

DETACHMENT OF FINE CONTAMINATED SEDIMENTS FROM COARSE PARTICLES IN A FLUIDIZED BED

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SUMMARY

The resistance of cohesive sediment (particle size $< 16 \mu\text{m}$) deposits to erosion and re-suspension is determined by interparticle forces acting over particle separation distances $< 100 \text{ nm}$. The physico-chemical properties of interacting particle surfaces and the physical and chemical properties of the eroding fluid control these forces. The effect of solution chemistry on the strength of inter-particle forces can be studied by measuring the detachment of fine sediments from granular filter media in a fluidized bed. Previous studies have focused on relatively simple, well-defined experimental systems. In this study, the detachment of natural cohesive sediment from river sand was studied at constant fluidized bed expansion and varying backwash pH.

1. INTRODUCTION AND BACKGROUND

Contaminants such as trace metals and pesticides tend to accumulate in the bottom sediments of rivers, lakes and estuaries, but may be re-mobilized by changes in water chemistry and/or re-suspension of the sediments due to storm events or dredging activities. In order to assess the risk posed to the water quality of a system by the presence of contaminated sediments, both the chemical partitioning between the aqueous and sediment phases and the potential transport of the sediments themselves have to be considered.

The study of sediment transport traditionally belongs to the field of hydraulics. The majority of sediment transport models consider only macroscopic physical factors: particle size, shape and weight of non-cohesive sediments, the physical properties of the eroding fluid, and the hydrodynamic properties of the flow field.

Pollutants tend to concentrate in the finer sediment fractions due to their high specific surface area. The mechanisms involved in the transport of very fine sediment ($< 16 \mu\text{m}$) are quite different from those for coarse particles. At very small particle sizes, physico-chemical forces begin to play an important role in the erosion and transport of sediments. These forces exist between all particle surfaces in aqueous environments; however, at very small particle weights and high specific surface areas, they become the dominant factor in determining how deposited particles orient themselves with respect to each other, and the critical hydrodynamic force required to re-suspend them. Traditional sediment transport models therefore cannot be used to predict the re-suspension of the finer sediment fractions, which are most relevant to contaminant transport.

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Inter-particle forces depend on the physical and chemical properties of the interacting surfaces and the chemistry of the aqueous phase. Sorbed organics may dominate the physical and chemical structure of exposed particle surfaces.¹ The solution phase pH and ionic strength control the surface charge of both uncoated and organic coated mineral surfaces. Consequently, a rigorous general model of the transport of the fine fraction of river sediment would have to include all of these factors. While empirical site-specific models of cohesive sediment transport have been developed,² no general predictive model currently exists.

Amirtharajah and co-workers^{3,4,5} have developed a micromechanical force model to describe the forces involved in the attachment and detachment of colloidal particles to and from filter media grains during filtration and backwashing. Currently, the model includes van der Waals attraction, electrostatic double layer forces, Born repulsion, hydration forces and hydrophobic interactions. Experimental validation of the model was obtained from fluidized bed column studies.⁴ Collaborative studies using a tilting flume have shown that the model also applies to the erosion of clay deposits under conditions designed to simulate a section of stream bed.^{4,6,7}

Up to now, column studies have focused on relatively simple, well-defined model systems. Raveendran^{3,5} studied the detachment of latex microspheres from glass beads, while Mahmood⁴ looked at the behaviour of pure kaolinite. Kaolinite particles exist as thin plates with a pH-dependent charge on their edges and a relatively pH-independent negative charge on their faces. The isoelectric point for the edges of kaolinite particles occurs at approximately pH 7.3.⁸ The edges therefore have a net positive charge below pH 7.3, and a net negative charge above it. As a result of their shape and surface properties, kaolinite particles flocculate and deposit in any of three structural arrangements: face-to-face (F-F), edge-to-face (E-F) and edge-to-edge (E-E), and as shown in Figure 1.

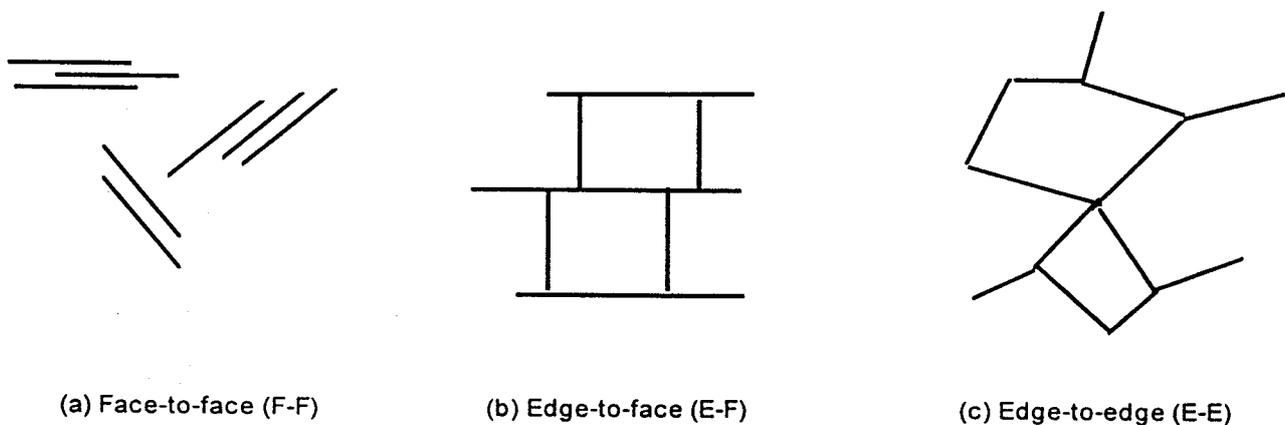


Figure 1: Modes of interaction of clay particles⁹

By incorporating the non-spherical shape and non-uniform surface properties of kaolinite into the force calculations, Mahmood⁴ developed a micromechanical model which is significantly more sophisticated than any of its predecessors. However, the system he studied was still greatly simplified compared to any natural system.

In the current force model, the clay particles have uniform size and structure and interactions occur between well-defined crystalline surfaces. Natural sediment consists of a mixture of mineral particles and precipitates, organic debris, micro-organisms and secretions, all of which contribute to its properties. Furthermore, mineral particles are likely to be partially or totally coated with natural organic matter and/or hydroxide precipitates, and it is the nature of these coatings, rather than the underlying clay mineral, which determine the transport properties.

This paper describes a series of experiments in which Mahmood's procedure was adapted to study the detachment of fine natural sediment from river sand. The ultimate objective of this research is to determine to what extent and how the micromechanical force approach may be applied to modeling the behaviour of complex natural sediments.

2. EXPERIMENTAL

The effect of solution chemistry on the strength of the interparticle adhesive forces was studied by measuring the detachment of fine sediments under constant hydrodynamic force (constant fluidized bed expansion) in a sand filter.

2.1. Materials

River sediments were collected from the Etowah River in Georgia, USA during a field study of sediment transport in the river. Sampling was carried out at various points downstream of the Allatoona Dam. Hydro-power releases from the dam resulted in stage increases of approximately 1,5 m twice a day. Consequently this was an ideal site to study the re-suspension of fine sediments under high flow conditions.

2.1.1. Filter media. Sediment, consisting predominantly of sand, was collected from the Etowah River just below the Allatoona dam. The sand was separated by dry sieving, and the 250 to 420 μm fraction was selected for use as the collector grains. This fraction was soaked in several batches for at least 16 hours each using a 20 g/l solution of the dispersant sodium metaphosphate to remove fine particles attached to the sand. The sediment was then rinsed repeatedly with tap water and the whole procedure repeated. This cleaning procedure was employed to ensure that fine particles, originally attached to the sand, would make a negligible contribution to the measured detachment in the backwash experiments.

2.1.2. Fine sediment. Sediment, consisting predominantly of silt and clay, was mixed with deionized water in a high speed mixer meeting the specifications of ASTM Method D 422 to break up aggregates, and then wet-sieved through a 75 μm sieve. The material passing through the sieve was oven dried at 40°C. This relatively low temperature was used to avoid altering the crystal structure of the sediment grains. The resulting hard cake was powdered and dry-sieved through a 125 μm sieve to remove lumps. Individual samples for each experiment were further ground using a pestle and mortar. However, it was found that relatively large lumps or aggregates were still settling in the filter influent lines and reservoir. Therefore the powdered material was dry sieved further using a 37 μm sieve in a mechanical shaker.

2.1.3. Background electrolyte. The background electrolyte used was sodium nitrate. While this is not representative of the composition of natural water, it was chosen to simplify the chemistry in the initial series of experiments. Solution pHs were adjusted using nitric acid and sodium hydroxide or bicarbonate.

2.2. Methods

Filtration and backwashing were carried out using 27 mm glass columns. The experimental apparatus is shown in Figure 1.

2.2.1. Experimental procedure.

1. A sample of sand was cleaned by backwashing with air scour. It was then soaked for at least 24 hours in a solution of pH and ionic strength controlled to be the same as the filter influent.
2. The filter influent was prepared by adding 1g of fine sediment to 10 l of deionized water, adjusting the pH and ionic strength to the desired values, and stirring for at least 24 hours at 450 rpm.
3. A precisely weighed mass of sand was transferred to the experimental column. The trial column, which contained the same mass of clean sand as the experimental column, was used to adjust the backwash flowrate to obtain the desired bed expansion. The test column and the experimental columns were backwashed with electrolyte solution of the same pH and ionic strength as the filter influent, until stable expanded bed heights and reproducible flowrates were achieved in both columns. Backwashing also ensured that all bubbles were flushed out of the columns and tubing.
4. The filter media was tapped down to a constant bed height (~10,2 cm).
5. The influent pump was primed and the filtration flowrate was set, using electrolyte solution.

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6. Influent suspension was pumped through the experimental column for 2,5 hours at a rate of approximately 42 m³/min (7 cm/min).
7. At the end of the filtration period, the filter influent line was disconnected from the columns and the flow was reversed to return the suspension to the influent reservoir. The filter effluent line was flushed at high flowrate to scour out deposited solids. This material was collected and filtered to determine the total mass of sediment.
8. Backwash solution was pumped through the test column until a constant flowrate and a total expanded bed height of 10,5 cm was achieved. The flowrate ranged from 640 - 720 m³/min (111-118 cm/min) depending on the temperature of the solution.
9. The flow was switched to the experimental column which was backwashed for 10 minutes.

2.2.2 *Sample collection.* All of the filter and backwash effluent was collected and analyzed. All samples were timed and collected in preweighed bottles so that the average flow rate for each sample could be estimated. The filter effluent and the last part of the backwash effluent was collected in 1 l plastic bottles. Fifteen 50 ml plastic centrifuge tubes were used to collect the initial portion of the backwash effluent to get a more detailed concentration profile.

2.2.3 *Sample analysis.* All samples were analyzed for total suspended solids (TSS) using Standard Method 2540 D. Selected samples were analyzed for particle size distribution using a Brinkmann Particle Size Analyzer 2010.

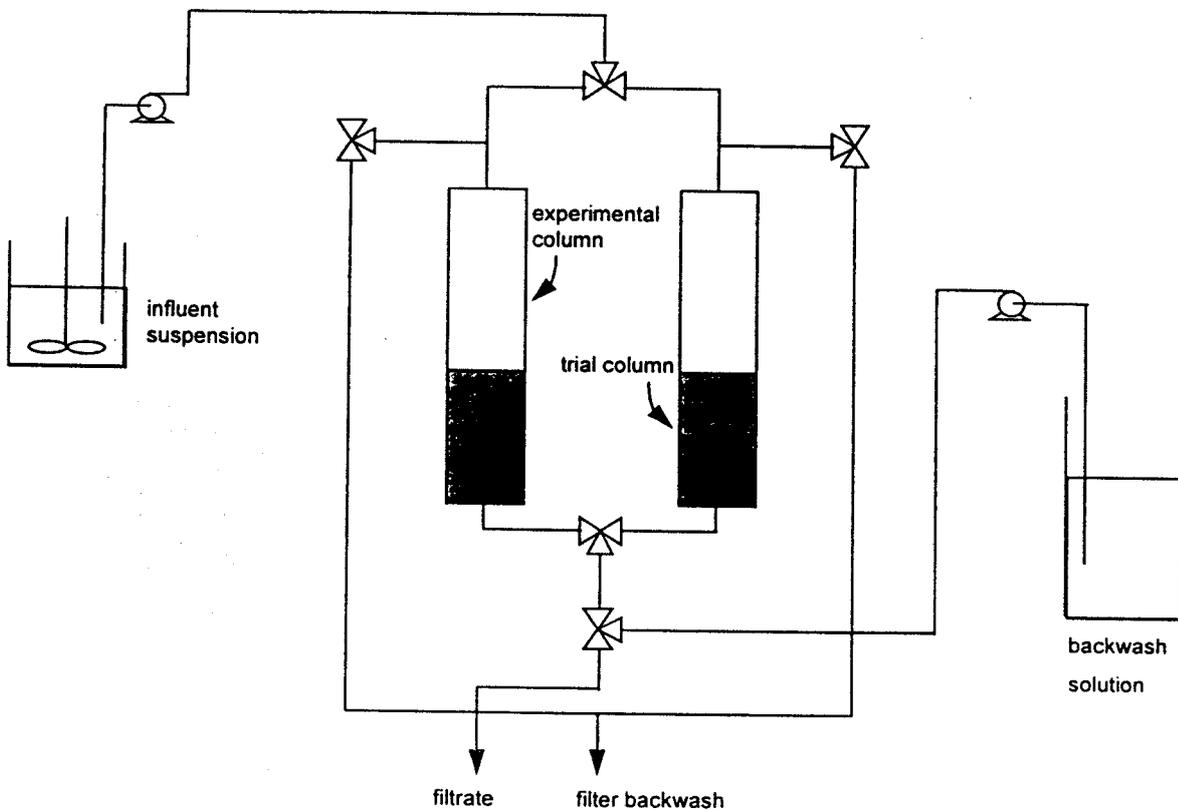


Figure 2: Experimental apparatus

Experimental conditions are summarized in Table 1. In this series of experiments, pH and ionic strength during filtration were kept constant while the backwash pH was varied at constant ionic strength.

Table 1 - Experimental conditions

Filter influent	
pH	5,9 – 6,0
Ionic strength (M)	0,0013-0,0015
Temperature (° C)	17,4 – 22,2
Fluid velocity (cm/min)	6,8 – 7,1
Filter backwash	
pH	3,6 – 9,0
Ionic strength (M)	0,0013 – 0,0015
Temperature (° C)	14,2 – 21,0
Fluid velocity (cm/min)	111 – 118

3. RESULTS AND DISCUSSION

3.1. Detachment as a function of backwash pH

For each experiment, the % detachment during backwashing was calculated as

$$\% \text{ detachment} = \frac{\text{total mass in backwash}}{1 \text{ g} - \text{mass in unused influent} - \text{total mass in filtrate}} \times 100 \% \quad (1)$$

The results are plotted in Figure 3. Figure 4 shows the results of a similar set of experiments using kaolinite and glass beads.^{10,11} In both sets of results, detachment is relatively constant at pH > 5 but decreases at pH < 5.

The attachment step in the kaolinite experiments was carried out at approximately pH 7 and an ionic strength of 10⁻³ M. Under these conditions, force calculations indicated that the dominant mode of particle-particle interaction would be edge-to-face.⁴ A decrease in pH in the backwash solution results in increasing positive charge on the edges and hence an increasing electrostatic attraction between particles which resists the eroding force of the backwash fluid.

While the exact nature and pH dependent behaviour controlling the surface charge of Etowah sediment is not known, in general, all particles in natural systems carry a negative surface charge which will tend to decrease as the pH decreases, due to the protonation of acidic functional groups. Consequently, electrostatic interactions will tend to strengthen the adhesive forces between particles as pH decreases, resulting in a decrease in detachment at constant hydrodynamic force.

An important difference between the fine Etowah sediment used and pure kaolinite is the relative particle sizes. The kaolinite particles had a mean size of 1.5 µm, while less than 10 % by volume of the Etowah sediment was < 2 µm in size. However, more than 80 % by volume of the Etowah sediment fell in the size range < 20 µm, that is, in the range in which colloidal forces are expected to be important.

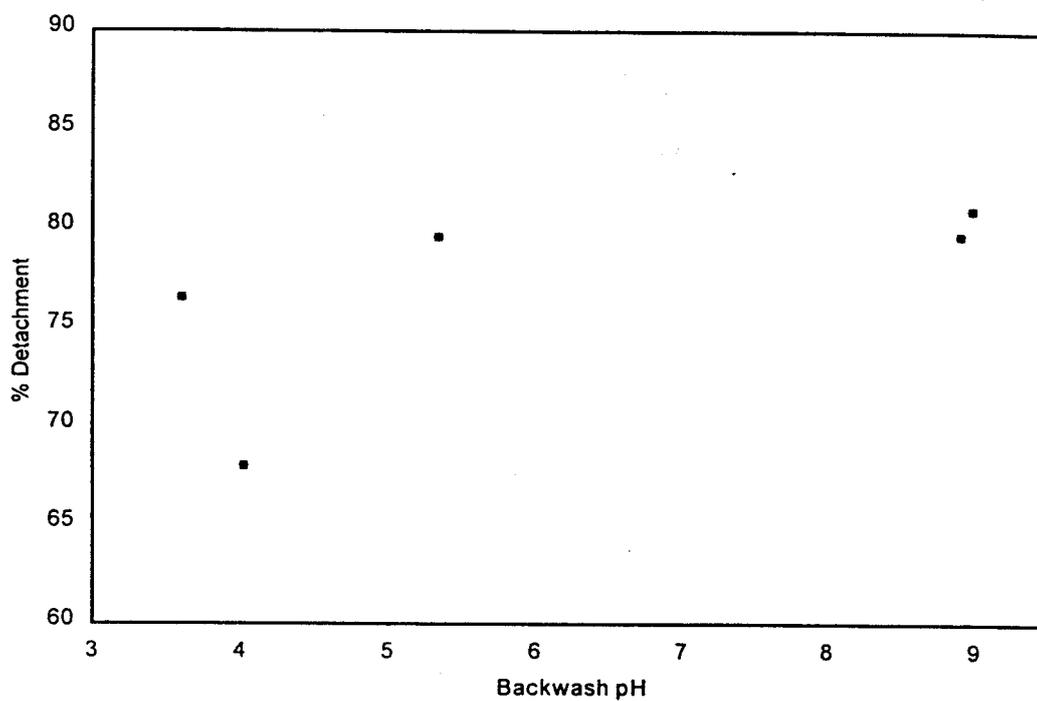


Figure 3: Detachment as a function of backwash pH for Etowah River Sediment

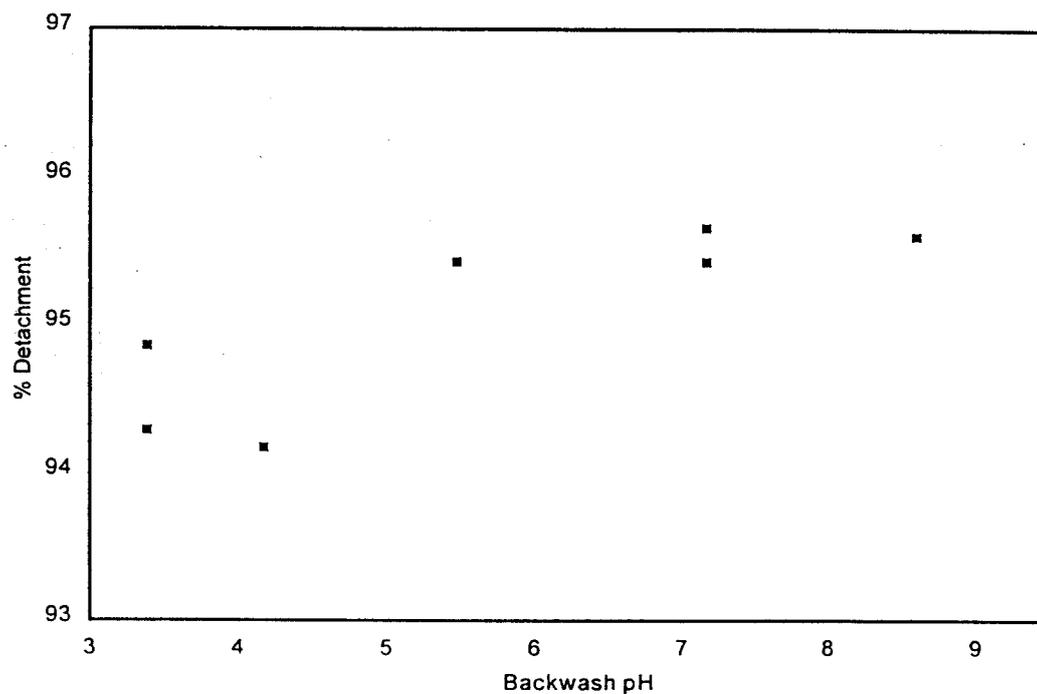


Figure 4: Detachment of kaolinite from glass beads as a function of backwash pH¹⁰

3.2. Transient backwash sediment discharge

The mode of attachment or retention of fine sediment in the filter bed is not expected to be uniform through out the pore space, and studying the transient sediment discharge may yield additional information about the forces and mechanisms involved in detachment. Figure 5 shows the variation in the total suspended solids (TSS) concentration as a function of backwash volume.

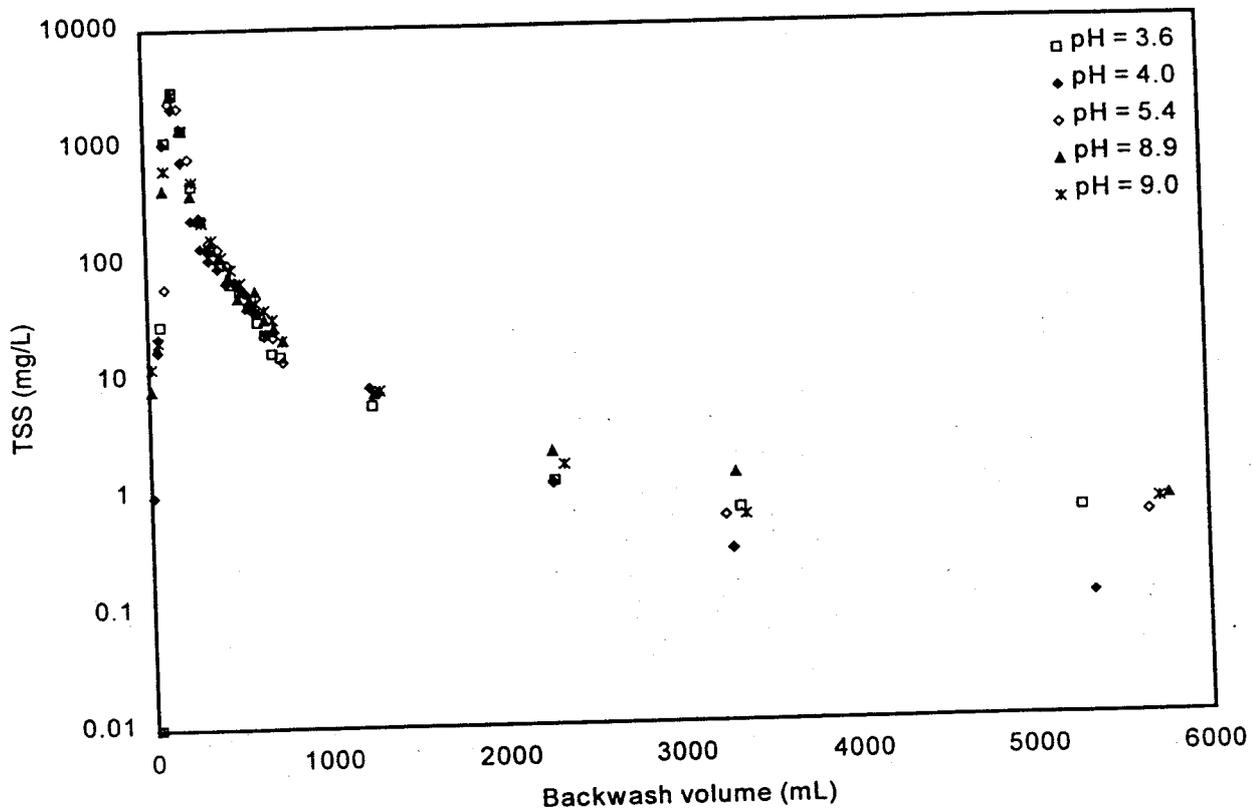


Figure 5: Sediment concentration as a function of backwash volume and pH

There appear to be three distinct regions in the log linear plot.

1. An initial spike in concentration, probably corresponding to material settled on top of the filter bed, and possibly loosely attached within the pore spaces.
2. A linear region between 300 mL and 1 L backwash volume. Amirtharajah¹² found that this linear region is characteristic of fluidized bed backwashing and provided some theoretical justification for its existence.
3. A tailing-off region, in which detachment becomes supply limited. Data scatter in this region may simply be due to the experimental uncertainty in measuring very small (< 1 mg) amounts of sediment.

4. CONCLUSIONS

Earlier work by Amirtharajah and co-workers showed that variations in the detachment of particles in a fluidized bed under various chemical conditions could be explained in terms of inter-particle force calculations for relatively simple

model systems. The experimental procedure has now been modified to study the behaviour of more complex natural sediments.

Preliminary results show that the detachment of Etowah river sediment as a function of backwash pH follows a similar trend to that exhibited by kaolinite. This suggests that the same forces are controlling the detachment in both cases, and more importantly, that the experimental procedure is able to measure variations in the inter-particle forces in natural river sediments caused by changes in solution chemistry. Further characterization of the sediments used is required to fully explain and model the observed behaviour.

5. ACKNOWLEDGMENTS

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