

Modelling the Soil Surface Seal from a Filtration Perspective

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نمذجة إحكام سطح التربة من منظور الرشح

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خلاصة: تم وضع نموذج لإحكام سطح التربة بصورة طبيعية. ولقد صيغت المعادلات الحاكمة بناءً على قانون حفظ الكتلة وعلى اعتبار أن المواد العالقة ينطبق عليها قانون "دارسي" عند تسربها من خلال سطح التربة. ويتضمن النموذج فيزيائية إحكام سطح التربة عند احتجازها للمواد العالقة في المياه المتسربة. ونتيجة لاحتباس الجزيئات في نظام التربة تقل المسامية الذاتية للتربة وتزداد كثافتها الظاهرية، مما يحدث تغييراً في خاصيتها الهيدروليكية مثل قدرتها على الاحتفاظ بالماء والتوصيل الهيدروليكي. ولقد تم تطوير دالات تجريبية لقياس التغييرات في هذه الخواص عند إحكام سطح التربة. من هذا المنطلق يمكن وصف عملية الإحكام رياضياً عن طريق الظروف الابتدائية والحدودية المعرفة جيداً، وبهذا يمكن محاكاة الخواص الانتقالية للإحكام بطريقة واقعية.

ABSTRACT: A physically based model of soil surface sealing is proposed. The governing equations are formulated on the principle of conservation of mass assuming Darcy's law applies to a suspension flowing through the soil surface. The model incorporates the physics of surface sealing by mechanisms that capture suspended particles moving with infiltrating water. As a result of particle retention in the soil system, the intrinsic porosity is reduced and bulk density is increased, resulting in changes to soil hydraulic properties such as moisture retention and hydraulic conductivity. Empirical functions are developed to describe the changes of these properties as the seal develops. With this approach, the seal can be mathematically described by well defined initial and boundary conditions and transient seal properties can be simulated in a physically realistic manner.

Modification to the soil surface by rainfall may be mechanical or physico-chemical in nature (Romkens *et al*, 1990). These changes are dependent on the physico-chemical characteristics of the soil and chemical composition of the water, which alters the soil structure, and its associated physical and hydraulic properties. These alterations are commonly described as seal formation.

The texture and structure of the surface seal have been observed using microscopic and scanning electron microscope techniques (McIntyre, 1958 a,b; Tackett and Pearson, 1965; Farres, 1978; Chen *et al*, 1980; Tarchitzky *et al*, 1984; Onofiok and Singer, 1984). These studies showed that the seal generally consists of a thin compact layer of reduced porosity gradually extending to a more open underlying layer of uniform pore and particle size distributions comparable to the undisturbed soil.

During seal formation, the infiltration rate or

saturated hydraulic conductivity is reduced and a number of mathematical models have been proposed to quantify this process. Most of these models are either empirical (Seginer and Morin, 1970; Moore, 1981; Morin *et al*, 1981) or based on the well known Green and Ampt infiltration model assuming a thin layer of surface seal overlying an undisturbed soil (Hillel and Gardner, 1970; Ahuja, 1983).

Mualem and Assouline (1989) modeled the seal as a non-uniform layer. They considered the seal as a disturbed zone in which compaction by raindrops and washed-in material caused an increased bulk density. The increase in bulk density, $\Delta\rho(z)$ at any depth, z , is related to the increase in bulk density at the soil surface, $\Delta\rho_0$ by an exponential depth function of the form:

$$\Delta\rho(z) = \Delta\rho_0 e^{-\alpha z} \quad (1)$$

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Where γ has been described as the characteristic constant of soil-seal-rain system. In order to determine γ , they considered that the non-uniformity of the seal is limited to a finite upper layer of depth d , below which the soil remains undisturbed. With this hypothetical lower boundary of the seal, it was defined that:

$$\frac{\Delta\rho(d)}{\Delta\rho_0} = 10^{-3} \quad (2)$$

By combining Equations 1 and 2, they defined the parameter γ in terms of the seal thickness d by:

$$\gamma = -d^{-1} \ln 10^{-3} \quad (3)$$

By using this increase in bulk density as a depth function, they described soil hydraulic properties of the seal as a function of depth.

With this model it is no longer necessary to consider an abrupt interface between the undisturbed soil and the seal. However, their model is applicable only to the case of a well-established surface seal and not to the transient process of seal formation.

In this paper, we present a theoretical basis for the process of surface sealing as filtration phenomenon and we illustrate the link between the theory of Mualen and Assouline (1989) and a more generalised approach, based on filtration theory and extended to the characterize transient seal properties.

Review of Filtration Process

When raindrops strike bare soil, practically all of the kinetic energy dissipates as work done against the soil surface. The kinetic energy transferred contributes towards physical disruption of soil aggregates. As soils containing silt and clay becomes wetter, then the force required to breakdown the soil aggregates becomes less resulting in greater destruction of soil structures. Commonly, silt and clay particles become dispersed in the rain water during the aggregates destruction and can infiltrate into the soil.

In a dispersed medium, if the infiltrating (percolating) water carries suspended sediments, the final particles are deposited along the pathways of flow. This filtration process increases the bulk density of the solid matrix and as a result, porosity and intrinsic hydraulic conductivity are decreased. Herzig *et al.*, (1970) described two types of deep filtration. They defined mechanical filtration to be for particles with an effective diameter $>30 \mu\text{m}$ and physico-chemical filtration to be for particles with an effective diameter $\leq 1 \mu\text{m}$. For intermediate sized particles, both

mechanical and physico-chemical filtration processes are involved.

Several factors affect particle migration. It has been recognized that mechanical bridging at pore restrictions can occur if certain conditions such as particle size and concentration are met (Muecke, 1979). In addition to mechanical bridging, particles smaller than the smallest distance between soil particles may be retarded in the pores by the attraction between the grains and by electro-chemical forces acting on their surfaces.

There are four possible retention sites described in the filtration literature; i) surface sites: the particle stops and is retained on the surface of a porous bed grain; ii) crevice sites: the particle becomes wedged between two convex surfaces of the grain (Figure 1); iii) constriction sites: the particle cannot penetrate into a pore of a smaller size than its own; iv) cavern sites: the particle is retained in a sheltered area, a small pocket formed by several grains.

Herzig *et al.*, (1970) described the particle capture processes in deep bed filtration as; i) sedimentation: if the particles have a mass density different from that of the liquid, they are subjected to gravity and their velocity is no longer that of the fluid. Thus, by sedimentation they can come in to contact with the soil grain; ii) inertia forces: still owing to their apparent weight, particles cannot follow the same trajectories as the fluid. They deviate from the stream lines and can be brought into contact with soil grain; iii) hydrodynamic effects: owing to the non-uniform shear field and the non-sphericity of particles, hydrodynamic effects may occur. These effects cause a lateral migration of suspended particles which may be brought into contact in this way with retention sites; iv) direct interception: even with exactly the same density as the fluid, the particles would not be able, owing to their size, to follow the smallest tortuosities of the streamlines of the carrier fluid and they will thus collide with the walls of the convergent area of soil pores (Figure 2); v) diffusion by Brownian motion: the particles in suspension are subjected to random bombardment by molecules of the suspending medium, resulting in Brownian movement. The particles diffuse

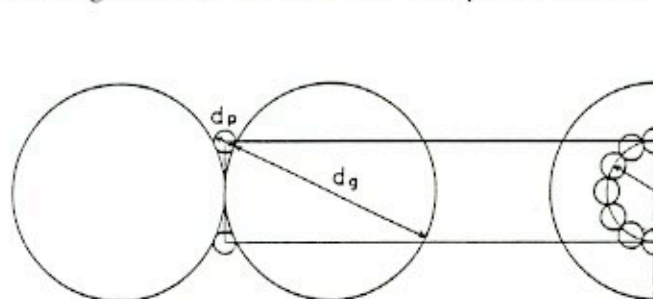


Figure 1. Particle retention in a crevice site (Herzig *et al.*, 1970)

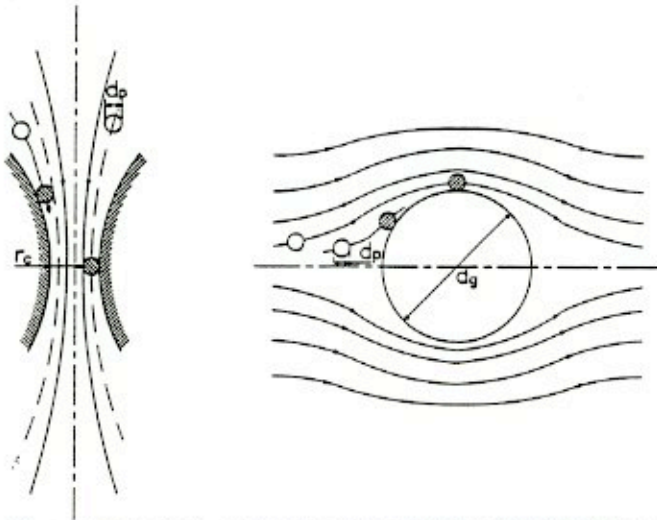


Figure 2. Particle capture by direct interception (Herzig *et al.*, 1970)

and can thus reach areas which are not normally irrigated by the suspension and they are retained there; vi) straining in the contact zones of adjacent pores: a major particle capture mechanism at the soil surface is that of particles wedging at constrictions. Straining takes place when a particle in suspension flowing through pore, is larger than the pore opening. This may occur as a result of the simultaneous arrival of a number of particles, or by successive blockage of particles in a crevice (Figure 3). Theoretically, a particle of any diameter may wedge in a void between two grains, however if the ratio of suspended particle to grain diameter is small it can be then assumed that the particle lies on a surface site rather than in a crevice.

Maroudas and Eisenklam (1965) and Maroudas (1965) studied the particle deposition and clogging development process. According to them, particles may settle by gravity on the graintops or on the

horizontal pore surfaces and thus block the channels. They found that an important parameter was the ratio of the particle diameter, d_p to the grain diameter, d_g . For $d_p/d_g > 0.15$, the porous medium is irreversibly blocked and a filter cake is formed. For $d_p/d_g < 0.065$ the retention always remains low and for intermediate values a partial blocking of the porous medium may occur.

While straining mechanism is frequently mentioned as the cause of suspended particle removal, little quantitative analysis has been attempted (McDowell-Boyer *et al.*, 1986). The most critical factor determining straining within the porous medium is the ratio of particle diameter to media grain diameter (d_p/d_g). Kovac (1981) used the capillary tube model to characterize the maximum and minimum diameter of the pores between the grains and used this model to determine maximum particle diameter (d_{pm}) entering the pores as a function of initial porosity (ϵ_0) and the grain diameter of the medium by:

$$d_{pm} \leq \frac{1}{2} \left[\frac{\epsilon_0}{1 - \epsilon_0} \right] d_g \quad (4)$$

Once larger particles are strained at or near the surface, the concentration of the suspension entering into the underlying soil profile is smaller than that of applied suspension at the soil surface (c_0). This is approximated by (Kovac, 1981):

$$c_{oc} = \frac{S(d_{ps})}{100} c_0 \quad (5)$$

Where $S(d_{ps})$ is the percentage by weight of the particles in the suspension having a smaller diameter than the lower limit of strained particle diameter, d_{ps} .

Herzig *et al.* (1970) explained that for a particle to remain wedged in such a site, the fluid must bring it to the site with a sufficient kinetic energy. They estimated the significance of this effect on particle retention assuming all available sites are occupied on the surface and therefore:

$$\sigma = \frac{(1 - \epsilon_0)}{2} \pi C \left(\frac{d_p}{d_g} \right)^2 \sqrt{\left(1 + \frac{d_p}{d_g} \right)^2 - 1} \quad (6)$$

Where σ is the volume of particle retention per unit volume of soil and C is the coordination number. The

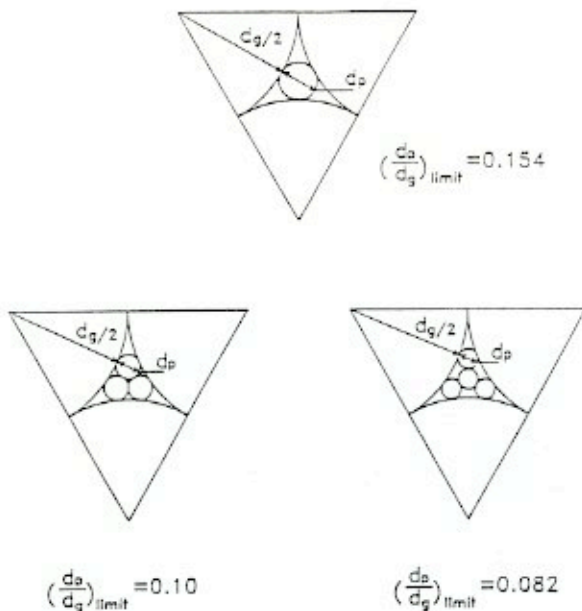


Figure 3. Particle capture by direct interception (Herzig *et al.*, 1970)

coordination number C , indicates the interconnect-
edness in the network of a porous medium. Haughey
and Beveridge (1966) indicate that the network of a
porous medium. Haughey and Beveridge (1966)
indicate that the value for the coordination number C
for closed random packing of equal sized spheres is
between 8 and 9.

At a macroscopic level, the theoretical description
of the process of clogging is based on the analysis of
the change in concentration of the suspension in
position and time. The aim of the formulation is to
define the quantity of fine materials deposited on the
soil matrix and therefore to obtain an expression for the
reduction in soil porosity.

In this case, a basic distinction has to be made
between two extreme types of fine particle transport
with infiltrating water. There may be soil systems with
large cracks and fissures which are continuous, and
therefore much of the suspension may be transported
with infiltrating water to the deeper layers. On the
other hand, water carrying fine particles may flow on
the soil surface, and only some of the particles may
enter into the soil system with infiltrating water.

In practice, particle capture takes place with more
than one particular mechanism dominating the filtration
process. However, while treatment of all the processes
is theoretically rigorous, experimental parameterisation
is not possible and therefore, only the dominant
processes are considered in this study.

Theory

A differential expression can be developed to
describe water and particle movement in a soil by
accounting for the mass balance of water and particles
passing through a soil volume. Consider a flow of
suspension in vertical downward direction, and assume
that the flow obeys Darcy's law. A unit volume of
suspension contains a volume of c particles and a
volume of $(1-c)$ of water. For a negligible
concentration change, the moisture balance equation
can be written (Somaratne, 1994):

$$-\frac{\partial v_z}{\partial z}(1-c) = \left(c(\psi) + \frac{\theta}{\epsilon} s_s \right) \frac{\partial \psi}{\partial t} \quad (7)$$

Where c is the volume concentration of the particles in
the suspension, v_z is the flow rate, θ is the volumetric
moisture content, ϵ is the porosity, s_s is the specific
yield, t is the time, Ψ is the matrix pressure potential,
and $c(\Psi)$ is the specific moisture capacity. The
hydraulic potential head ϕ is constituted of pressure
head Ψ and gravitational head z , which is the vertical
distance from the soil surface downwards (i.e. depth).

Therefore, from Darcy's law, the seepage velocity can
be written as:

$$v_z = -k(\psi) \left(\frac{\partial \psi}{\partial z} - 1 \right) \quad (8)$$

combining Equations 7 and 8

$$(1-c) \frac{\partial}{\partial z} \left(k(\psi) \left(\frac{\partial \psi}{\partial z} - 1 \right) \right) = \left(c(\psi) + \frac{\theta}{\epsilon} s_s \right) \frac{\partial \psi}{\partial t} \quad (9)$$

If the volume occupied by particles is negligible with
respect to the bulk volume of water, then $(1-c) = 1$,
and Equation 9 reduces to:

$$\frac{\partial}{\partial z} \left(k(\psi) \left(\frac{\partial \psi}{\partial z} - 1 \right) \right) = \left(c(\psi) + \frac{\theta}{\epsilon} s_s \right) \frac{\partial \psi}{\partial t} \quad (10)$$

The numerical solution of Equation 10, the saturated -
unsaturated flow equation, to obtain the unknown Ψ
and v_z , is well documented (Neuman, 1973; Neuman *et al.*,
1975; Hyuarkon and Pinder, 1983; Ross, 1990.
Details are not given here.

The process of particle deposition can be
conveniently divided into two sequential steps: transport
and attachment. In the transport step, the particles are
transported from the bulk of the solution to the vicinity
of a soil grain surface. The transport of Brownian (sub
micron) particles is dominated by convection and
diffusion while that of larger (non-Brownian) particles
is controlled by gravity, fluid drag and interception due
to the finite size of the particle (Elimelech and
O'Mellia, 1990). In deriving the mathematical
expression for the particle capture process, the
combined influence of unretarded London-van der
Waals forces and diffuse double layer interaction
(Spielman and Cukor, 1972; Spielman and Fitzpatrick,
1973; and Spielman and Friedlander, 1974) is not
considered in this analysis.

The general mass balance equation for particles in
suspension in the z -direction can be written as:

$$\frac{\partial}{\partial t} (\sigma + \theta c) = D \frac{\partial^2 \theta c}{\partial z^2} - v_z \frac{\partial c}{\partial z} \quad (11)$$

In principle, Equation 11 is simply a statement
that particles removed from suspension are deposited in
the soil matrix. The first term in the right hand side of
Equation 11 is the particle transported by diffusional
fluxes. The dispersion term D represents the combined
effects of molecular diffusion and mechanical

dispersion. The second term represents particle transport by convection. In order to obtain a mathematically amenable form of Equation 11, the following approximations are made. Firstly, particle diffusion is negligible when the size of a particle is larger than $1\mu\text{m}$ and for ultra-fine particles, convective flow is always the most significant term. Therefore, the diffusion term in Equation 11 may be neglected. Secondly, as is often assumed, all moving particles are neglected with respect to the retained particles (Herzig *et. al.*, 1970). This is only reasonable if θc is small compared with σ , and may be invalid at the start of clogging.

These approximations enable the use of the simplified and already accepted form of the particle balance Equation (Herzig *et. al.*, 1970; Ives, 1975; Tien and Payatakes, 1979; Adin and Rebhun, 1977; Rajagopalan and Tien, 1979):

$$\frac{\partial \sigma}{\partial t} = -v_z \frac{\partial c}{\partial z} \quad (12)$$

The macroscopic conservation Equation 12 involves two dependent variable c and σ . In order to obtain a solution for c and σ as function z and t , a second expression is required relating c and σ . The rate equation proposed by Iwasaki in 1937 is a widely used and commonly accepted form of the expression for the filtration rate (Rajagopalan and Tien, 1979):

$$\frac{\partial \sigma}{\partial t} = v_z \lambda c \quad (13)$$

Where λ is the filtration coefficient. Equations 12 and 13 can be solved in two steps to obtain σ with the initial and boundary conditions of:

$$\sigma = 0, \quad z \geq 0, \quad t = 0 \quad (14)$$

$$c = c_0, \quad z = 0, \quad t > 0 \quad (15)$$

Where c_0 is the volume concentration of the particles at the soil surface and t is the time. The initial conditions 14, imply that at the beginning of the infiltration process, the soil system is free from clogging or seal development. Boundary condition 15 suggests that for all $t > 0$, a suspension of concentration c_0 exists at the soil surface. Substituting Equation 13 into Equation 12 yields:

$$\frac{\partial c}{\partial z} = -\lambda c \quad (16)$$

Integrating Equation 16 with the boundary condition 15 yields:

$$\frac{c}{c_0} = e^{-\lambda z} \quad (17)$$

Substituting the value of c in Equation 17 into Equation 13 and integrating using the initial conditions 14 yields:

$$\sigma = v_z \lambda c_0 e^{-\lambda z} t \quad (18)$$

Here, λ and v_z are taken as constants at solution time t , but they have different values at different times. Similarly, retention at the soil surface, $z=0$, is given by:

$$\sigma_0 = v_0 c_0 \lambda t \quad (19)$$

For a steady state flow condition for a finite seal depth z , $v_0 = v_z$. By dividing Equation 18 by Equation 19 we obtain:

$$\frac{\sigma}{\sigma_0} = e^{-\lambda z} \quad (20)$$

The proportionality factor in the Iwasaki (1937) relation between rate of particle removal and concentration, λ , in Equation 13 was described as the filtration coefficient. The filtration coefficient can be computed from Equation 17 if c/c_0 values are obtained at various depths. Alternatively, it can be estimate by:

$$\lambda_0 \propto \frac{1}{d_g} \left(\frac{d_p}{d_g} \right)^{1.5} \quad (21)$$

Determination of the hydraulic properties of the flow field as influenced by clogging is necessary in order to predict the properties of the surface seal. After determining the amount of particle deposition resulting from settling of the fine particles into the solid matrix, changes to the soil physical and hydraulic properties within the clogging field (sealing layer) can be calculated (Somaratne, 1994) and the vertical porosity profile produced by clogging can be described.

TOTAL POROSITY: Once the particle deposition with the soil system is known, the instantaneous porosity can be written (Ives, 1975):

$$\varepsilon = \varepsilon_0 - \sigma \quad (22)$$

VOLUMETRIC MOISTURE CONTENT AT SATURATION:

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Since $\epsilon_0 = \theta_s$, the instantaneous saturated volumetric moisture content of the sealing layer is:

$$\theta_{sc} = \theta_s - \sigma \quad (23)$$

BULK DENSITY: It is expected that as the clogging of soil pores increases, its mechanical resistance and filtering ability also increases. Multiplying both sides of Equation 18 by ρ_s we have:

$$\sigma \rho_s = v_z \lambda c_0 \rho_s e^{-\lambda z} t \quad (24)$$

Where $\sigma \rho_s$ is the increase in mass due to particle deposition at any depth z in the sealing layer. Since the bulk volume does not change due to particle deposition Equation 24 can be written as:

$$\Delta \rho = v_z \lambda c_0 \rho_s e^{-\lambda z} t \quad (25)$$

Where $\Delta \rho$ is the increase in bulk density at any depth z in the sealing layer. Similarly, for the steady state condition, Equation 20 yields:

$$\Delta \rho = \Delta \rho_0 e^{-\lambda z} \quad (26)$$

Equation 26 is of the same form as the Mualem and Assouline (1989) hypothetical model described by Equation 1, where the characteristic constant of the soil-seal-rain system, γ is now replaced by a well-defined parameter, the filtration coefficient λ .

SOIL WATER RETENTION CURVE: For $\Psi < \Psi_c$, the water retention curve may be described by the function (Campbell, 1985):

$$\Psi = \Psi_c \left(\frac{\theta}{\theta_s} \right)^{-b} \quad (27)$$

Where b is the slope of $\ln \Psi$ vs $\ln \theta$. A small correction could be made to b in Equation 27 to account for an increase in the seal bulk density. The effect of an increase in bulk density is to favour an increase in moisture retention, therefore:

$$b_c = b \left(1 + \frac{\sigma}{\epsilon_0} \right) \quad (28)$$

EFFECT OF AIR ENTRY POTENTIAL: With the development of clogging, the mean pore size also decreases. Therefore, one can expect Ψ_c to decrease (become more negative) with seal development. This relation is expressed in an empirical Equation of the form:

$$\Psi_{cs} = \Psi_c \left(1 + \frac{\sigma}{\epsilon_0} \right)^m \quad (29)$$

Where m is an empirical constant. If the pore size distribution function is to be the same throughout the porous body, then the pore radii are related to water content. The effect of clogging is to reduce the pore radii in the seal, and therefore the numerical value for m is taken equal to b , provided that due consideration is given to account for the value of b in clogged zone (seal), according to Equation 28.

RESIDUAL MOISTURE CONTENT: Another property affected by clogging development is the residual moisture content. Mualem and Assouline (1989) assumed that θ_r is mainly a function of the surface area of the soil particles, so that, on a weight basis, it remains unchanged as a result of the soil compaction. This reasoning leads to:

$$\theta_{rc} = \theta_r \left(1 + \frac{\sigma}{\epsilon_0} \right) \quad (30)$$

EFFECT ON SATURATED HYDRAULIC CONDUCTIVITY: The saturated hydraulic conductivity of a soil depends on the size and distribution of pores in the soil and therefore on bulk density and texture (Campbell, 1985). The clogging of pores by clay migration can markedly reduce the saturated hydraulic conductivity. Perhaps the soil parameter most affected by seal development is the saturated hydraulic conductivity. The seal hydraulic conductivity k_{sc} is expressed by an empirical relation:

$$k_{sc} = k_s \left(\frac{\theta_{sc}}{\theta_s} \right)^n \quad (31)$$

Substituting Equation 23 into Equation 31 yields:

$$k_{sc} = k_s \left(1 - \frac{\sigma}{\epsilon_0} \right)^n \quad (32)$$

Where n is an empirical constant taken equal to $2b+3$, with an appropriate correction for the b in the seal Equation 28. When $\sigma=0$, $k_{sc} = k_s$. If the total pore volume is occupied by retained particles, then $\sigma = \epsilon_0$, and $k_{sc} = 0$.

Materials and Methods

In order to address the fundamental question of how the flow rate decreases due to particle deposition on saturated packed beds, a series of experiments were conducted using packed glass bead columns of uniform bulk density and dispersed kaolinite suspension.

The packed columns were acrylic (plexiglass) cylinders with internal diameters of 0.08 m and lengths of 0.10 m (Experiment 2), 0.14 m (Experiment 3), 0.15 m (Experiment 4) and one with a square cross section of 0.056 m^2 having a length of 0.29 m (experiment 1). A teflon screen of $45 \mu\text{m}$ mesh opening, covered with a nylon gauze, was used to support the uniform size of $40 \mu\text{m}$ glass beads in the columns. The density of glass beads was $2.66 \text{ kg}\cdot\text{m}^{-3}$. Columns were packed to a uniform density of $1.5 \text{ kg}\cdot\text{m}^{-3}$ thus having a clean bed porosity of 0.423. The packing procedure used in the experiments was to weigh the glass beads required to fill 0.02 m column intervals to the required bulk density and slowly filling with a vibrating action on a vibration table.

For Experiment 1, a suspension was prepared by adding 10 g of kaolinite clay to a litre of clean water and thoroughly mixing with a mechanical stirrer. The suspension was chemically dispersed with 0.05 N sodium hexameta phosphate. The particle density of kaolinite was $2.65 \text{ kg}\cdot\text{m}^{-3}$. The particle size distribution of the suspension prepared for experiment 1 was determined using a laser beam sub-micron particle size analyzer and is given in Figure 4.

It can be seen in Figure 4 that some large particles of up to $50 \mu\text{m}$ were present. Therefore, for Experiments 2, 3 and 4, the original suspension was allowed to settle for 19 hours in measuring cylinders, and the top 0.3 m of the suspension was decanted to remove larger particles. The largest particle remaining in this suspension was determined by Stoke's law to be approximately $2.2 \mu\text{m}$. Before each experiment, 10 ml of suspension was pipetted out to determine the mass concentration by oven drying at 105°C for 24 hours. This was $0.0180 \text{ g}\cdot\text{cm}^{-3}$ for Experiment 1, $0.0035 \text{ g}\cdot\text{cm}^{-3}$ for Experiment 2 and $0.0041 \text{ g}\cdot\text{cm}^{-3}$ for Experiments 3 and 4.

The saturated hydraulic conductivity of each column prior to addition of the clay suspension was determined using de-aired water under a constant head. Thereafter, the suspension was added to the reservoir flask in which a set of magnetic stirrers maintained

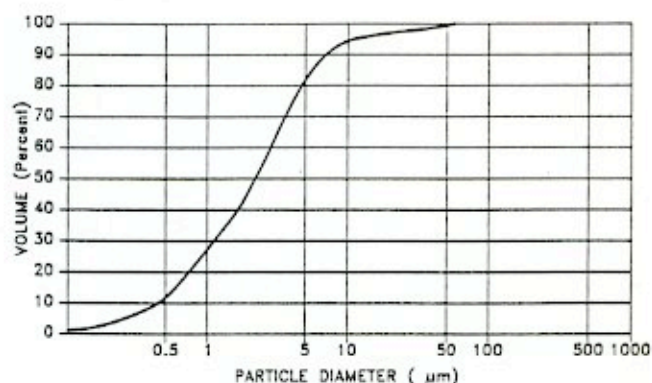


Figure 4. Particle size distribution of clay suspension

uniform dispersion of the suspension entering the column. A schematic diagram of the experimental setup is given in Figure 5.

The outflow from the bottom of each column was collected in measuring cylinders at regular intervals until steady-state flow was observed. This flow data was used to determine the hydraulic conductivity of clogged columns. The mass concentration of kaolinite in the effluent was determined by oven drying and by measurements of turbidity. The column then was allowed to drain for 48 h and sectioned into 0.01 m lengths. The mass of clay present in each section was determined on a suspension made by adding 200 ml of clean water.

Results and Discussion

In Experiment 1, the saturated hydraulic conductivity reduced from $24.4 \text{ mm}\cdot\text{h}^{-1}$ to $2.2 \text{ mm}\cdot\text{h}^{-1}$. During the initial stage of filtration, the large particles in the suspension settled on the column surface, followed by smaller particles settling into the voids

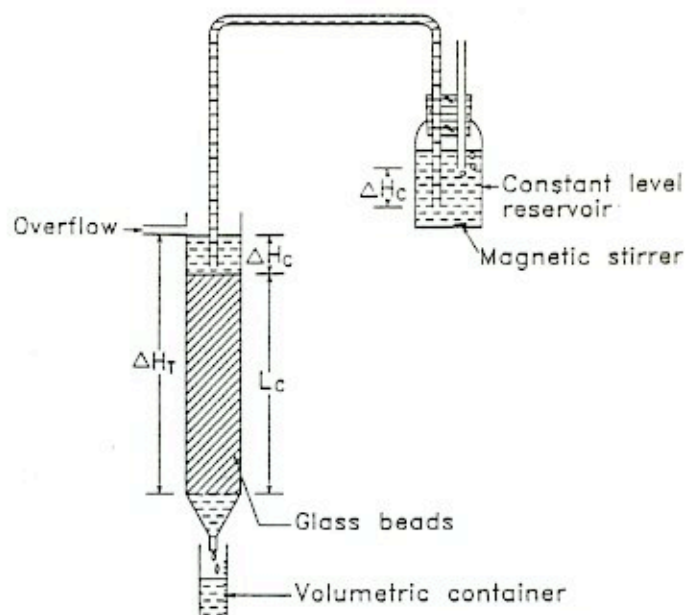


Figure 5. Schematic diagram of experimental set up

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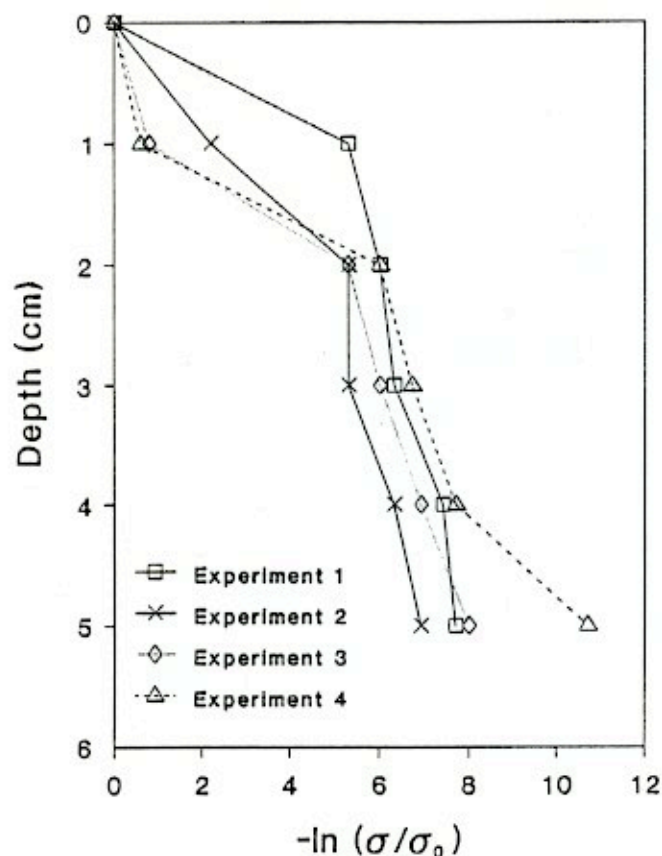


Figure 6. Plot of $\ln(\sigma/\sigma_0)$ versus depth for column experiments

between the large particles. This type of surface mat formation is generally referred to as a filter cake. With continued filtration, the thickness of the filter cake increased causing a further reduction in hydraulic conductivity. Clay was not observed in the effluent from Experiment 1.

In Experiments 2, 3 and 4, the reduction in hydraulic conductivity was small compared to Experiment 1. In these experiments, formation of a surface mat was not observed and clay appeared in the column effluent.

In all experiments, most of the particles were deposited in the top 0.01 m of the column, but some were deposited further down. Particle removal was negligible at depths greater than 0.01 m. This retention of clay particles in the column surface caused the reduction of flow rate. In Experiment 1, particle deposition was greatest as the suspension contained a range of particle sizes up to $50 \mu\text{m}$. In Experiments 2, 3 and 4 the deposited volumes and reductions of flow rate were of the same order and considerably smaller than Experiment 1 (Figure 6).

In Experiments 2, 3 and 4 the relative flow rate declined slowly throughout the runs. The relative concentrations of the outflow, c/c_0 also reached constant values after a number of pore volumes of effluent had been collected.

Approximate curvilinear dependence of $\ln(\sigma/\sigma_0)$ with depth was observed (Figure 6). The accumulation of particles in the first 1 cm of column was much

greater than Equation 19 predicted. Below this depth, a reasonably good linear fit exists. This suggests that large particles are removed at and near the surface by straining, while below this, small particle deposition occurs according to the first order kinetic model as given by Vinten *et al.*, (1983). The finest particles are removed from the suspension by physico-chemical absorption, because they have a stronger tendency to be adsorbed when they approach the media grains.

Particle deposition at the top layer of columns were predicted using Equations 6 and 19. The coordination number in Equation 6 was taken as 8 for randomly packed spheres. The grain diameter of glass beads, d_g , was $40 \mu\text{m}$. According to Equation 4, the maximum diameter of particles that can enter into the medium is $29 \mu\text{m}$. In order to retain particles in crevice sites the particle diameter, d_p , should be greater than $3 \mu\text{m}$, according to $d_p/d_g > 0.082$ (Herzig *et al.*, 1970).

The only unknown parameter in Equation 19 is the initial filtration coefficient of the medium, which was obtained from Equation 21. The proportionality constant in Equation 21 was determined by plotting $1/n(c/c_0)$ vs z for Experiments 2, 3 and 4. This was found to be 0.05 (Somaratne, 1994). The prediction of particle retention at the column surfaces using Equations 6 (straining in crevices) and 19 (adsorption) against the observed values are given in Table 1. Comparison of predicted particle retention at the column surface was lower than the experimentally obtained values given in Figure 6. Correlation of reduced hydraulic conductivity due to particle retention was made using Equation 32. The parameter b , used to obtain n in Equation 32, was taken as the slope of the moisture retention curve on a log-log plot. For glass beads, $b=1.5$, giving $n = 6$.

For comparison, the observed hydraulic conductivity of the clogged-columns and predicted saturated hydraulic conductivity using experimentally obtained σ and predicted σ (from Table 1) are given in Table 2. Data in Table 2 suggest that the markedly reduced hydraulic conductivity of the clogged column (Experiment 1) is primarily due to the blocking of pore channels by straining of particles. This process occurs at and near the soil surface as observed by Onofriok and Singer (1984), leading to a non-uniform sealing layer.

TABLE 1

Predicted particle retention at column surface					
Exp. No.	d_p/d_g	Straining $\frac{\sigma}{\sigma_0}$ $\text{cm}^3 \cdot \text{cm}^{-3}$	λ_0 cm^{-1}	Absorption $\frac{\sigma}{\sigma_0}$ $\text{cm}^3 \cdot \text{cm}^{-3}$	Total $\frac{\sigma}{\sigma_0}$ $\text{cm}^3 \cdot \text{cm}^{-3}$
1	0.1350	0.136	0.62	0.005	0.141
2	0.0525	0.001	0.15	0.006	0.007
3	0.0525	0.003	0.15	0.006	0.009
4	0.0525	0.002	0.15	0.006	0.008

TABLE 2

Comparison of observed and predicted conductivity of clogged columns with clogged-free k_s

Exp. No.	Clogged-free bed k_s (mm-hr ⁻¹)	Clogged bed k_s (mm-hr ⁻¹)		
		Observed	Using Experimental σ	Using predicted σ
1	24.4	2.2	5.5	2.1
2	28.5	21.0	24.0	25.7
3	29.7	24.1	21.8	25.9
4	27.0	22.2	20.2	24.0

Conclusions

The proposed model describes the filtration component of the soil surface sealing process. The seal properties are obtained by applying the principle of conservation of mass and Darcy's law, not only for the undisturbed soil but also for the seal layer.

The outcome of seal formation is represented through particle retention by various capture mechanisms. This is related to the seal hydraulic properties. With this approach to modeling the soil surface sealing, the seal can be described by well defined initial and boundary conditions and transient seal properties can be simulated. These properties provide more insight on the physical aspects of seal formation and give a better understanding of its effect on infiltration and soil water movement.

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