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Steady convective flow in an unsaturated state dependent anisotropic soil profile: Analysis of the affected zone from a contaminating point source

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SUMMARY

Anisotropy of the medium plays a dominant role in shaping the flow pattern in the soil profile. This study analyses the effect of anisotropy on the horizontal spreading of the flow trajectories from a contaminating source point at the soil surface to a high water table. It considers a phreatic aquifer with infinite lateral extension and uniform sedimentary-layered soil profile, where a state dependent anisotropy factor (SDAF) – $A(\psi)$, and Mualem's (1984) anisotropy model might be applicable. The numerically calculated streamlines portray the effect of anisotropy, and allow discernment among various anisotropic media. Different flow cases are analyzed with regard to their dependence on $A(\psi)$, as well as their dependence on the infiltration rate, and on the orientation of the principal axes. Theory indicates that the flux direction is dependent on the capillary head and thus on the flow rate. Consequently, it is the infiltration rate, which determines the particular path line from the contaminant source point to the ground water table. Accordingly, we have defined the "affected domain" as the domain within the unsaturated profile which is vulnerable to contamination from a source point at the soil surface, and the "affected segment" as the segment on the phreatic surface where pollutants may potentially reach the ground water aquifer. Both are determined with respect to anisotropy, infiltration rate, and depth. The non-linear horizontal shift of the contaminant trajectory indicates that a substantial error may result when adopting a constant anisotropy factor.

This study suggests that the maximal horizontal shift is the relevant scale when characterizing the anisotropic flow system. This measure should be taken into consideration when designing a related laboratory experiment or a field monitoring system.

1. Introduction

The anisotropic nature of undisturbed structured soils and sedimentary rock formations has been well recognized, yet not fully understood. Still the extent to which the medium under investigation is anisotropic is extremely important for better perception of the related flow phenomena and definitely essential for improving our prediction capabilities of water and pollutant path lines and transport in such medium.

The factors affecting flow path lines are numerous. Each natural system, with its specific geological formation, textural and structural pattern, fracturing and layering, displays a different particular pattern, with variety of preferential flow, funneled flow, etc. Thus, appropriate definition of the flow domain and accurate formulation of the relevant soil factors are of primary importance. The anisotropy of the porous medium is one of the most important properties among these factors, creating a lateral component to the flux vector. However, observations of the lateral flow component near a sloping soil surface, has not to be necessarily attributed to anisotropy as in Zaslavsky and Sinai (1981a,b,c). This might also be due to boundary condition effect of the slope surface and changes in rainfall intensity (Sinai and Dirksen, 2006). In anisotropic soil, however, the flux vector will have a lateral component even in the case of a horizontal soil surface and steady state flow conditions. This diagnosis has been systematically analyzed by Jackson (1992) with regard to McCord and Stephens (1987) observations of lateral flow.

Measurement of the unsaturated anisotropic hydraulic conductivity is hard to accomplish and rare (if it exists at all) in the literature. For the sake of simplicity, scientists tend to assume that the anisotropy factor – the ratio between the conductivity values in the principal direction of the anisotropy unsaturated hydraulic conductivity tensor – is a constant independent of the saturation degree and thus equal to the saturated value (e.g. Neuman, 1973; Sawhney et al., 1976; Giorgini and Bergman, 1986; Philip, 1986, 1987). Applying this assumption of constant anisotropy, Giorgini and Bergman (1986) analyzed the infiltration into sloping bed. According to their analysis, the transient nature of the process,

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and the presence of sloping boundary surface, cause the flux vector direction to change with soil depth, i.e. the trajectories are curved. However, in the case of a horizontal surface, the trajectories would present inclined straight lines.

The above analysis is questionable since there is no experimental evidence that anisotropy factor is a state independent constant. On the contrary, theoretical analysis of sedimentary soil and bedrocks (Mualem, 1984) and simulation by capillary network (Bear et al., 1987), as well as laboratory investigations (Friedman and Jones, 2001; Ursino et al., 2001) all indicate that the anisotropy factor is dependent upon the saturation degree, such that it is a state dependent factor. Moreover, the experimental studies of Stephens and Heermann (1988) and Ursino and Gimmi (2004) showed a clear evidence of a saturation dependent lateral component due to anisotropy.

In an anisotropic field under steady state conditions, a constant anisotropy factor will yield a constant direction of the flux vector, but different flow patterns will be observed in the case of state dependent anisotropy, which will reflect the characters of the anisotropy function and its dependence on the capillary head. The typical functional dependence, presented by Mualem (1984) for uniform anisotropic sedimentary soil, posits that the medium anisotropy initially decreases with desaturation down to a minimum close to isotropy. Further desaturation of the medium results in monotonic increase of anisotropy. Similar behaviour is observed also for other models of anisotropy (Yeh et al., 1985a,b,c). Other studies presented different saturation-dependent patterns. The anisotropy factor derived by Bear et al. (1987) using computer simulations of capillary tube network model, showed that its value decreases following desaturation. It rapidly dropped towards the saturation value, and approached a constant less than unity with further desaturation. Friedman and Jones (2001) measured the anisotropy of the apparent electrical conductivity of various packing forms of mica particles during desaturation. In that case, anisotropy displayed an initial increase toward a maximum, and decrease for further desaturation. Assouline and Or (2006) applied Mualem's (1984) anisotropy model to study the effect of textural variation on anisotropy. Considering coarse-textured media, they found an anisotropy function with three extremes. After a slight decrease of anisotropy during desaturation it exhibited a sharp increase to a local maxima about threefold the saturated value then sharply decreased to a minimum close to unity, and then sharply increased with subsequent drying.

The aim of the present study is to quantitatively determine the expected unsaturated zone confined by the path lines from a point source of miscible pollution at the soil surface, down to the phreatic surface, for steady unsaturated infiltration in a uniform anisotropic sedimentary profile as modelled by Mualem (1984). The principal objectives are to identify the effect of anisotropy upon the flow pattern, via inspection of each of the relevant anisotropy characteristics: (i) The anisotropy factor parameters; (ii) the orientation of the anisotropic tensor principal axes; (iii) The soil surface flux vector magnitude; (iv) based on the above, to draw some practical and theoretical implications regarding such a flow system.

2. Theory

In order to examine the net effect of anisotropy, the studied flow profile is assumed to be uniform and the Darcy–Buckingham law and Richards' equation are applicable. It addresses a medium frequently appearing in nature of sedimentary medium. As determined applying Mualem's (1984), the anisotropy factor of the medium (A) is a state dependent anisotropy factor (SDAF), namely being dependent on the soil water content, or capillary head:

$$A(\psi) = K_P(\psi)/K_N(\psi) \quad (1)$$

where ψ is the capillary head of the soil water, and P and N indicate the anisotropy axes in the principal directions. A typical Mualem's $A(\psi)$ function (Fig. 1) shows that $A(\psi) \geqslant 1$ for all ψ values. With the initial desaturation process, it decreases from its saturated value (A_s) toward a minimum close to unity (A_{min}). Further desaturation however results in sharp monotonic increase of $A(\psi)$.

2.1. The flow system

Consider an anisotropic two-dimensional field in the vertical plane, which is infinite in the horizontal direction (x) (Fig. 2). The principal axes of anisotropy are inclined with an angle β relative to the global axes system. The lower boundary ($z = 0$) is the phreatic surface and the upper is at the soil surface ($z = H$), where negative (infiltration) or positive (evaporation) flux (IR) exists.

Solution of flow problems in porous media requires the solution of the continuity equation for the system involved. In a two dimensional flow, the equation is:

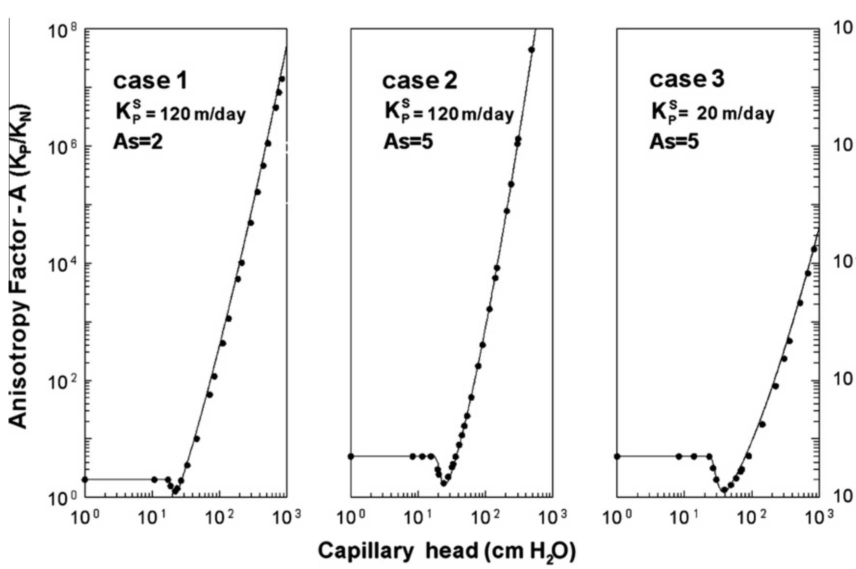

Fig. 1. Mualem's (1984) anisotropy $A(\psi)$ function.