# PERMEABILITY REDUCTION OF SOIL FILTERS DUE TO PHYSICAL CLOGGING

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**ABSTRACT:** Soil filters, which are commonly used to provide stability to the base soils in subsurface infrastructure, are prone to long-term accumulation of fine micron-sized particles. This causes reduction in the permeability, which in turn may lead to intolerable decreases in their drainage capacity. In this paper, the extent of this reduction is addressed using results from both experimental and theoretical investigations. In the experimental phase, a sandy soil commonly used as a filter or drainage layer was subjected to pore fluids containing polystyrene or kaolinite particles, and their permeability reductions were determined in terms of the pore fluid suspension parameters. In the theoretical phase of the investigation, a representative elemental volume of the soil filter was modeled as an ensemble of capillary tubes and the permeability reduction due to physical clogging was simulated using basic principles of flow in cylindrical tubes. The results from the experimental and theoretical investigations were in good agreement. In general, the permeability reduced by more than one order of magnitude, even when the migrating particles were smaller than the majority of the soil filter pores. The concentration of particles in the pore stream affected the rate at which the permeability reduced. Self-filtration of particles, which is prominent at higher flow rates, may itself lead to a 20% reduction in the permeability for these sands.



## INTRODUCTION

Design of soil filters and drainage layers is a crucial element governing the stability and performance of subsurface infrastructure in geotechnical and geoenvironmental engineering. The motivation for earlier studies on filter design (Bertram 1940; Lund 1949; U.S. Bureau 1955) was primarily the protection of base soils from erosion and the stability of structures such as earth dams and retaining structures. Many studies during the recent decades were fueled by unending revelations of dam failures associated with inadequate filter design (Vaughan and Soares 1982; Von Thun 1985; Peck 1990; Vick 1996). Reddi and Bonala (1998) and ICOLD (1994) documented the state of the art in filter design. In general, current practice in filter design is largely based on a comparison of the particle sizes of the soil filter and the base soil. The existing literature documented the general validity of this approach (Sherard et al. 1984a,b; Honjo and Veneziano 1989; Indraratna and Vafai 1997) for the problems where stability of the base soils is of primary concern.

However, when soil filters are also expected to serve as drainage layers such as in the case of a pavement drainage layer or a leachate collection system underneath a landfill, the permeability changes of the soils become important. Soil filters might be successful in preventing the erosion of base soils, but they might undergo significant reductions in permeability as a result of progressive fine particle entrapment. Studies pioneered by Cedergren, the essence of which was presented in Cedergren (1994), show that poor drainage caused by particulate clogging of the pavement materials continues to cost the United States billions of dollars. In the context of geoenvironmental engineering, Koerner et al. (1994) highlighted the impact of poor drainage on the performance of leachate collection systems in landfills. Koerner and Koerner (1991) concluded that particulate clogging was a major factor in flow rate reductions of drainage layers. A need thus exists to assess the impact of particulate clogging on drainage capacities of soil filters and to consider the factors responsible for the clogging in the design process. This paper addresses this need using both experimental and theoretical investigations.

Particulate clogging in porous media is a subject of importance in several disciplines in addition to geotechnical and geoenvironmental engineering. It was studied in (1) wastewater filtration literature that was surveyed in numerous articles (McDowell-Boyer et al. 1986; Amirtharajah 1988; Tobiason and O'Melia 1988); (2) oil recovery processes in petroleum engineering that are affected by the reduction of permeability due to particle entrapment in porous media (Gray and Rex 1965; Muecke 1979; Baghdlklan et al. 1989); (3) ''sealing of liners'' of canals, reservoirs, and lagoons in the hydraulic and agricultural engineering disciplines (Sakthivadivel and Einstein 1970; Barrington et al. 1987a,b). These studies provide diverse yet useful perspectives on particulate clogging of porous media. Modeling of particulate clogging was also addressed at different scales in these disciplines. In general, they belong to the following four categories: (1) empirical methods (Tien and Payatakes 1979) that treat the particle entrapment in porous media using a rate law without considering the physics of the deposition process; (2) trajectory analyses (Payatakes et al. 1973) that track the individual particles using streamline functions and consider the balance of such forces as gravitational, inertial, hydrodynamic, electric double layer, and van der Waals forces; (3) stochastic methods (Fan et al. 1985) that simulate the particle deposition problem as a birth-death process, with the birth event representing an open pore getting blocked and the death event representing a blocked pore getting unblocked due to scouring of particles; and (4) network methods (Rege and Fogler 1988) that represent the porous medium using either a regular or a random network and track the individual particles as they move through the network.

Thus, the problem of fine particle entrapment in porous media is of interdisciplinary importance. In this paper, we address clogging of soils in geotechnical/geoenvironmental engineering as it pertains to soil filters and drainage layers, which may be permeated with micron-sized particulate suspensions from base layers upstream. We restrict our discussion to physical clogging only. Chemical and biological aspects of clogging, and extension of the principles to geotextile filters are reserved

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for future studies. In the first part of the paper, the experimental investigation is described, where the seepage behavior of a sandy soil (representative of those used as filters and drainage layers in practice) is studied using particulate suspensions as influents. In the second part, a conceptual model is developed to present a rational basis for assessing the magnitude of permeability reduction in soil filters or drainage layers as a result of physical clogging.

## EXPERIMENTAL MATERIALS AND METHODS

The current practice of filter design to protect fine-grained soils involves using sandy soils with grain size distributions comparable to that of concrete sand (Lowe 1988; Terzaghi et al. 1996, p. 82). In accordance with this practice, a sandy soil, hereafter called filter sand, from a local concrete manufacturer was used in the experiments. The grain size distribution of this sand in comparison with the band of concrete sand distributions shown in Fig. 1. Two kinds of particulate suspensions were used to permeate the soil samples—a suspension prepared with kaolinite particles, and another prepared with polystyrene microspheres. These two particle types differ in their specific gravity, and in their size distributions. The size distributions of the two particle types are shown in Fig. 2. These were obtained using a Coulter particle analyzer, which was also used to determine the particle sizes in the effluent during the course of the experiments described below. The Coulter analyzer employs an electrical impedance method to determine accurate particle size distributions and particle population numbers within the size range of 0.4–1,200 microns. The size of migrating clay flocs in most filter systems, used to protect cohesive base soils, is of the order of 10 microns (Vaughan and Soares 1982). Thus, the two suspensions chosen in this study cover the range of migrating particles in practice, and together they will enable an examination of the role of the size of migrating particles on particulate clogging.

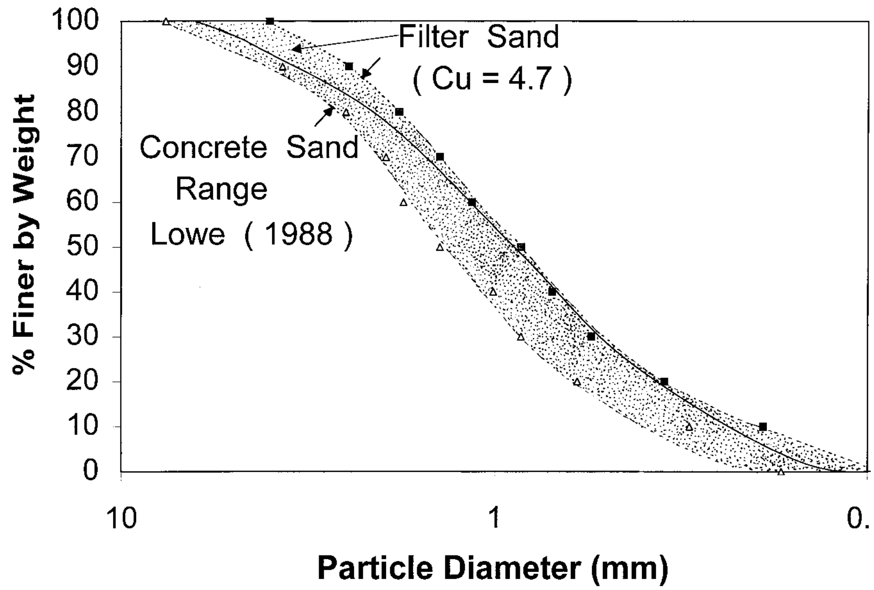


**FIG. 1. Grain Size Distribution of Filter Sand in Comparison with Band of Concrete Sand Distributions**

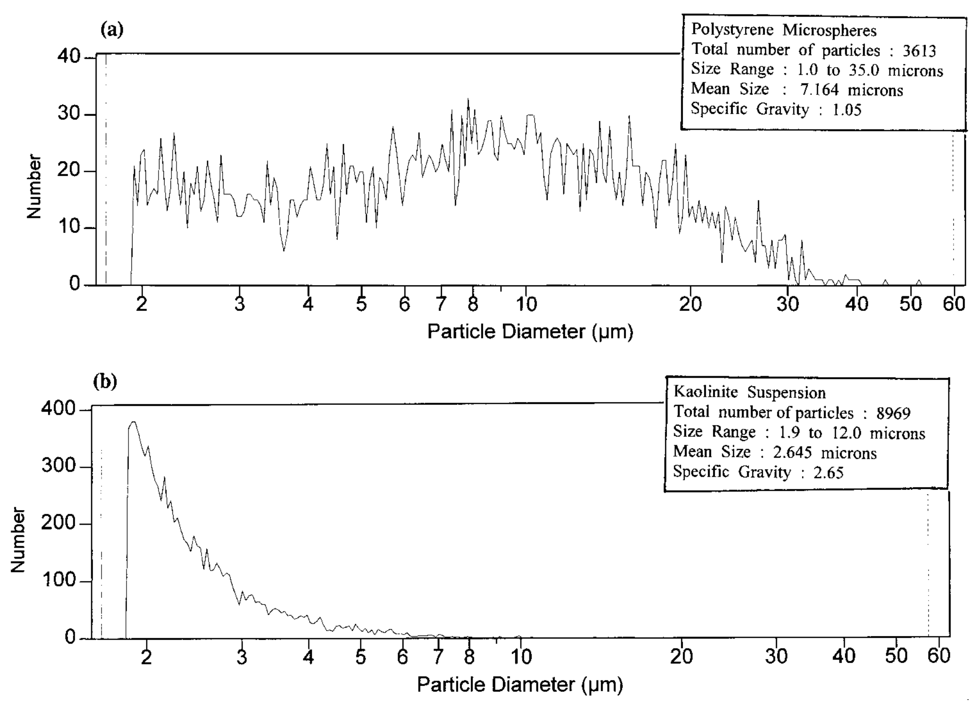


**FIG. 2. Particle Size Distributions of: (a) Polystyrene Spheres; (b) Kaolinite**



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Fig. 3 shows the schematic of the experimental setup. The influent is prepared in a suspension tank at a desired particle concentration. To keep the suspension stable and uniform in the tank, an electrical stirrer is used throughout the duration of the experiment. The influent suspension was sampled from various locations in the tank at regular intervals during the experiment, and the particle concentration (in terms of number of particles) and size distribution were monitored in these samples. The particle suspension was pumped using a programmable flow pump at the desired flow rate into the soil sample. The flow pump was calibrated for the flow rates used in this study (50 and 100 mL/min), and was found to be accurate for a range of pressure gradients developed in the experiments. In the preliminary runs of the experiment, the pulses created in the flow resulted in significant fluctuations in the pressure difference across the sample. Therefore, a pulse dampener, which absorbs the pulses, was used between the pump and the sample. The dampener was located on a magnetic stirrer to prevent particle settling. The pressure increase across the sample, caused by gradual particulate clogging, was monitored using a differential pressure transducer, which is sensitive in the range of 1–55 in. of water head. The transducer was connected to a data acquisition system. The effluent passes through a continuous flow turbidimeter, which records the turbidity in terms of the nephelometric turbidity units (NTUs). Effluent samples were also taken at periodic intervals for particle number and size analyses using the Coulter particle analyzer.

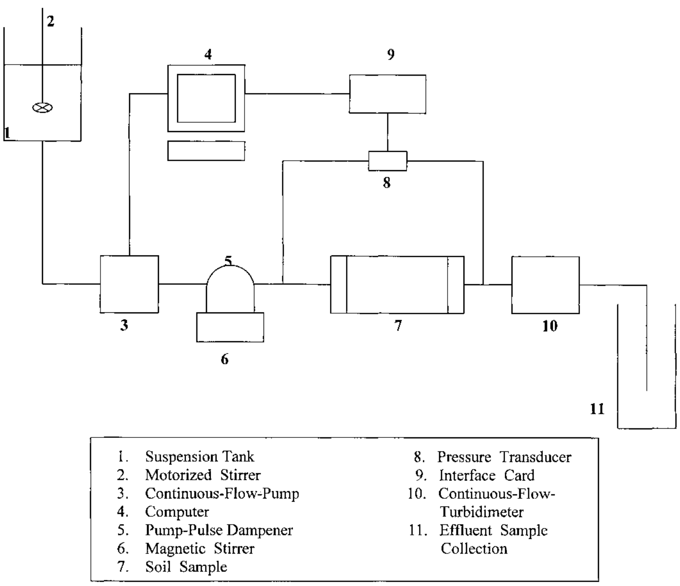


**FIG. 3. Schematic of Experimental Setup**

Prior to using particulate suspension, each experiment was conducted with distilled deaired water to obtain the initial permeability of the soil filter and to ensure accurate working of the various segments of the experimental setup. The size of the soil filter sample (64 mm long, and 76 mm diameter) was kept short enough to minimize the spatial dependence of the particulate clogging problem, and long enough to provide a representative sample. The area of cross section was chosen to be large enough to allow a suitable range of flow rates within which the programmable pump was very accurate. Each experiment was terminated when the effluent concentration (reflected in the turbidimeter reading) was steady, and the pressure readings from the data acquisition system show no further reductions in the permeability of the soil. The permeability was calculated using Darcy's law, with the recorded pressure differences across the sample and the flow rate of the pump. The initial permeability of the soil, with respect to pure water, was found to vary within a narrow margin of $3–4 \times 10^{-2}$ cm/s.

In view of the data required to model physical clogging of the filters, pore size distribution of the soil was determined using Haines method (Rowell 1994). This method involves subjecting a saturated soil sample in a Buchner funnel to gradually increasing suction pressures, and monitoring the water content released by the soil at each suction pressure. The capillarity principle was then used to transform the suction pressures to pore diameters. Fig. 4 shows the cumulative pore size distribution obtained for the filter sand. As seen in Fig. 4, the majority of the pore water was contained in this soil in pores with sizes ranging from 50 to 150 microns. These sizes are considerably greater than the sizes of the particles used in influent suspensions.

## RESULTS AND DISCUSSION

The results for a representative experimental run with the kaolinite particulate suspension are shown in Fig. 5. The effluent concentrations and the permeability of the sample, normalized by the influent concentration and initial permeability,

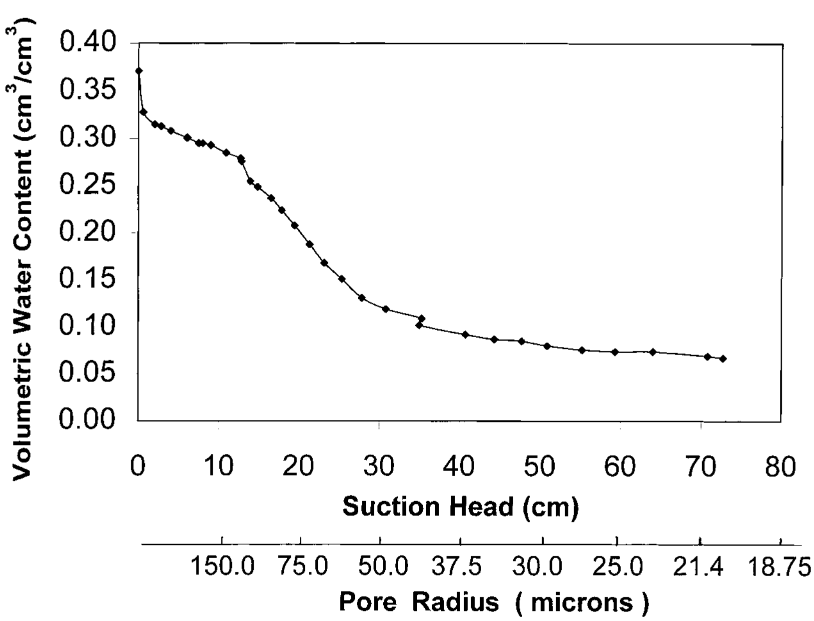


**FIG. 4. Pore Size Distribution of Filter Sand Determined Using Haines Method**

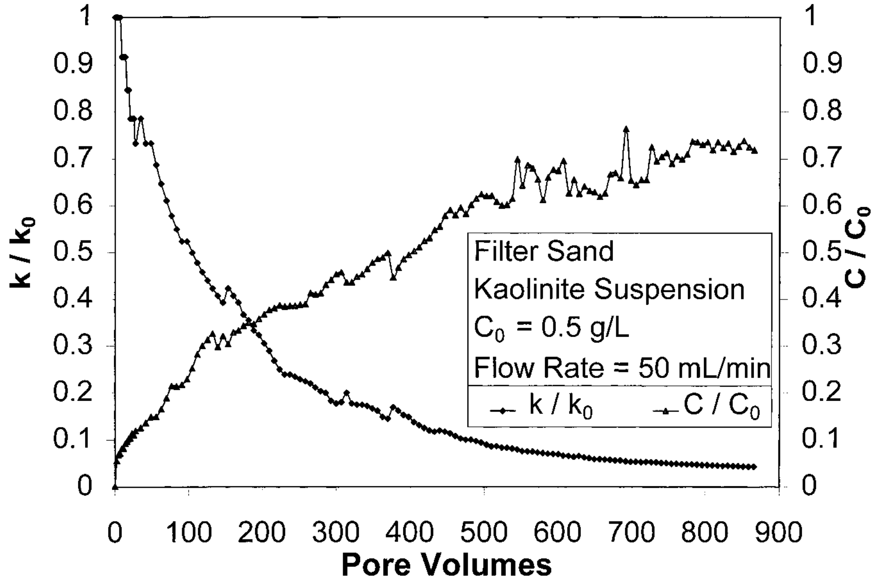


FIG. 5. Results from Representative Experimental Run with Kaolinite Particulate Suspension

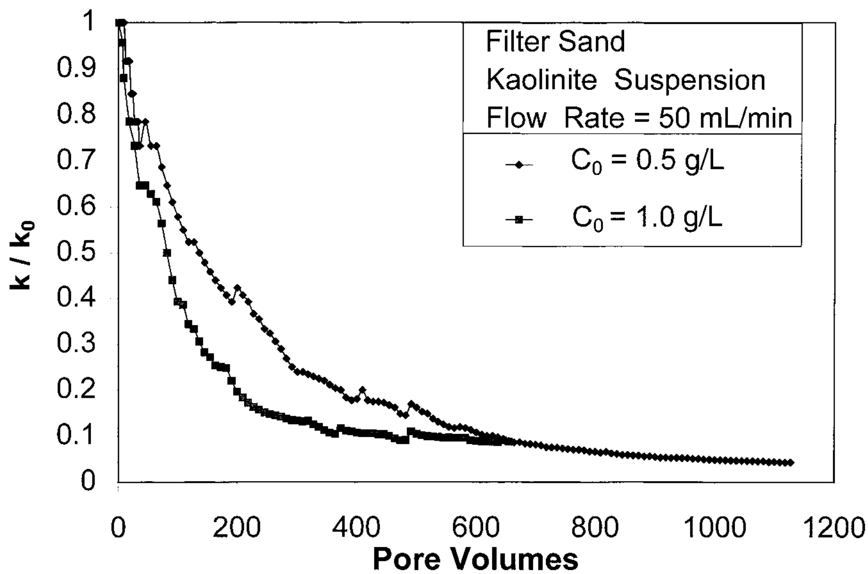


FIG. 6. Effect of Particle Concentrations in Influent on Permeability Reduction

respectively, are plotted against the number of pore volumes exiting the sample. The number of pore volumes that traveled through the sample was chosen as the *x*-axis, instead of time, to facilitate upscaling of laboratory results to field cases, where the filter volumes and the travel times are much greater. As seen in Fig. 5, the permeability reduced one order of magnitude in about 450 pore volumes for this experimental run. The effluent concentrations were less than the influent concentrations during these pore volumes as a result of kaolinite particle entrapment in the soil. They steadily increased in all of the experiments; however, the influent concentrations were not reached in the majority of the experiments during the period of testing. Although not apparent from the arithmetic axis of $k/k_0$ in Fig. 5, permeability continued to decrease throughout the duration of the experiment, albeit at a smaller rate at the end, as a result of continuous entrapment.

Fig. 6 shows the effect of increase in influent concentrations on permeability reduction. It is seen that the concentration affects the rate at which $k/k_0$ is reduced. The drainage capacities are reduced faster in the cases where the pore stream is more turbid. This is obviously due to the increased loading of the pore stream with particles. The magnitude of the total reduction, however, remains nearly the same in both cases. This indicates that beyond a certain state of clogging, the flow velocities in clogged pores are high enough to conduct the particles without significant deposition, regardless of the concentration of particles in the pore stream. This is also evident from the modeling results described subsequently.

Fig. 7 shows the comparison of the effects of particle concentration and particle sizes in the suspension. Although the polystyrene spheres resulted in slightly higher and faster reductions in *k* than kaolinite particles, the particle size effect is not as noticeable as the change in particle concentrations. Polystyrene suspensions generally had bigger particles than did kaolinite suspensions. According to the particle size distributions shown in Fig. 2, the majority of the kaolinite particle population was smaller than 4 microns, and the maximum size was 10 microns. The polystyrene sphere sizes, on the other hand, extend up to 50 microns. Thus, one would expect much smaller reductions in permeability with kaolinite particles than what are exhibited in Fig. 7. Particle size distributions determined using influents and effluents during the course of the experiment [Figs. 8(a) and 8(b)] provide an explanation for this behavior. As seen in Fig. 8(a), the size distributions of the



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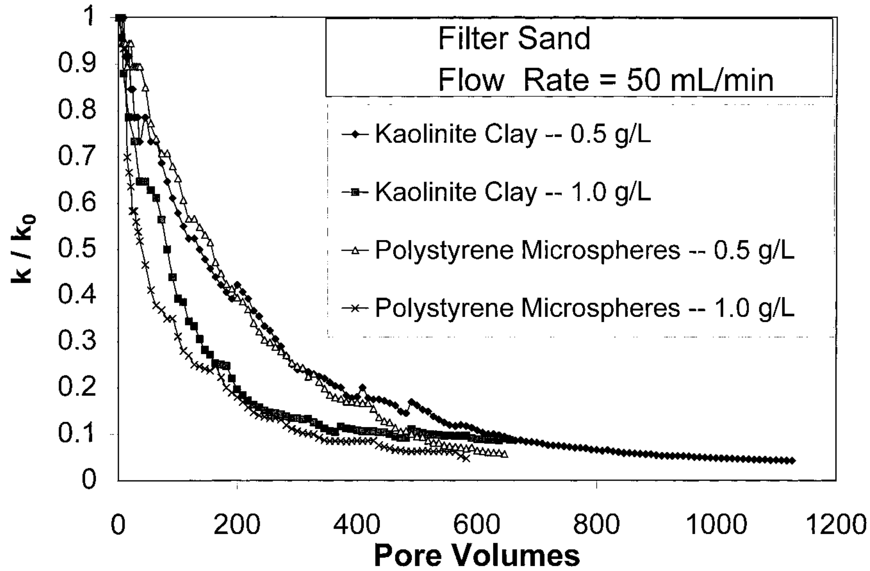


**FIG. 7. Comparison of Effects of Particle Concentrations and Particle Sizes on Permeability Reduction**

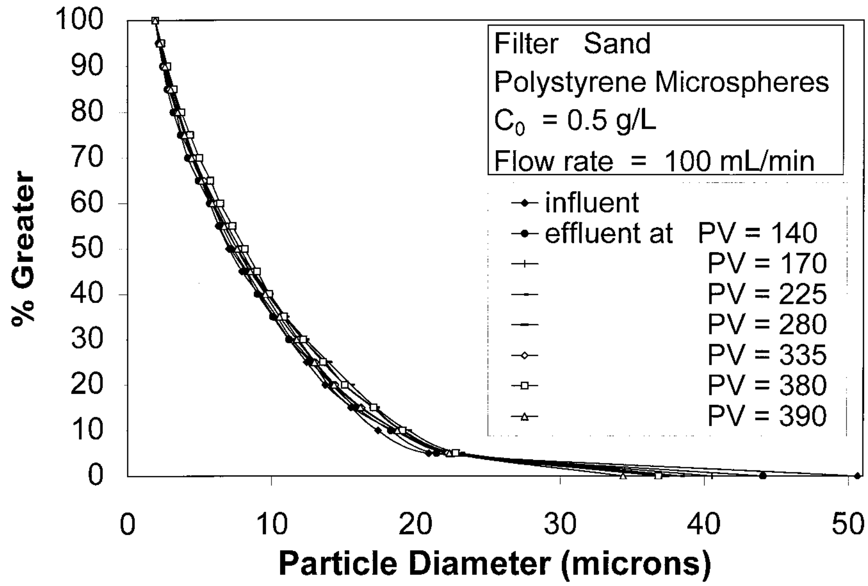


**FIG. 8(a). Size Distributions of Migrating Particles during Course of Experiment: Polystyrene Spheres**

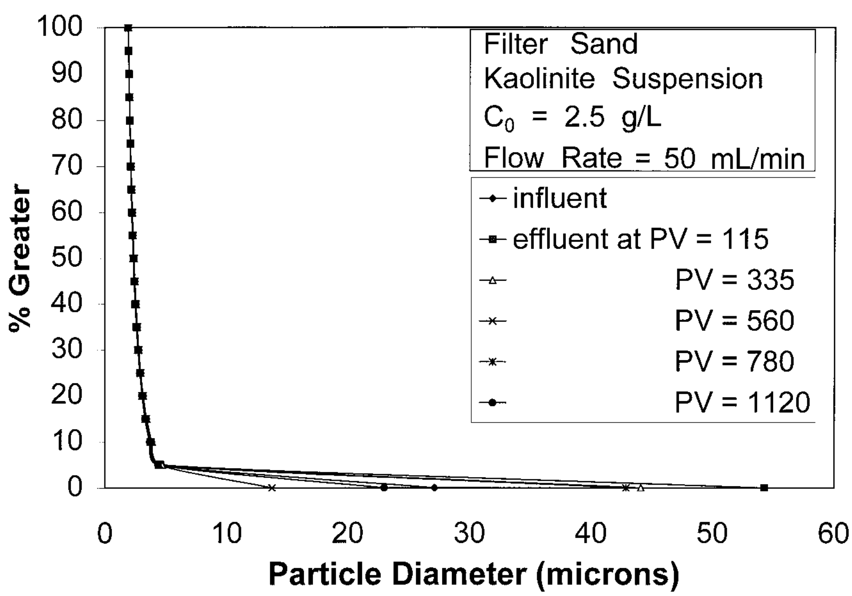


**FIG. 8(b). Size Distributions of Migration Particles during Course of Experiment: Kaolinite Particles**

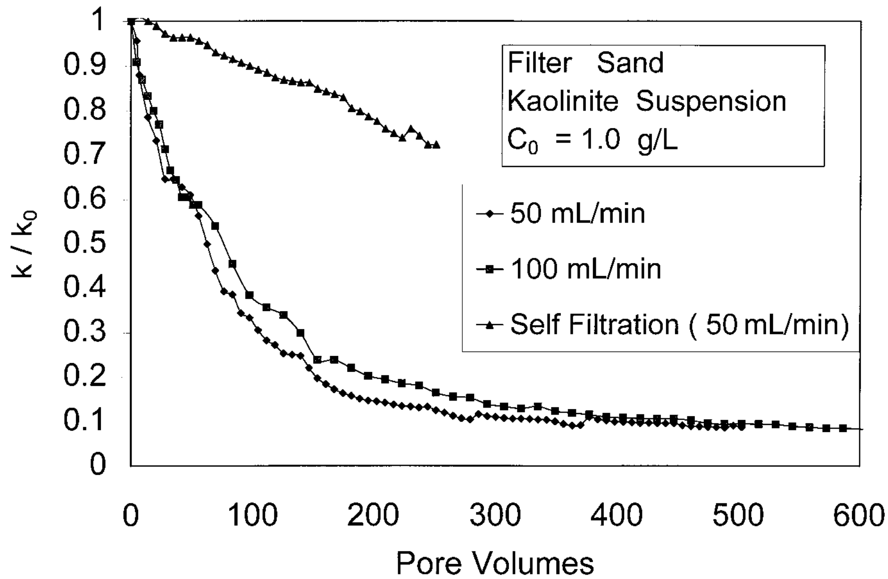


**FIG. 9. Effect of Flow Rates and Self-Filtration on Permeability Reduction**

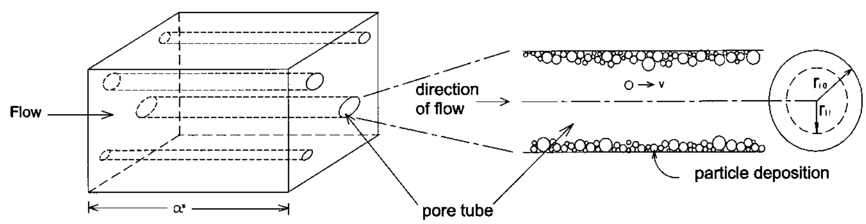


**FIG. 10. Capillary Tube Representation in Model**

polystyrene spheres during the course of the experiment are the same as those shown in Fig. 2. Thus, the inert spheres did not flocculate during the experiments. However, the size distribution of kaolinite particles [Fig. 8(b)] during the experiment showed about 5% (by number) of the population in size ranges between 4 and 55 microns. This indicates that, in spite of the constant agitation of the influent, the kaolinite particles flocculated during the course of their travel through the connecting tubes and the sample. The fact that a mere 5% of flocculated particles could cause significant reductions in the permeability (Fig. 7), almost close to that of polystyrene spheres, is also evident from the modeling studies described later. It is also seen from Figs. 8(a) and 8(b) that the particle size distributions are nearly the same in both influent and effluent, indicating that particles of all sizes are being entrapped in the filter. The minor exception is with a small percentage of the bigger particles. A gradual reduction in the maximum size of the particles in the effluent as the pore volumes increased is noticed in the case of polystyrene spheres [Fig. 8(a)].

Fig. 9 shows the effect of flow rate on permeability reduction for the kaolinite particle suspension with an influent concentration of 1 g/L. No appreciable differences were observed either in the rate or in the total magnitude of reduction in permeability. As discussed below, the flow rate governs the hydrodynamic forces created in the pore tubes, which influence the particle deposition. In general, a high flow rate results in higher hydrodynamic forces, which in turn reduce the likelihood of deposition. This general trend was clearly shown in the experimental studies conducted by Baghdlklan et al. (1989) involving very small flow rates in porous media. In the present study, however, this flow rate effect was not noticed. This is attributed to the rearrangement and migration of filter particles themselves at high flow rates (known as self-filtration), tending to gradually segregate the fine particles and reduce the permeability. Self-filtration was studied in the context of internal stability of granular filters (Kenney and Lau 1985; Indraratna and Vafai 1997). In the current experiments, it tends to negate the lesser likelihood of deposition caused by high flow rates in the filter. To experimentally evaluate the extent of self-filtration on permeability reduction, the filter sand was subjected to flow rates increasing from 50 to 100 mL/min with pure water using the same experimental setup. As shown in Fig. 9, a reduction in $k/k_0$ of about 0.2 was noticed due to self-filtration alone at high flow rates.

## MODELING OF PHYSICAL CLOGGING

The purpose of the modeling investigation is to develop a rational basis for determining the extent of permeability reduction of filters and drainage layers due to physical clogging. Our approach differs from the theoretically rigorous stochastic or particle-tracking approaches used in allied disciplines (surveyed in the earlier section) and the analytical solutions for combined particle release and entrapment processes (Reddi and Bonala 1997). Our attempt here is to develop a method that is easy to implement and that is valid for any irregular pore size distribution of a real-life filter or drainage material. To estimate the permeability of the soils, we adopt the Kozeny hydraulic radius model used in various studies in the past (Leonards 1962; Scheidegger 1974; Garcia-Bengochea et al. 1979). This model is an extension of the Hagen-Poiseuille equation, and is expressed as

$$k = C_s n \left(\frac{\gamma}{\mu}\right) \left[\frac{1}{4 \sum_i^1 \frac{f(d_i)}{d_i}}\right]^2 \qquad (1)$$

where $k$ = permeability; $C_s$ = shape factor (1/32) for cylindrical pores; $n$ = porosity; $\gamma$ = unit weight of water; $\mu$ = absolute viscosity of water; $d_i$ = $i$th pore diameter; and $f(d_i)$ = volu-



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metric frequency of the pore group $d_i$. The change in pore structure as a result of clogging will be reflected in the two parameters, $n$ and $d_i$. As with the Poiseuille equation, this equation is suitable to represent permeability of coarse-grained soils, which lend themselves to be adequately represented by capillary tubes. To allow application of the hydraulic radius model [(1)], we idealize the soil filter using an ensemble of parallel capillary tubes of various diameters (Fig. 10). The characteristic length, $\alpha^*$, over which idealization of straight cylindrical pore tubes is valid, was studied in detail by Arya and Paris (1981) and Arya and Dierolf (1989) for various types of soil. In an attempt to relate particle sizes and pore sizes of granular soils using water retention curves, they found that the effective cylindrical pore lengths varied from 0.3 to 1.5 cm for three texturally different soils. We therefore use a representative elemental volume (REV) of soil with length equal to $\alpha^*$ to simulate the particle clogging process.

To simulate time-dependent reductions in the pore tube diameters, we express the particle deposition rate in each pore tube as

$$\frac{dN(r_i, a_j)}{dt} = q(r_i)p(r_i, a_j)C(a_j) \tag{2}$$

where $N(r_i, a_j)$ = number of particles of radius $a_j$ deposited in the pore tube of radius $r_i$; $q(r_i)$ = flow rate through the tube $r_i$; $p(r_i, a_j)$ = probability of deposition of particles of radius $a_j$ in the tube $r_i$; and $C(a_j)$ = concentration of particles, in terms of number per unit volume, of radius $a_j$ in the pore stream. The flow rate through each tube $q(r_i)$, may be expressed using the Poiseuille law

$$q(r_i) = \frac{\pi\gamma J}{8\mu} r_i^4 \tag{3}$$

where $J$ = hydraulic gradient across the tube. Stein (1940) gave one of the original expressions for probability of fine particle deposition on the walls of a pore tube, which was used subsequently in several studies, including those by Rege and Fogler (1988) and Reddi and Bonala (1997). This expression is ideal to simulate capture of particles passing through pores when the majority of the particle population is smaller in size compared to the radius of the pore tube. It conceptualizes that the probability of particle capture is equivalent to a fraction of total flow in the annulus of a pore tube between $r_i$ and $(r_i - \theta a_j)$, and is expressed as

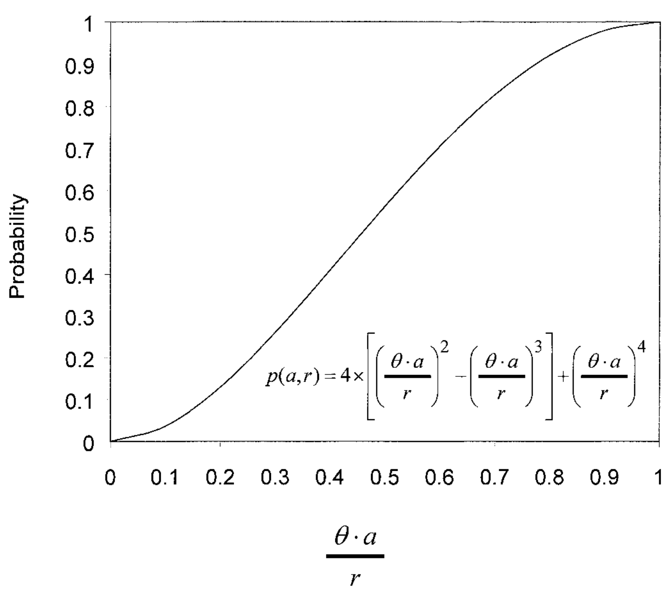


**FIG. 11. Variation in Particle Deposition Probability with ($\theta a/r$)**

$$p(r_i, a_j) = 4\left[\left(\frac{\theta a_j}{r_i}\right)^2 - \left(\frac{\theta a_j}{r_i}\right)^3\right] + \left(\frac{\theta a_j}{r_i}\right)^4 \tag{4}$$

where $\theta$ = lumped parameter that takes into account the effect on deposition of several interparticle forces such as gravitational, inertial, hydrodynamic, electric doubler layer, and van der Waals forces. The variation in probability given by (4) is shown in Fig. 11. The probability of particle deposition increases with an increase in $(\theta a_j/r_i)$, which might result from either an increase in $\theta$ and $a_j$ or a decrease in $r_i$. A high value of $\theta$ indicates that conditions are favorable for deposition. The nature of $\theta$ and the effects of various parameters such as fluid velocity, ionic strength, and pH were studied by Rege and Fogler (1988) and were incorporated in an exponential function, which in the present context may be written as

$$\theta = \theta_0 \exp[-v(r_i)/v_{cr}] \tag{5}$$

where $\theta_0$ = constant dependent on ionic conditions; $v(r_i)$ = velocity of flow in the pore tube; and $v_{cr}$ = critical velocity beyond which no particle clogging is likely. The value of $\theta_0$ is governed by ionic strength of the pore fluid and pH, and was found to vary from 1 to 10 in systems with bentonite suspensions with KC1 concentrations ranging from 0.0 to 0.01 M, respectively (Rege and Fogler 1988). Using (2)–(4), the total number of particles of various radii deposited in each pore tube may be estimated as a function of time. The change in pore radius as a result of the particle deposition would depend on the deposition morphology, which can neither be predicted nor be modeled from a practical standpoint. The effect of particles is merely to increase the resistance to flow and thus effectively reduce the pore size. Based on drag forces experienced by particles in cylindrical tubes, the pressure drop $\Delta J(a_j)$, caused by a single particle of radius $a_j$ in a tube of radius $r_i$, may be expressed as (Happel and Brenner 1973)

$$\Delta J(a_j) = \frac{12\mu a_j v(r_i)}{r_i^2}[1 - (1 - a_j/r_i)^2]^2 K(r_i, a_j) \tag{6}$$

where

$$K(r_i, a_j) = \frac{1 - 0.667(a_j/r_i)^2 - 0.202(a_j/r_i)^5}{1 - 2.1(a_j/r_i) + 2.09(a_j/r_i)^3 - 1.71(a_j/r_i)^5 + 0.73(a_j/r_i)^6} \tag{7}$$

where (6) and (7) are valid for laminar flow in cylindrical tubes for a wide range of $a_j/r_i$. The pressure difference across a clogged pore tube $r_i$ is equal to the sum of pressure differences caused by the individual particles and the pressure difference across the clean tube with no deposition. Using the Poiseuille law [(3)] to represent gradients across the clean and clogged tubes for a constant flow rate, the new pore radius may be expressed as

$$\frac{1}{(r_{i1})^4} = \frac{1}{(r_{i0})^4}\left\{1 + 3\sum_{j=1}^{M} N(r_i, a_j)\frac{a_j}{\alpha^*}[1 - (1 - a_j/r_i)^2]^2 K(r_i, a_j)\right\} \tag{8}$$

where $M$ = number of different migrating particle sizes; and subscripts $i0$ and $i1$ refer to the radii before and after the deposition. The reduced porosity after deposition is thus obtained by taking the sum of the volumes of new pore tubes into account. With the new pore sizes and the reduced porosity, the time-dependent permeability reduction can be estimated using (1).

## APPLICATION OF MODEL

For the sake of validation, the model was applied to the experimental conditions reported in the earlier section. The pore size distribution shown in Fig. 4 and the particle size



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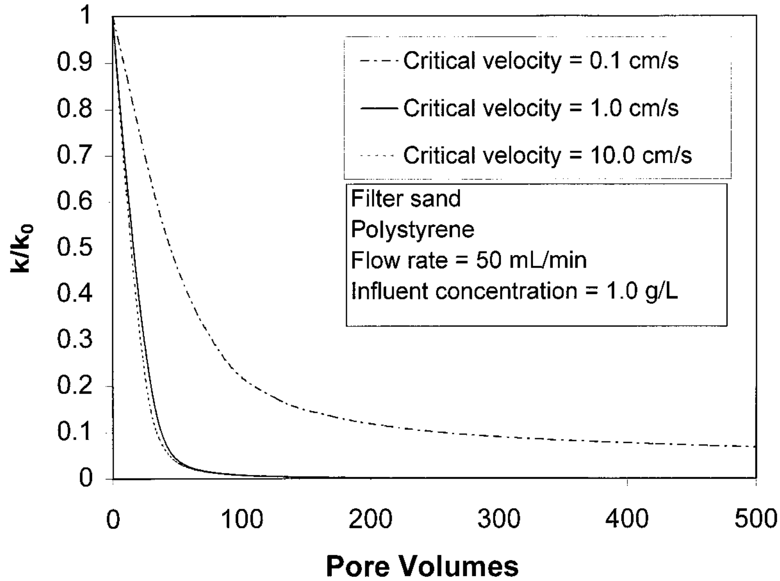


FIG. 12. Sensitivity of Model Predictions with Respect to $v_{cr}$

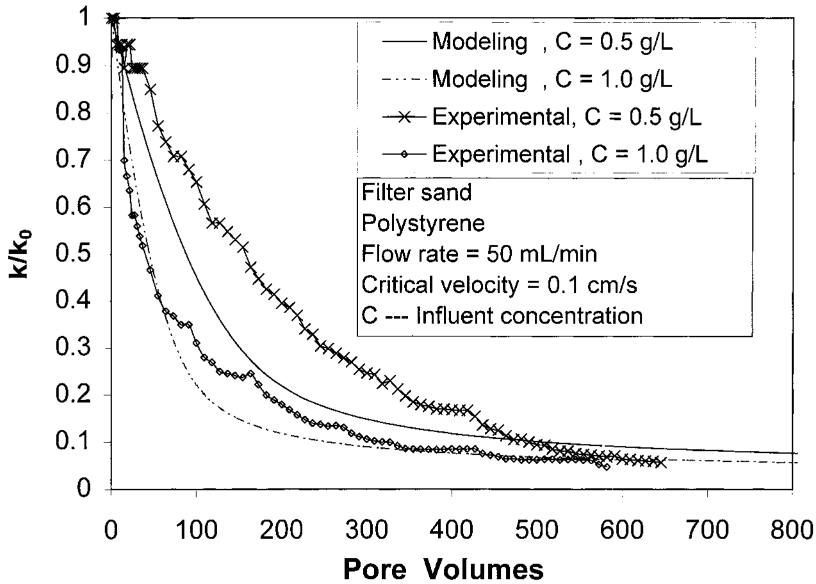


FIG. 13. Model Predictions and Experimental Observations for Two Different Particle Concentrations

distributions in the particulate suspension (Fig. 2) were used to simulate the particle deposition process. Based on the characteristic lengths reported in Arya and Dierolf (1989), $\alpha^*$ was chosen to be 0.911 cm. The value of $\theta_0$ is taken to be 3, as suggested by Rege and Fogler (1988) for a pore fluid with no salts present. To account for the scale differences between the experimental sample size and the REV of the model, the flow rate in the model $q_m$ was reduced in proportion to the area of the cross section. Thus

$$q_m = \left(\frac{q_e}{A_e}\right) A_m \tag{9}$$

where $q_e$ = flow rate used in the experiment; and $A_e$, $A_m$ = areas of cross section of the experimental soil sample and the REV of the model. Direct measurements of pore velocities $v_{cr}$ at which hydrodynamic forces are so great that deposition is unlikely were difficult to make. Gruesbeck and Collins (1982) provided an indirect evaluation of this parameter based on interstitial velocities at which particles are entrained by pore fluids of varying viscosities from a deposited medium. Their studies involving granular soils indicate particle entrainment for pore velocities greater than 0.1 cm/s. The sensitivity of the model predictions with respect to $v_{cr}$ is shown in Fig. 12. For $v_{cr}$ values of the order of 1–10 cm/s, the pore velocities are low enough to cause complete clogging of the pores. Complete clogging was not seen in any of the experiments of this study. Thus, $v_{cr}$ suggested in the studies by Gruesbeck and Collins (1982) appears to be valid for the filter sands of this study. The remaining modeling runs were therefore made with $v_{cr}$ = 0.1 cm/s.

Fig. 13 shows the model predictions for polystyrene spheres at two different concentrations along with the experimental observations. Consistent with the experimental results, the model predicted a faster deterioration of the filter in the case of higher particle concentration in the suspension, with the ultimate reduction in $k$ remaining nearly the same. In general, the agreement between the model predictions and the observations was good. The slight overpredictions of the rate of reduction might be due to the fact that the pressure drops due to individual particles were all summed together [(8)] without considering particle interactions or particle deposit morphology. However, it could be perhaps viewed as conservative to estimate slightly higher permeability reductions in practice.



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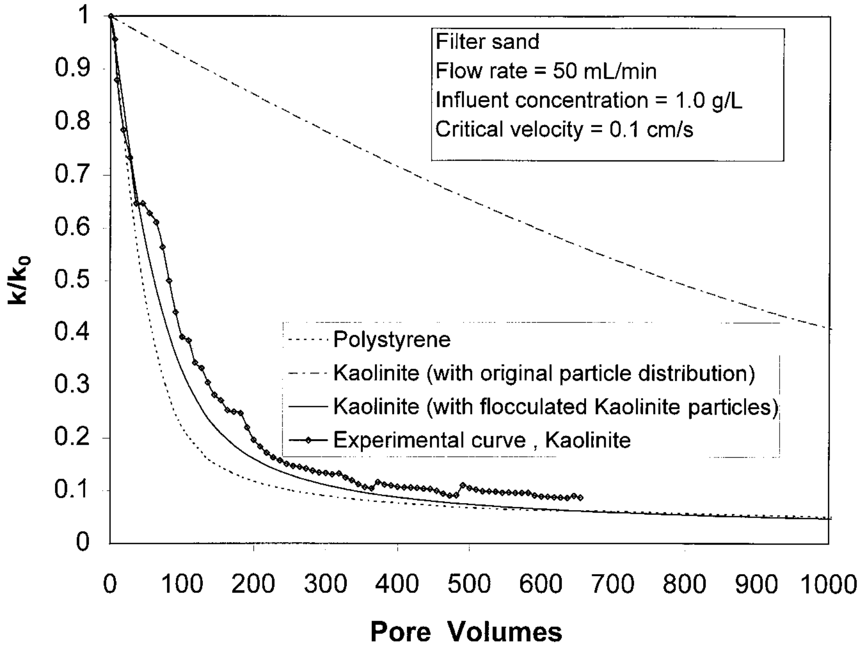


**FIG. 14. Model Predictions for Kaolinite Particles with Original and Flocculated Size Distributions**

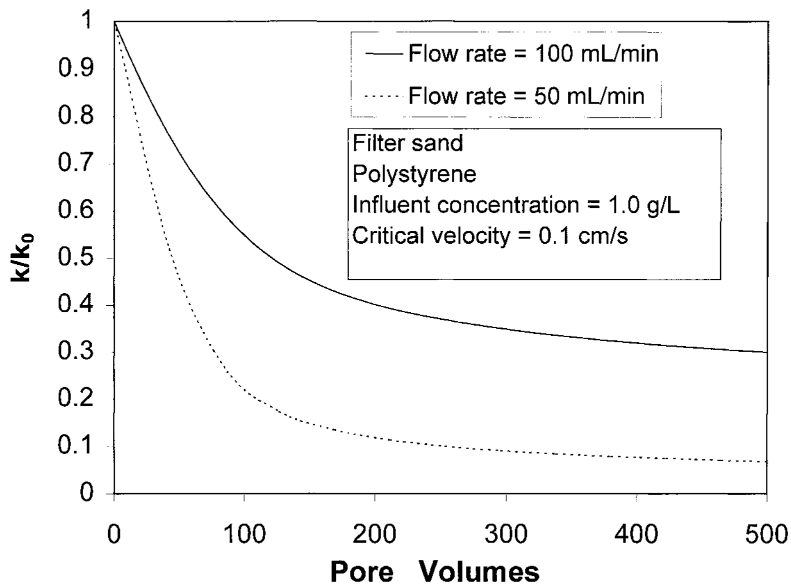


**FIG. 15. Model Predictions for Different Flow Rates**

The effect of particle size distribution in the suspension is simulated in Fig. 14. As expected, kaolinite suspensions yielded a very low reduction in permeability when the initial particle size distribution was chosen from Fig. 2. However, when the particle size distribution was changed to reflect the presence of flocculated particles [Fig. 8(b)], the model predictions agreed very well with the experimental observations. It is apparent that the 5% of the flocculated particles controlled the permeability reduction significantly. It is therefore important to consider the sizes of the bigger particles in turbid waters while assessing the drainage capacity reductions, although these particles may be fewer in number.

The model predictions for the two different flow rates are shown in Fig. 15 for polystyrene particles at an influent concentration of 1 g/L. A lower reduction in permeability is indicated at the higher flow rate. As stated in the experimental section, the velocities in individual pore tubes are greater at higher flow rates, and the model reduces the probability of deposition in accordance with the ratio of $v(r_i)/v_{cr}$ in (5). This is the general trend to be expected at low flow rates, and was demonstrated in the experimental results reported by Baghdlklan et al. (1989). However, as indicated above, the self-filtration at high flow rates (Fig. 9) tends to alter the pore structure, segregating all of the fine particles and the associated pores during the course of permeability reduction. This tends to increase the likelihood of particle deposition, thus negating the effect of the increased hydrodynamic forces at high flow rates. The difference in the ultimate magnitudes of permeability reduction between the two flow rates is about 0.2, which is about the same reduction observed in the self-filtration test (Fig. 9). Modeling the fine particle entrapment with the simultaneous self-filtration process is beyond the scope of this paper. It is recommended, however, that the predictions of the model for lower flow rates be used as a guide to estimate the permeability reduction of drainage layers.

A few comments on the particle implementation of this modeling approach are in order. In addition to the particle size and concentrations of suspended particles in the influent sus-



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pension, the model requires the pore size distribution of the sands. The Haines method described above is a simple method, requiring no more than a couple of hours to determine the pore size distribution of granular materials. However, in the absence of such facilities, the particle size distribution could be used to deduce the pore size distributions in the case of sandy soils. A number of expressions relating the particle size and pore size distributions are documented in the literature (Arya and Dierolf 1989), and one could resort to these in the absence of pore size distribution data. The modeling investigation does, however, indicate that a size distribution of migrating particle population is an important input. When available in mass units per unit volume, suspended particle concentrations could be transformed to number per unit volume using the size distribution of the particles.

## CONCLUSIONS

The experimental phase of this study allowed an accurate assessment of the permeability reductions of a filter and subjected to particulate suspensions. The major findings from this phase are summarized below.

1. Permeability reductions of more than an order of magnitude were noticed after about 300–600 pore volumes, for nominal concentrations (0.5–1.0 g/L) of polystyrene and kaolinite particles (which represent a range of migrating particle sizes) in the pore stream. The particles were smaller than the majority of the soil pores.
2. An increase in particle concentration led to a faster reduction in permeability. In spite of their small and uniform sizes, kaolinite particles in the pore fluid caused permeability reductions comparable to those of polystyrene spheres, which are relatively large. This was concluded to be the effect of flocculation, resulting in 5% (by number) of particles in the size range of 4–55 microns.
3. Difference in flow rates did not cause any noticeable change in the clogging behavior, although particle deposition is generally known to be less likely at higher flow rates. This was concluded to be the result of self-filtration at higher flow rates, which was experimentally shown to cause about a 20% reduction in the initial permeability.

A simple model was developed to simulate particle clogging and its effect on permeability. The porous medium was represented using an ensemble of capillary tubes, and particle clogging and its effect on pore radii were modeled using basic principles of flow in cylindrical tubes. With the exception of two parameters, $v_{cr}$ and $\theta_0$, whose values were adopted from similar studies in the literature, all other parameters in the model were simple and experimentally determinable. In spite of the simplifications, the model predictions agreed well with the experimental observations. The model supported the experimental finding that a few flocculated particles may significantly reduce the permeability in the case of kaolinite particle suspensions. Self-filtration of the porous medium was not represented in the model; therefore, the model yielded lower reductions in permeability for the high flow rates. Although this differed from the trend seen in the experiments, it is consistent with the trend reported by others in the literature for flow rates much smaller than the magnitudes used in the experiments. The extent by which the model underpredicted the permeability reductions for the higher flow rate is approximately the same as the extent due to self-filtration observed in the experiments. Modeling self-filtration simultaneous to pore fluid particle migration is a complicated task, as it requires tracking of the time-dependent pore structure and handling of layered systems. This is beyond the scope of this study. Finally, the methods developed in this study could be extended, perhaps with simple modifications, to geotextiles and other materials, if these materials could be represented as equivalent porous media. The writers hope that this study fuels future studies along these lines.

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