_2, D_3 are the pressure head measurement positions 50, 150, 250 mm, respectively, along the column from the inlet or inflow.

ratio) and the physical properties of the soil and fluid, and, these can contribute to various flow regimes described as Darcian, inertial, unsteady laminar or turbulent flows. Further particle deposition and deposit morphology depend on the characteristics of the porous media and the flow field (Mays and Hunt, 2005).

Assuming a Darcian flow, saturated hydraulic conductivity K can be expressed as:

$$K = \frac{Q}{A} * \frac{\Delta L}{\Delta H}, \tag{1}$$

where Q is volumetric flow rate, A is column cross-sectional area and , L is distance from the inlet of column ΔH is the hydraulic head.

The experimental flow conditions were also evaluated for Darcian flow, using Reynolds number Re (Happel, 1958; Happel and Brenner, 1973), which expresses the ratio of inertial to viscous forces as a criterion to distinguish between laminar flow occurring at low velocities and turbulent flows. For the flow through porous media; $Re = qd/\gamma$ where q, is the specific discharge, d is pore length dimension (mean pore size) and γ is kinematic viscosity. The specific discharge $q = Q/A$ where Q is the flow rate and A is column cross-sectional area (4.91 cm^2). Similarly, the flow conditions were assessed using Fanning's friction factor f (Rose, 1966), where $f = 1000/Re$. The Reynolds number and Fanning fraction were estimated from pore diameter of 25 and 30 μm, for Balkuling soil and the mining residue, respectively. The pore diameters were obtained from experimentally determined pore size distribution curves measured using Hanging column method (Haines 1923), respectively. The kinematic viscosity estimated at 1×10^{-6} m^2/s (for water at 20 °C) i.e 0.6 cm^2/min. The results showed Re values of $6.4 * 10^{-4}$ and f value of $1.5 * 10^6$ for the Balkuling soil while for the mining residue; $Re = 1.8 * 10^{-3}$ and $f = 5.6 * 10^5$. Laminar flow occurs when $Re < 10$ (Happel, 1958) and $f > 10^3$ (Rose, 1966). Thus both Reynolds and Fanning friction values indicate that under the present experimental flow conditions laminar flow occurred for all electrolyte concentrations at low constant flow rates (Table 2). The experimental constant flow rates were approximately 1 cm^3/min for Balkuling soil and 2 cm^3/min for the mining residue and were consistent with structural cohesiveness of these two soil materials with the former being more cohesive.

3.2. *Decrease in saturated hydraulic conductivity with time*

Data obtained from the pressure transducers with time following column leaching under constant rates (Table 2), were used to calculate hydraulic gradient ($\Delta H/\Delta L$) and saturated hydraulic conductivity (K) along the columns by assuming Darcian flow and using Eq. (1). The initial saturated hydraulic conductivity (K_o) was estimated at the start of the leaching for each column experiment. The results show steady increases in $\Delta H/\Delta L$ and decreases in relative hydraulic conductivity (K/K_o) with time for both soil materials and follow similar trends and distinct patterns at all column depths (Figs. 3 and 4), indicating that pore clogging occurs at all depths in the column. Firstly, K/K_o decreased more rapidly with decreasing ionic strength, reaching substantially lower conductivity values for deionized water after 3 and 2 h for the Balkuling soil and the mining residue, respectively. Irregular K/K_o decline in the Balkuling soil is attributable to randomly sized and interconnected pore space (Lee and Koplik, 2001) associated with hydrodynamic shear (Schelde et al., 2002). Secondly, the relative decrease in K/K_o at the end of each experiment for the 10, 1 mmol/L and deionised water are very similar with a reduction of about 85% and 90% of the Ko for the Balkuling soil and the mining residue, respectively. Thirdly, the greatest K/K_o reduction occurs near the inlet of column (D_1D$_1$ in Figs. 3 and 4) and is most pronounced for the higher concentrations of 10 and 100 mmol/L. This is attributable to hydrodynamic shearing thus initiating particle removal and rapid self-filtration of soil particles at this point. Mays and Hunt (2005) attributed rapid decreases in K/K_o to more concentrated deposits

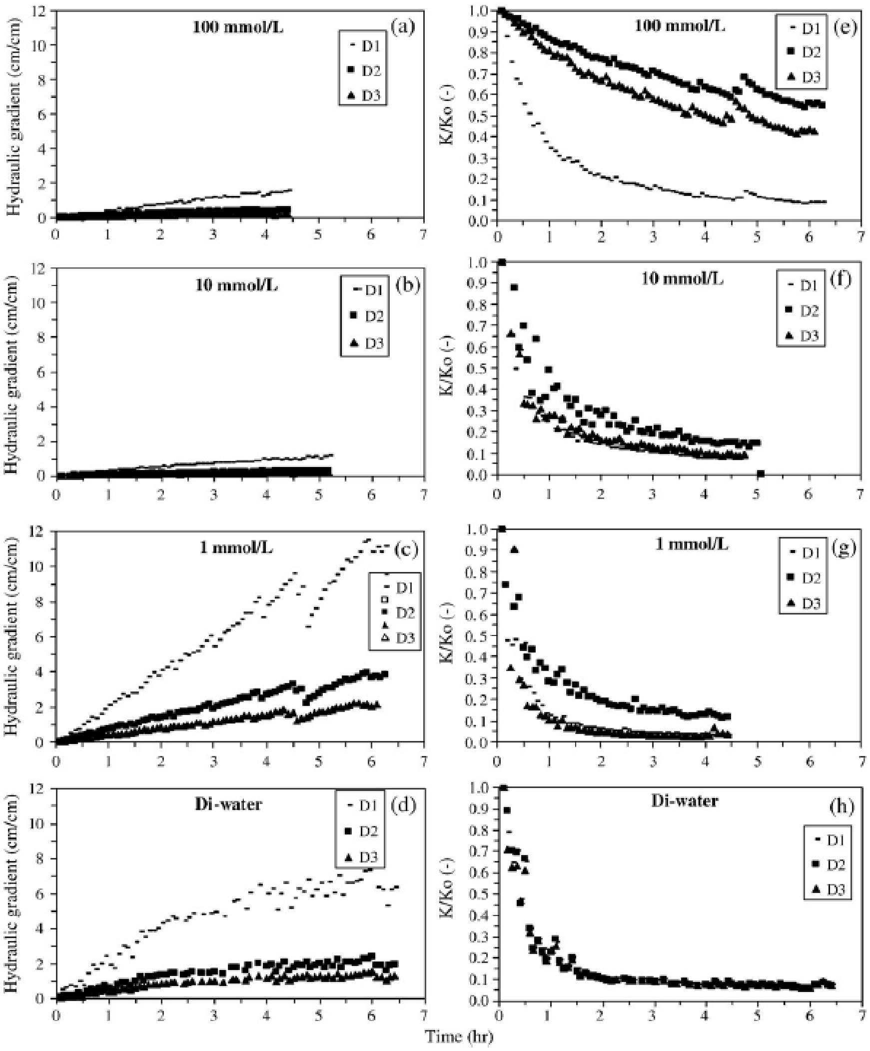

Fig. 4. Hydraulic gradients (a–d) and relative saturated hydraulic conductivities (e–h) during particle deposition for the mining residue leached with different electrolyte concentrations and symbols D_1, D_2, D_3 are the pressure head measurement positions 50, 150, 250 mm, respectively, along the column from the inlet or inflow.

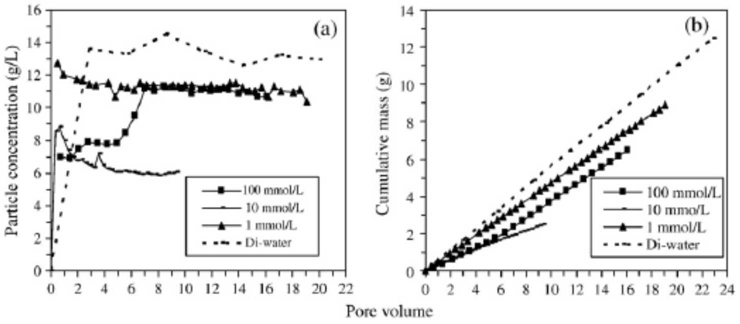

Fig. 5. Effect of ionic strength in terms of (a) particle concentration and (b) cumulative mass of particle released during migration for Balkuling soil.

near the inlet due to deposit compaction. However this trend is consistent with other research findings (Moghadasi et al., 2004; Kohler, 1993; Mays and Hunt, 2005).

Both soil materials show different behaviours with respect to the variations in the pressure transducer reading with Balkuling soil showing much slower response in K/K_o reductions especially at low ionic strengths. The mining residue shows relatively a much quicker decrease of K/K_o with time to a lower value near the inlet compared to the rest of column for the high ionic strength experiments. These behavioural differences are explained by the distinctness in soil structural properties of both soil materials. The Balkuling soil was disturbed by passing it through a 2 mm sieve, essentially leaving micro aggregates relatively undisturbed. Hence attractive forces between fine particles of the Balkuling soil are associated with all aspects of the formation of soil structure including organic matter interaction with clay minerals.

In contrast, the mining residue material is an artificially substrate that was produced by mixing fines of the clay and silt fraction with a processed sand. Accordingly, particle arrangement within the mining residue is caused by the mixing processes and not by the formation of soil structure. Hence, it is evident that the mining residue is far more sensitive to self-filtration and is also more likely to encounter constriction and retention thus allowing smaller sized particles entrapped behind the coarser fraction, forming a filtration zone (Okita and Nishigaki, 1993). Similar studies (Abadzic and Ryan, 2001; Mays and Hunt, 2005) showed that the release and increase of particles in pore stream caused more reductions in K/K_o when fine grained material was present in soil columns. However this irregular trend, especially in Balkuling soil, provides some explanation as to why existing filtration theories do not apply well to natural soils characterized by wider particle size distribution and complex pore geometry (Kretzschmar et al., 1999).

3.3. Concentration of effluent particles

Figs. 5 and 6 show temporal changes of particle concentration and cumulative mass as a function of ionic strengths for Balkuling soil and mining residue, respectively. The Balkuling soil, with greater initial porosity, led to smaller effluent concentration, but contributed to greater overall particle removal with particle concentration remaining essentially constant with pore volumes passed (Fig. 5). After some initial variation the effluent particle concentration from the mining residue at 100 mmol/L, similarly remained relatively constant with pore volumes passed (Fig. 6). However at the lower solution concentration and with de-ioinised water, the initial flush of effluent particles of the mining residue was followed by a rapid decrease in effluent particle concentration. In fact, the lower the ionic strength of the solution, the higher and earlier the peak effluent concentration of fines (Fig. 6a). This was associated with a more rapid drop of the effluent particle concentration yielding a distinct plateau in the cumulative particle concentration (Fig. 6b), a phenomenon called "self-healing" due to the formation of filter bridges (Lee et al., 2002). Similar particle release trends were observed by Laegdsmand et al. (1999), Karathanasis (1999) and Karathanasis and Johnson (2006).

Furthermore the initial increase followed by a decrease in particle concentration are probably caused by diffusion and straining

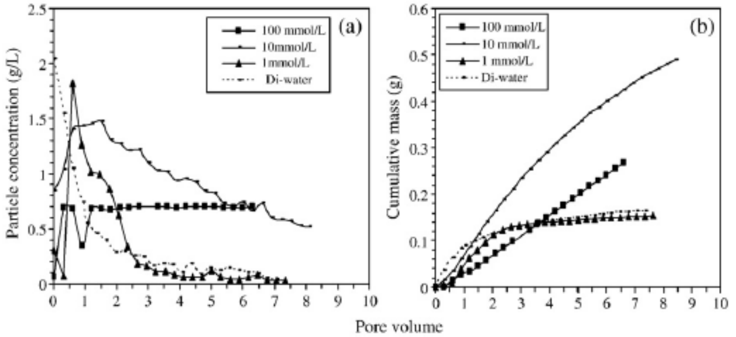

Fig. 6. Effect of ionic strength in terms of (a) particle concentration and (b) cumulative mass of particle released during migration for mining residue.

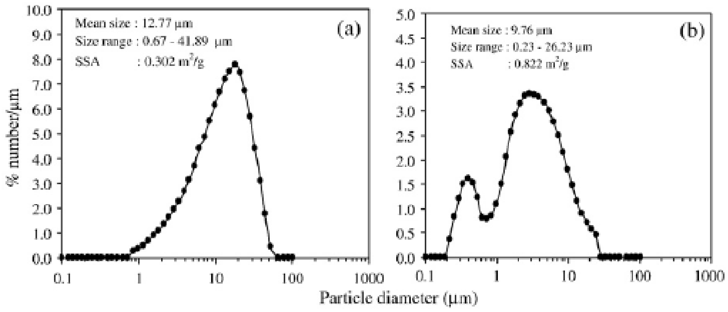

Fig. 7. Particle size distribution of the effluent for Balkuling soil; (a) 10 mmol/L and (b) 1 mmol/L.

associated with the nature and properties of the mobilized clays in the pore stream (Ranville et al., 2005) and reflect reopening of clogged macropores (Schelde et al., 2002). At low constant concentration diffusion is likely to control particle release especially for the least permeable medium. This is because the development of a cumulative particulate layer downstream slows down diffusion thus limiting particle release and effluent particle concentration to "near zero" (Karathanasis, 1999), (as in the case of the mining residue during leaching with deionised water).

3.4. Particle size distribution of effluent fines

The particle size distributions of the effluents for the Balkuling soil and mining residue columns at 10 and 1 mmol/L are presented in Figs. 7 and 8, respectively. The average effluent particle size decreased significantly as the ionic concentration decreased from 10 mmol/L to 1 mmol/L for Balkuling soil (Fig. 7). In contrast the average effluent particle size for the mining residue increased significantly with this change in concentration (Fig. 8). However at 10 mmol/L the effluent particle size ranges were 0.67 µm to 41 µm for Balkuling soil (Fig. 7a) and were somewhat larger than the mining residue ranging from 1 µm to 19 µm (Fig. 8a) thus indicating generally larger particles leaving the system for the Balkuling soil. The finer mobile particles in the mining residue appear to be clearly more readily self-filtered (probably due to swelling and dispersion within the soil matrix) than the larger Balkuling particles, thus producing more rapid increases in $\Delta H/\Delta L$ and decreases in K/K_o (see Figs. 3 and 4). This contrasts with studies by Hajra et al. (2002) who concluded that the higher ionic strength caused more flocculation of particles resulting in more rapid decrease in K/K_o.

3.5. Dynamics and characterization of particle release: effects of pH and salinity

Measurements of pH in the effluents collected here show that there was little significant change in pH during particle release. For example only slight changes from 5.4 to 5.5 and from 6.5 to 6.8 were observed for the Balkuling soil and mining residue, respectively, following leaching with 100 mmol/L. Further, Grolimund and Borkovec (1999), in their long-term release kinetics studies found the release pattern to be insensitive to pH variations. Similarly, Roy and Dzombak (1997), in their study of colloid transport found that pH changes are unlikely to have significantly influenced sorption or desorption of colloids. Although, this is in contrast with other studies (Ryan and Elimelech, 1996; Kaplan et al., 1996; de Jonge et al., 1998) who found a combination of higher pH and lower ionic strengths to enhance colloid release.

The electrical conductivity (EC) was found to decrease with electrolyte concentration (Fig. 9). The initial input solutions were 11.2, 5.6, 1.1 and 0.06 mS/cm for 100, 10, 1 mmol/L and deionised water, respectively, for Balkuling soil and were 9.5, 3.0, 0.37 and 0.07 mS/cm for the mining residue. A decrease in EC from 11 mS/cm to 0.5 mS/cm was observed during leaching with concentration from 100 mmol/L to deionised water and this similar trend was observed with particle release patterns (Figs. 5 and 6). Furthermore the erratic and irregular particle release during leaching contributed to the observed phenomenal behaviour in the EC breakthrough curves (Fig. 9).

3.6. Relationship between hydraulic conductivity and particle release

A coherent pattern appears to form when particle release is being associated with the hydraulic conductivity decrease (Fig. 10). This is

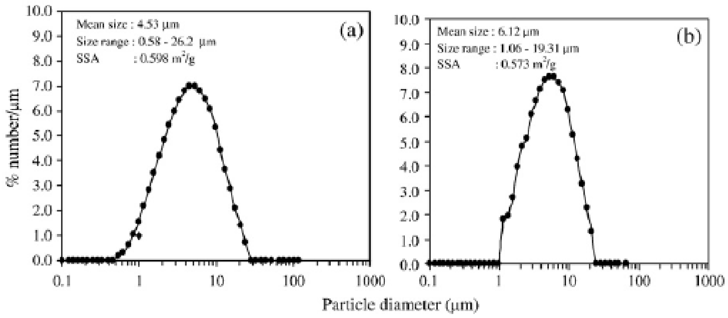

Fig. 8. Particle size distribution of the effluent for a mining residue; (a) 10 mmol/L, (b) 1 mmol/L.

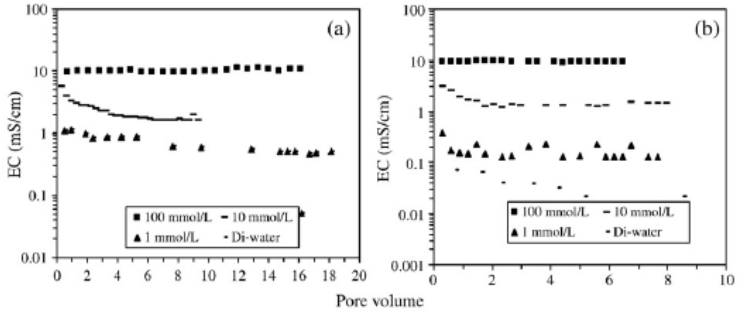

Fig. 9. Changes of electric conductivity with time during particle release; (a) Balkuling soil and (b) mining residue.

particularly true for the mining residue for which the highest peak in particle release is associated with the steepest change of K/K_o, quite distinct when comparing the 100 mmol/L and the deionised water treatments. It is assumed that part of the column that is closest to the outlet, is the most determining for the particle out flow. Furthermore, most particles are being released from columns that had the least decrease in K/K_o. Hence the more clogging occurs the greater is the decrease in K/K_o and the smaller is the amount of particles being released (Fig. 10). This has interesting implication for particle removal within pore matrix as well as particle mobility in soils. For soil solutions that are high in calcium and have a high ionic strength we expect that few particles will be mobilized and that the hydraulic conductivity remains constant. Once the solution composition is shifted toward sodium and low ionic strength values it was found that greater amounts of particles are being released at intermediate concentrations associated with intermediate reductions in K/K_o. When pore clogging becomes very severe, particle mobility is substantially reduced, with a decrease in K/K_o indicates marked pore clogging preventing particulate material from reaching the effluent point.

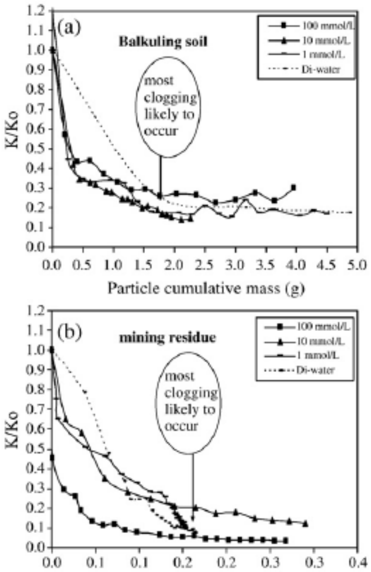

Fig. 10. Relative hydraulic conductivity (K/K_o) as a function of cumulative particle release 4 during leaching of soil columns; (a) Balkuling soil and (b) mining residue.

4. Summary and conclusions

Particle mobilization and self-filtration have been shown to result in reductions in hydraulic conductivity and to be significantly influenced by solution chemistry. The decline in hydraulic conductivity increased with pressure drop associated with particle deposition and infilling of soil voids by smaller sized particles of soil filters resulting in subsequent pore clogging during leaching of saturated columns. Decreasing ionic strength increased colloidal release from the parent material from both soils and increased particle size resulted in relatively increased hydraulic gradients and faster reduction in saturated hydraulic conductivity associated with clogging of microscopic filter pores.

A more dramatic decrease of saturated hydraulic conductivity was noticeable for the less cohesive mining residue than for the aggregated Balkuling soil. Due to differences in the clay mineralogy and its treatment history involving greater disruption, the mining residue is far more sensitive to particle mobilisation and pore clogging than the Balkuling soil. The mining residue is therefore more likely to encounter constriction and retention thus allowing smaller sized particles to become entrapped behind the coarser fraction, forming a filtration zone. The more clogging occurs the greater is the decrease of hydraulic conductivity and the smaller is the amount of particles being released. This is particularly enhanced at the lower electrolyte concentrations.

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