Fingering as a possible mechanism of efficient water transport in a barkhane

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Resumé L'instabilité de l'écoulement de l'eau dans un milieu poreux résultant dans la formation de "colonnes" qui servent de conduites d'eau dans le sol est décrite. Comme le suggére Dr. Rognon dans son article ce mécanisme pourrait être utile pour le transport rapide de l'eau au centre d'une barkhane où elle serait protégée du soleil et utilisable par les plantes immobilisant la dune. Si ce mécanisme est bien compris, on pourrait l'utiliser pour minimiser les pertes d'eau par évaporation.

Abstract Water flow instability in a soil and the resulting formation of fingers/columns are described. Those may provide an efficient mechanism to carry water rapidly from the surface deep into the dune where it is sheltered from evaporation. As suggested by Dr. Rognon (this Proceedings) "fingering" could be used for transporting water to the center of a barkhane where it would be largely protected from evaporation and available for the growth of plants used to fix the dune. If the mechanism of fingering is well understood then it might be possible to optimize designs, e.g. minimize the loss of water.

Key words Infiltration, flow instability, hysteresis

Nomenclature

d	finger diameter	S	sorptivitiy
K	soil-water conductivity	*Symboles grecs*	
Q	rainfall rate	θ	water content

Following experiments by Hill and Parlange [1] in stratified soils, Philip [2] recognized its practical implications and predicted that this work on stratified soils "is certain to stimulate further studies of stability". This indeed has been the case and the field has had tremendous growth both experimentally and theoretically.

We shall first review the physical processes controlling fingering in stratified soils and what distinguishes it from fingering in other situations. Then we shall suggest some of the implications for fingering in barkhanes.

Although wetting effects and air compressibility will enhance formation of fingers [3] they are not crucial for stratified soils and are largely ignored in the following.

It was pointed out, e.g. see Baker and Hillel [4] that water does not penetrate readily from a fine to a coarse soil layer (one refers to a coarse layer as a "capillary barrier"). Thus it is necessary for the water in the fine layer to reach a sufficient pressure before it penetrates the coarse layer (its "water entry" value). When that water entry pressure is reached then water will penetrate the coarse layer at the sites where it is sufficient for entry. Figure 1 shows many points where this occurs. There will be too many points of entry, usually, for each point to become a finger, so fingers will try to merge until the "optimal" size is reached [5] (see Fig. 1). The region where merger takes place was dubbed "the induction zone" by Hill and Parlange [1] and for usual packing, or in the field, mergers in that region are difficult to observe (see Fig. 2). The optimal size can be estimated by the formula [6] [7].

$$d = 4.8 \frac{S^2}{K\theta} \frac{1}{1 - Q/K}. \tag{1}$$

Here S^2, the sorptivity, represents the balance between capillarity (surface tension effect) and viscosity of water, and is such that for a horizontal porous layer $S\sqrt{t}$ is the cumulative amount of water entering the layer. K is the conductivity, representing the balance between gravity forces and viscosity, such that in a vertical column with a uniform water content, K is the flux of water, θ is the water content, and Q is the total flux of water entering the coarse layer. Because S^2 and K enter through the ratio S^2/K, viscosity disappears from that term as a factor. Thus viscosity can have an effect only through the term $[1 - Q/K]^{-1}$. Note that Q/K is the fraction of soil being wetted by the fingers and for fingers to be important as a mechanism to transport water and bypass most of the soil we must have

$$Q/K << 1. \tag{2}$$

Thus, if fingering is important viscosity effects are irrelevant and Eq. (1) becomes

$$d = 4.8\ S^2/K\theta. \tag{3}$$

Both S^2 and K are strong functions of water content but their ratio increases slowly as θ decreases from saturation. This means that there is some ambiguity in the determination of d. As fingers form at the same place in subsequent infiltration events, they might penetrate in a soil retaining some water from the previous event. If this is the case it becomes more difficult for the finger to enter and thus it becomes wider and drier. Under repeated infiltration and drainage the fingers finally reach a fixed configuration and further infiltration provides no further widening [8]. This final value of d is the most important for fingering applications. It may seem paradoxical that fingers stop diffusing laterally and not fill the whole soil eventually. Indeed it is a fundamental property of soils that at equilibrium two different water contents are possible [9]. This hysteresis phenomenon is responsible for the persistence of fingers.

Prior to the experiments of Hill and Parlange [1], Saffman and Taylor [10] wrote a well known paper on fingering and it is important to point out that it is misleading to apply its results uncritically for stratified soils. Their title reads "The penetration of a fluid into a porous medium or Hele-Shaw cell containing a more viscous liquid". Clearly viscosity is crucial in their case, even though it is largely irrelevant here, even though the expression "viscous fingering" is still used sometimes, incorrectly. Also their porous media are limited to Hele-Shaw cells, which are a very poor model for soils. First they obtain an equation similar to Eq. (1) but with surface tension instead of the sorptivity, since indeed in a Hele-Shaw cell the curvature of the finger is important, whereas with a soil the relevant curvature is that of the menisci between grains. This has not prevented some soil physicist to use the Hele-Shaw result to soils, the surface tension, becoming an "effective" (i.e. unphysical) surface tension [11]. Also since they have no stratified layers, the instability was induced with a compressed gas which is not necessary here. Finally fingers in Hele-Shaw cells look very differently from those in Fig. 2. They look more like fingers in a hand, i.e. they connect at their base and the connection moves downwards with the flow, whereas in Fig. 2 they look like columns starting under the induction zone. This is a fundamental difference because hysteresis has no equivalent in the Hele-Shaw cell and lateral diffusion continues until fingers all connect. In retrospect it was a mistake in Hill and Parlange [1] to refer to "fingers" because of Saffman and Taylor's [10] prior study; "columns" would have been a more descriptive term.

That the instabilities look like columns does not imply that they have a uniform water content. It was shown by Selker et al. [12] [13] that they are wetter at the tip and become progressively drier toward the surface (Fig. 1). This, of course, makes them the perfect tool to carry the water deeply within the dune with a minimal amount left near the surface to be lost to evaporation.

To apply the concept of fingering in stratified soils to barkhanes one must be cautious as obvious differences arise.

The first is that stratifications are likely to appear in the dune and having a slope, water will tend to run down over the coarser ones, acting as capillary barriers [14] until there is enough pressure buildup for the water to penetrate the coarser sand. However by possibly remaining close to the surface this water would remain susceptible to evaporation. Hence it is crucial that stratification be destroyed where fingering starts. Driving (and then removing it or not) a stake to a depth where water would be unaffected by evaporation is most likely all that is necessary, although some experimentation will be required.

Second the dune being made up of fairly coarse sand without the benefit of a fine layer, one has to imagine the process leading to fingering (like the points of entry in the stratified case). Indeed fingering following rainfall directly on a coarse soil is well documented in the lab [12] [13]. Although contact angle effects may be a factor in the field [15] they do not seem to have had any bearing in the experiments of Selker et al. [12] [13]. One may speculate that raindrops being much larger than pore size will enter more readily the larger pores due to their inertia and these will act as "points of entry". More importantly the columns of water forming in the dunes should also be the positions for the bushes and their roots to grow. The bushes' canopy will indeed be a collector of rainfall and bring the water where the column should start. Rainfall falling between bushes will collect as fingers and run along capillary barriers until they join one of the main fingers under the bushes. Obviously only natural rainfall would pose a problem as drip irrigation would be used at each bush, to start their growth and as supplemental to rainfall to control the depth reached by the finger tips.

In conclusion, fingers/columns seem likely to form in barkhanes and would provide an ideal mechanism to carry rainfall and irrigation water rapidly away from the surface where it would be wasted to evaporation. Stratification within the dune will have to be examined carefully either as a hindrance to the vertical movement of water or a help to gather the rain falling between bushes.

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Figure 1: *Fingering in a sand cell showing mergers near the top in the induction zone. The fingers are wetter (lighter) near the tips and drier (darker) near the top.*

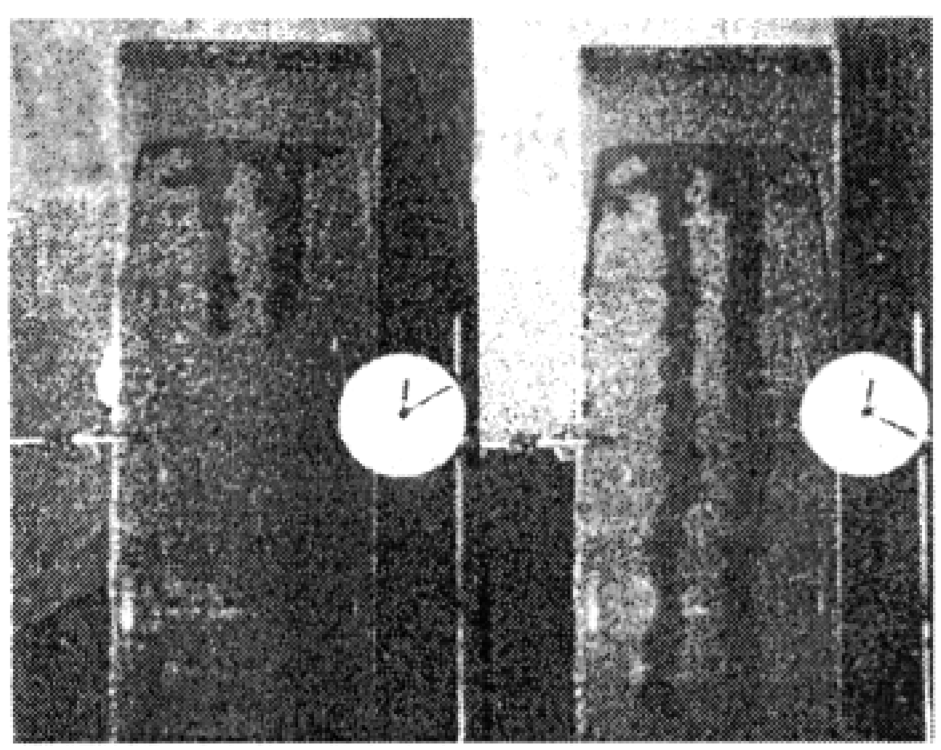

Figure 2: *Column-like fingers forming in a coarse sand underneath a layer of fine sand. The details of the induction layer are not clear and the appearance of the fingers is close to what is observed in the field.*