Original Research Article

Analysis of hydraulic resistance of soil surface seals in relation to sediment particle size

ABSTRACT

Surface sealing, and their role in runoff and erosion, especially, in agricultural fields have been recognized as major set-backs to irrigation operations. Though the process is restricted to only the topmost soil layer of some few millimetres in depth, surface sealing can substantially impede the infiltration of water into the soil. However, information on this process is much less documented. The aim of this study was to investigate the possible relationships between seal type and hydraulic resistance. The paper presents a simple theoretical approach which allows the estimation of changes in hydraulic resistance at the soil surface as a function of time following the formation of surface seals formed from different sediment particles at different concentrations in suspension.

Keywords: Slaking, Surface seal, Hydraulic conductivity, Hydraulic resistance, Infiltration

1. INTRODUCTION

Slaking of soil aggregates with resultant surface sealing are common characteristics of many cultivated soils, especially, in arid and semi-arid areas [1]. These processes of soil slaking and sealing are the result of the kinetic impact of raindrops on the soil surface and the translocation of soil particles by flowing water. The formation of seal depends on many factors, including the texture and stability of the soil, intensity and energy of rainfall, gradients and length of slope, and electrolyte concentration of the soil solution and rainwater [2]. The extent of surface sealing has been reported to be highly dependent on soil texture, with the silt content being a good indicator of the soil's susceptibility [1, 3]. Upon deposition, the translocated particles could clog soil pores and form superficial layers characterised by higher bulk density and lower saturated hydraulic conductivity than the soil beneath [1, 4]. Due to the loss of soil water storage and infiltration capacities, soil erosion and flooding are significantly increased [1]. The reduction in infiltration rate under sealed conditions is controlled by the surface seal rather than the water content of the soil profile [5]. The objectives of this study were to measure the effect of surface seal formation from different sediment particles on infiltration under field conditions, and to develop a technique to quantify the hydraulic resistance of the developing seal. The technique would be useful for the management of irrigation practices in Ghana.

1.1 Theory

According to Segeren and Trout [6], the most direct method to simulate the process of soil surface sealing is to model a two-layer soil profile in which the seal is the top layer. In this case, the hydraulic conductivity of the seal $K_x(d)$ is measured as a function of time. From Darcy's law, the conductivity of the seal, which is a function of the particle diameter of the sediment [1] can be calculated as [6]:

$$K_x(d) = -q\left(\frac{Z_x}{\Delta m + \Delta g}\right) \qquad (1)$$

During transient state flow under unsaturated conditions, we assume that the matric potential gradient across the seal is larger than the gravitational gradient, hence, the gravitational component can be neglected and equation (1) reduces to:

$$K_x(d) = -q\left(\frac{\Delta m}{\Delta g}\right) \qquad (2)$$

However, during steady state flow under saturated conditions, we assume a unit hydraulic gradient. Therefore, equation (1) could be expressed as:

$$K_x(d) = q \qquad (3)$$

where,
Z_x = Seal thickness [L]
q = Flux through the soil [L/T]
Δg = Change in gravitational potential across the seal [L]
Δm = Change in matric potential across the seal [L]
$K_x(d)$ = Hydraulic conductivity of the surface seal [L/T] given as [1]:

$$K_x(d) = \left(\frac{K_s}{c}\right) d_* \qquad (4)$$

K_s = Hydraulic conductivity of the initial soil surface [L/T]
c = Concentration of soil sediment in suspension [M/L^3]
d_* = Dimensionless particle diameter of sediment defined as [1, 7]:

$$d_* = d\left[\sqrt[3]{\left(\frac{\rho f g \rho_\gamma}{\omega^2}\right)}\right] \qquad (5)$$

Since seal thickness is highly variable with time and is difficult to measure directly, the most convenient method to measure this parameter is given by modification of the relation by Tuffour et al. [1]:

$$Z_x = cK_x(D)t + cV_s t \qquad (6)$$

V_s = Settling velocity of sediment [L/T]
t = Time [T]

Swartzendruber [8] defined the hydraulic resistance R_h [T] of the seal to describe the resistance of the seal to flow regardless of thickness as:

$$R_h = \frac{Z_x}{K_x(D)} = \frac{ct(K_s + V_s)}{\left(\frac{K_s}{c}\right) d_*} \qquad (7)$$

The fundamental assumptions for this method as reported by [1, 6, 9] are:
1. The seal does not form instantly, but upon formation, it is saturated from the start.
2. The hydraulic resistance $\mathrm{R_h}$ is the only soil hydraulic property that changes after the start of infiltration.
3. Flux through the soil is uniform.

Additionally, the assumptions propounded by Tuffour and Bonsu [10] apply to this study. These assumptions require that all soil properties with influence on infiltration remain constant for the sub seal layer [6].

2. MATERIALS AND METHODS

The performance of the proposed model was verified with a series of ponded infiltration tests with clear and muddy water as described in Tuffour and Bonsu [10], and Tuffour et al. [1]. Laboratory infiltration studies were conducted with a series of ponded infiltration tests for 60 minutes with clear and muddy water. The muddy water were made of suspensions of different soil particle diameters, viz., fine-sand, clay and silt, at different concentrations. The different concentrations were made by adding clean (distilled) water to, 10 (T1), 20 (T2), 30 (T3) and 40 g (T4) of soil to make a total of 400 cm^3 and dispersed in a mechanical shaker for 60 minutes. Additionally, an infiltration test was conducted with distilled water (T5), which served as a reference for the study. The computation of the parameters and plotting of the graphs were done using Microsoft EXCEL.

3. RESULTS AND DISCUSSIONS

With consideration of the mass balances of sediment particles, the flux of suspension through the soil column was captured through infiltration measurements and thickness of a surface seal. Seal thickness from the different sediment particles as estimated from equation (6) as presented in Table 1 varied widely between sand and the finer sediments (clay and silt). However, no clear differences were observed between those of clay and silt. In addition, Figures 1 – 3 show that hydraulic resistance has a linear relationship with seal thickness, in that, an increase in seal thickness results in an increase in hydraulic resistance of the seal. Thus, increases in sediment concentration which eventually results in high seal thickness would be expected to result in seal hydraulic resistance by cursory analysis. However, a close observation of the results clearly showed that clay seals which produced lowest seal thickness had the greatest hydraulic resistance than sandy textured seals, which had the highest seal thickness as presented in Table. In addition to these discrepancies, silt seals, which had similar thickness as clay seals had the lowest hydraulic resistance. Thus, hydraulic resistance and infiltration rates followed the same pattern as total infiltration rates, that is, higher as crust development increased, except for the lichen crust on fine-textured soils, which generated steady state infiltration rates similar to the PSC.

Table 1: Estimated seal thickness for the different sediment particles at various concentrations in suspension

Time (S)	Seal thickness (mm)											
	Clay suspension†				Silt suspension†				Sand suspension†			
	10	20	30	40	10	20	30	40	10	20	30	40
30	1.875E-3	3.750E-3	5.625E-3	7.500E-3	1.875E-3	3.751E-3	5.626E-3	7.502E-3	3.750E-3	7.500E-3	1.125E-2	1.500E-2
300	1.875E-2	3.750E-2	5.625E-2	7.500E-2	1.876E-2	3.751E-2	5.626E-2	7.502E-2	3.750E-2	7.500E-2	1.125E-1	1.500E-1
600	3.750E-2	7.500E-2	1.125E-1	1.500E-1	3.751E-2	7.502E-2	1.125E-1	1.500E-1	7.500E-2	1.500E-1	2.250E-1	3.000E-1
900	5.625E-2	1.125E-1	1.688E-1	2.250E-1	5.626E-2	1.125E-1	1.688E-1	2.251E-1	1.125E-1	2.250E-1	3.375E-1	4.500E-1
1800	1.125E-1	2.250E-1	3.375E-1	4.500E-1	1.125E-1	2.251E-1	3.376E-1	4.501E-1	2.250E-1	4.500E-1	6.750E-1	9.000E-1
2100	1.313E-1	2.625E-1	3.938E-1	5.250E-1	1.313E-1	2.626E-1	3.939E-1	5.251E-1	2.625E-1	5.250E-1	7.875E-1	1.0500
2700	1.688E-1	3.375E-1	5.063E-1	6.750E-1	1.688E-1	3.376E-1	5.064E-1	6.752E-1	3.375E-1	6.750E-1	1.0125	1.350
3000	1.875E-1	3.750E-1	5.625E-1	7.500E-1	1.876E-1	3.751E-1	5.626E-1	7.502E-1	3.750E-1	7.500E-1	1.125	1.500
3600	2.250E-1	4.500E-1	6.750E-1	9.000E-1	2.251E-1	4.501E-1	6.752E-1	9.002E-1	4.500E-1	9.000E-1	1.350	1.800

†Mass of sediments in suspension (g)

The surface sealing process could be viewed to have resulted from a filtration process, wherein, there was a phase transition of the sediments from the flowing fluid phase into a solid phase upon settling on the soil surface or in the pore spaces [11, 12]. Two main mechanisms could explain this filtration process – Transport of fluidized sediments with characteristic size larger than the size of the pore constrictions of the pore network was not possible. This implies that the sediment material was blocked and settled only at the soil surface (i.e., the occurrence of pore clogging was restricted only at the surface), as could be depicted for the coarse fragments. On the other hand, in the case of the smaller fluidized sediments relative to the pore constrictions, transport depended solely on the hydraulic conditions (i.e., hydraulic gradient) of the soil column [12]. Of these, high concentrations of suspended sediment, irrespective of its characteristic diameter appeared to promote sealing capacity, with increasing seal thickness and hydraulic resistance. Herein, the sealing capacity was observed to be high for sediments with smaller diameter. This is a clear indication that the sealing process is related to the geometrical properties of the porous medium and of the sediments [11, 12].

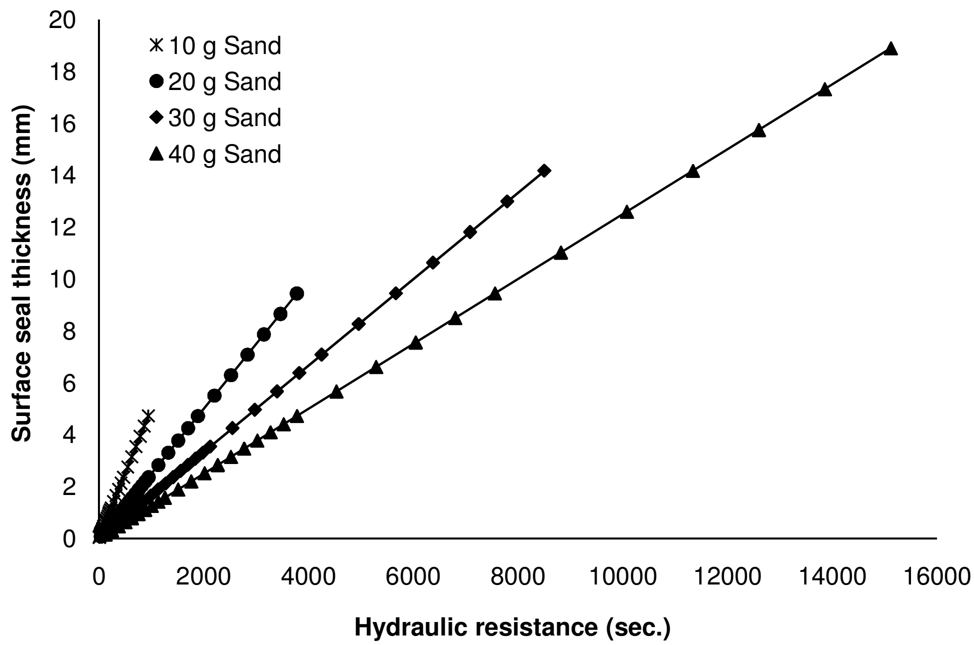

Figure 1: Relationship between surface seal thickness and hydraulic resistance of sand particles

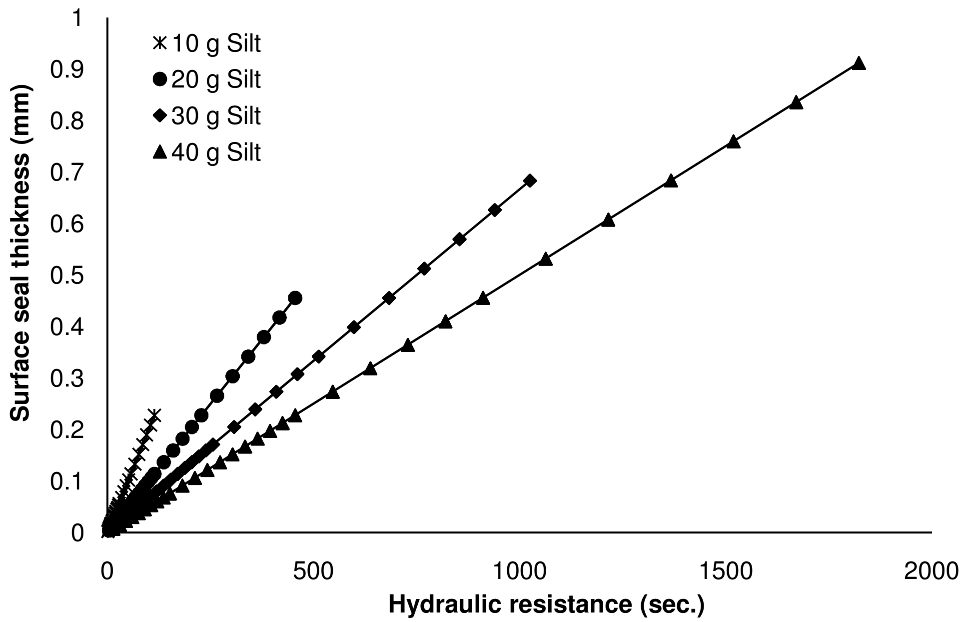

Figure 2: Relationship between surface seal thickness and hydraulic resistance of silt particles

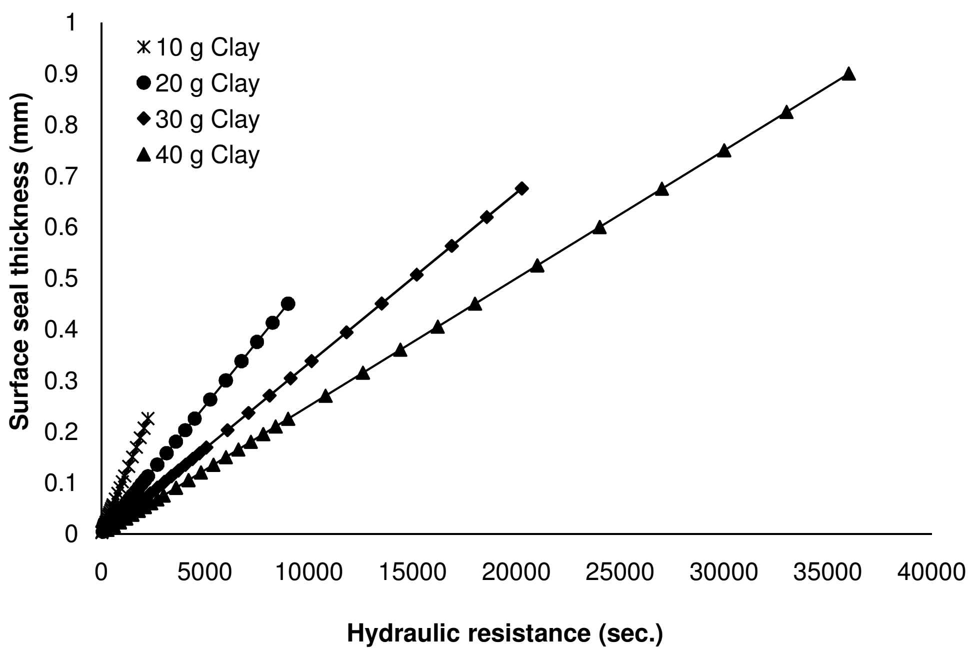

Figure 3: Relationship between surface seal thickness and hydraulic resistance of clay particles

It is clear from Figures 1 – 3 that increasing seal thickness results in increasing hydraulic resistance for the different seal types. At lower sediment concentrations, seal thicknesses were low with corresponding low hydraulic resistance. Thus, hydraulic resistance increased with increasing surface seal development. The type (i.e. texture) of seal significantly influenced hydraulic resistance which consequently affected infiltration parameter values [10]. As can be seen in Figures 1 – 3, the clay seal showed the highest seal hydraulic resistance, which eventually produced lower infiltration parameters as reported by [10]. Thus, the seals from coarse-textured sediments produced high infiltration parameter values, whereas those from fine-textured soils, produced lower infiltration parameters [10]. Thus, fine sediments in the irrigation water have high capability of soil surface seal formation.

The depositional layer densities and saturated hydraulic conductivities for the various sediments were assumed constant for each concentration. However, the characteristic thickness for the different sediment concentrations varied with time. The continuing gradual increase in hydraulic resistance during the infiltration process as observed in Figures 1 – 3 was as a result of the seal formation. This implies that the seal resistance continued to increase throughout the process. From the study, it is evident that although infiltration is directly related to the conductivity of the seal, the relationship is not proportional, as might be assumed from a cursory analysis [12]. Thus, a relative decrease in infiltration requires a larger relative increase in the seal hydraulic resistance [6]. Accordingly, Glanville and Smith [5] reported that in sealed soils, the surface seal rather than the water content of the soil profile determines the reduction in the infiltration rate. This report also clearly highlights the role of seal resistance in water infiltration.

4. CONCLUSIONS

Observations and measurements from the study showed that surface sealing, seal thickness and seal hydraulic resistance were highly dependent on the characteristics of soil sediment and fluid. Thus, the diameter of the sediment in suspension strongly affected the development of surface seals. Additionally, sediment concentration also greatly affected the surface sealing process. Moreover, the formation of the surface seals with increasing thickness irrespective of the sediment diameter had a marked influence in reducing infiltration rates. Therefore, hydraulic resistance can be a very useful parameter to describe the effects of surface seals on infiltration process in soils and the key effect of sealing in increasing surface runoff and the potential for erosion was made obvious from the study results.

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