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On the performance of capillary barriers as landfill cover

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Abstract

Landfills and waste heaps require an engineered surface cover upon closure. The capping system can vary from a simple soil cover to multiple layers of earth and geosynthetic materials. Conventional design features a compacted soil layer, which suffers from drying out and cracking, as well as root and animal intrusion. Capillary barriers consisting of inclined fine-over-coarse soil layers are investigated as an alternative cover system. Under unsaturated conditions, the textural contrast delays vertical drainage by capillary forces. The moisture that builds up above the contact will flow downdip along the interface of the layers. Theoretical studies of capillary barriers have identified the hydraulic properties of the layers, the inclination angle, the length of the field and the infiltration rate as the fundamental characteristics of the system. However, it is unclear how these findings can lead to design criteria for capillary barriers. To assess the uncertainty involved in such approaches, experiments have been carried out in a 8 m long flume and on large scale test sites (40 m × 15 m). In addition, the ability of a numerical model to represent the relevant flow processes in capillary barriers has been examined.

Introduction

A capillary barrier system consists of a layer of fine material overlying a coarse layer under a deep top soil (Fig. 1). The top soil stores infiltrated rainfall and attenuates the seepage to the capillary barrier. Under unsaturated conditions, the textural contrast between the fine material (capillary layer) and the coarse material (capillary block) can delay the vertical drainage by capillary forces. When the pores in the capillary layer near the interface are water filled, while the coarse sand is nearly dry, the hydraulic conductivity of the fine soil can be several orders of magnitude larger than that of the coarse soil (Fig. 2). Generally, medium sand and fine gravel fulfill the requirements best for both these layers. The soil moisture that builds up above the sloping contact will flow downslope along the interface of the layers. Due to additional infiltration in the downslope direction, the volume of water moving laterally increases. At some distance downslope, the saturation will be sufficiently large that capillary forces no longer prevent the moisture from entering the coarse layer. Additional water infiltrating will not then be diverted and so will percolate into the capillary block. The part downslope from this point will become ineffective. The flow rate at this regime is described as the diversion capacity of the capillary barrier (Ross 1990).

Recent progress on the theoretical study of capillary barriers has allowed the derivation of expressions describing the diversion capacity of such cover systems. These studies identified the hydraulic properties of the layers, the inclination angle, the length of the field and the infiltration rate as the fundamental characteristics of the system (Ross, 1990; Oldenburg & Pruess, 1993; Yeh *et al.*, 1994).

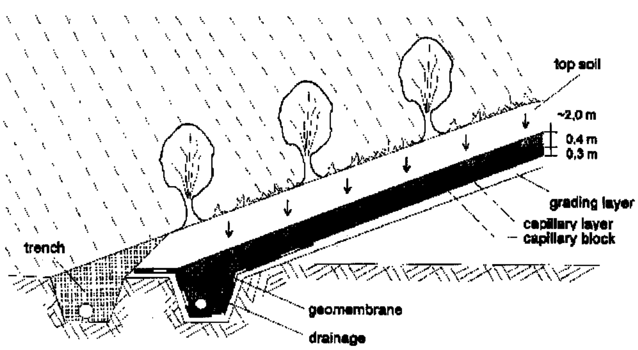

Fig. 1. *Landfill cover system with a capillary barrier.*

Field Measurements

After finding promising material combinations in flume experiments (von der Hude *et al.*, 1996) large scale test sites (15 × 40 m) with capillary barrier systems were installed on the landfills "Am Stempel" (Marburg, Germany) and "Monte Scherbelino" (Frankfurt a.M.,

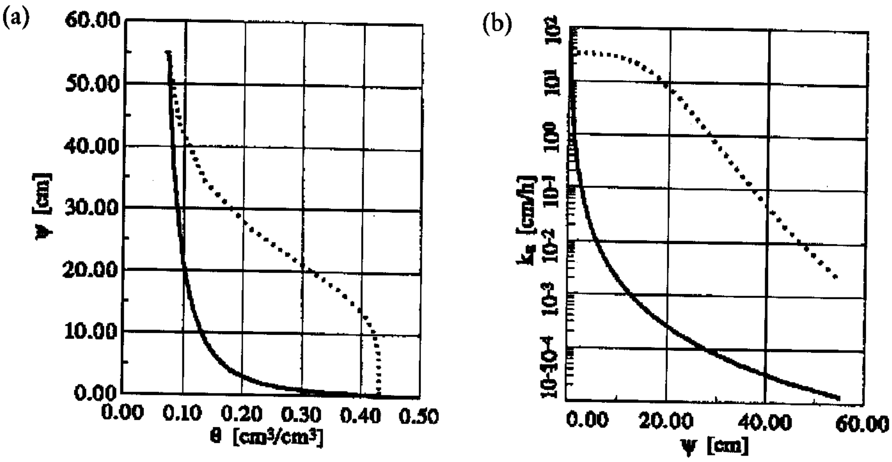

Fig. 2. *Water retention (a) and unsaturated hydraulic conductivity (b) for the fine sand (dashed) and the coarse material (solid) based on soil core imbibition experiments.*

Germany). To obtain a complete water balance, the sites were encapsulated with geomembranes. Details of the construction and the field instrumentation of these large scale test sites were presented by Jelinek (1995). Surface runoff, interflow from the top soil and discharges of the capillary barrier have been determined. The discharges from the capillary layer (downdip) and the block (vertical) permit the assessment of the sealing performance of the capillary barrier system (Fig. 3).

Figure 3 shows the discharge characteristics typical of a capillary barrier system. In winter, the lateral flux rate in the capillary layer increases due to water percolating from the top soil. In summer, the flux is less because evapotranspiration exceeds rainfall. After rewetting of the top soil in autumn, infiltrated water begins to percolate to the capillary barrier. The discharge characteristics of the capillary block are quite different. There were no significant fluxes apart from one event during a very rainy weather period (100 mm precipitation in 7 days) at the beginning of 1995. This was the only breakthrough measured during the observation period. In spite of a deep top soil layer, percolated rainfall could not be diverted by the capillary layer entirely and approximately 17 mm seeped through the barrier. The protective effect was reestablished as soon as the rate of percolation decreased below the diversion capacity. By these measurements the *in situ* diversion capacity was estimated to be 112 ld^{-1} per m width, hereafter written $l(d^*m)^{-1}$. During the rest of the observation period, no significant vertical capillary block discharge was observed. Considering a mean annual rainfall of 650 mm and an annual groundwater recharge of approximately 300 mm, the observed seepage through the barrier of less than 20 mm in three years proved the excellent sealing performance of capillary barriers under middle European climatic conditions.

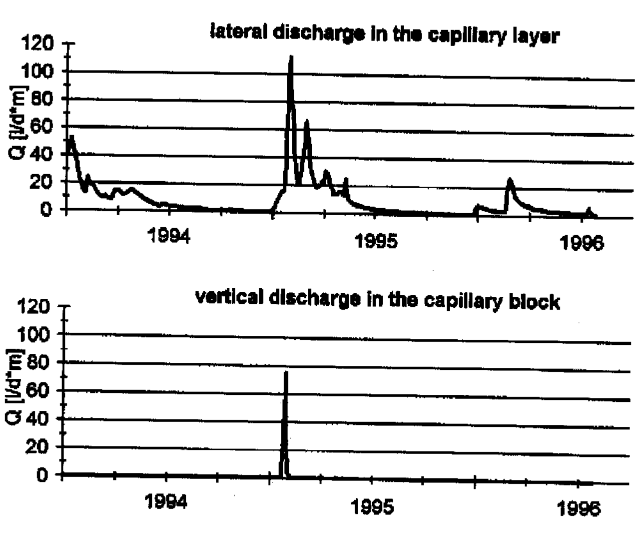

Fig. 3. *Discharges of capillary layer and capillary block of the test site on "Monte Scherbelino", Frankfurt a.M.*

Laboratory Experiments

For the efficient utilisation of capillary barrier systems, it is necessary to avoid expensive and long term investigations on large scale test sites. Therefore, the relevant flow processes of the test sites must be identified and design criteria have to be developed. An 8 m long flume was constructed in a laboratory for detailed examination of the relevant flow processes in a capillary barrier (Fig. 4).

The flume experiments represent the downslope part of a capillary barrier system, in which a considerable amount of water has infiltrated through the updip part of the system and has been diverted laterally above the layer interface. Under these circumstances, the local vertical infiltration is insignificant compared to the lateral flow accumulated from the updip part of the cover. Accordingly, vertical infiltration from the top soil can be neglected and only water injected from the left boundary

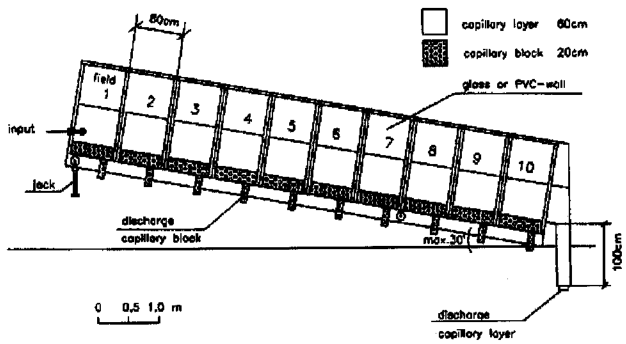

Fig. 4. *Experimental setup for the investigation of capillary barriers.*

is considered. One side of the flume is made of glass. The opposite side consists of PVC-plates to accommodate the temperature probes and tensiometers. The bottom of the flume is divided by 0.1 m high crossbars, in front of which the seepage water is collected. With such an experimental setup, it is possible to investigate the diversion capacity for different material combinations, dip angles, infiltration rates etc. The restricted dimensions of the flume may result in it taking up to 20 days at low injection rates to reach the desired steady state.

The combination of materials at the test sites on "Monte Scherbelino" were rebuilt in the flume to simulate the field measurements. The inclination of the flume was set to 10°, the dip angle of the test sites. The hydraulic loading (injection rate) of the flume was raised stepwise until the diversion capacity was reached. When the loading of the capillary barrier was lower than the diversion capacity, no significant discharge from the capillary block (< 1% of the loading) was observed. These results are consistent with the measurements on the test sites. The diversion capacity was estimated to be 180 $l(d^*m)^{-1}$ at 20°C. The laboratory experiments overestimated the value of the diversion capacity compared to that obtained by the field test by more than 50% (Fig. 5). However, consideration must be given to the effects of temperature.

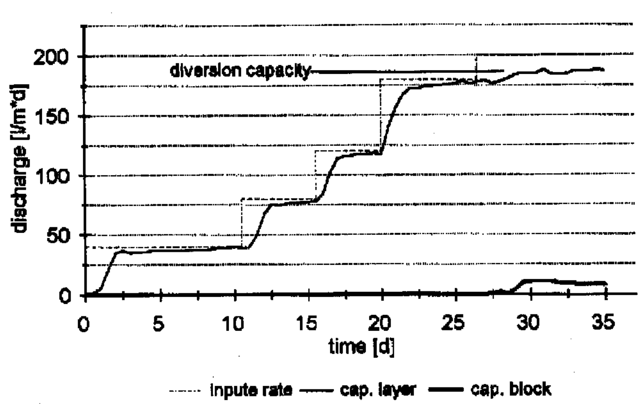

Fig. 5. *Discharges of capillary layer and block at stepwise raised injection rate.*

Temperature has a considerable effect on soil hydraulic properties (Nielsen *et al.* 1986) and previous experiments pointed out a significant influence of temperature on the flow processes in capillary barriers (Kämpf & von der Hude, 1995). To bridge the gap between the laboratory and field results, the diversion capacity had to be estimated at different temperatures to take account of the temperature dependence of water viscosity. This resulted in a satisfying agreement between laboratory and field results can be found (Fig. 6).

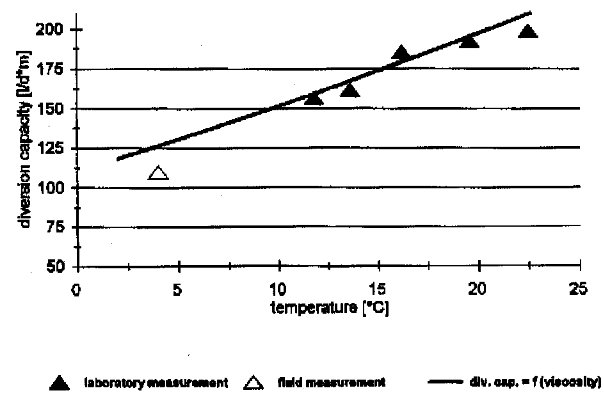

Fig. 6. *Diversion capacity of the material combination from the test sites "Monte Scherbelino" at different temperatures.*

In a further step, the system behaviour was evaluated for varying dip angles. In addition to the tests at 10° inclination, the dip angle was changed to 5° and 15°. Below the breakthrough point, no significant discharge from the coarse material was measured. The diversion capacity of 95 l/d*m at 5° rose to 283 l/d*m at 15° at a constant temperature of 17 °C. These experimental results agree with the findings developed (e.g. by Ross, 1990), that the diversion capacity is proportional to the inclination of the barrier at low angles.

Numerical Simulations of Flume Experiments

To bridge the gap between the laboratory experiments and the complexity present in capillary barriers in the field, numerical experiments were performed with a Galerkin type finite element programme to compute water flow in variably saturated porous media (Šimůnek *et al.* 1994). The flow domain of the test flume (see Fig. 4) was divided into a network of over 2600 triangular elements and 1400 nodes. The region is 8 m in length; the fine layer is 0.6 m and the coarse layer 0.2 m thick, which effectively represents a two dimensional, vertical plane section (Fig. 7). The two layers are assumed to be homogenous and isotropic. In the programme as published the soil properties are assigned to each nodal point and do not coincide

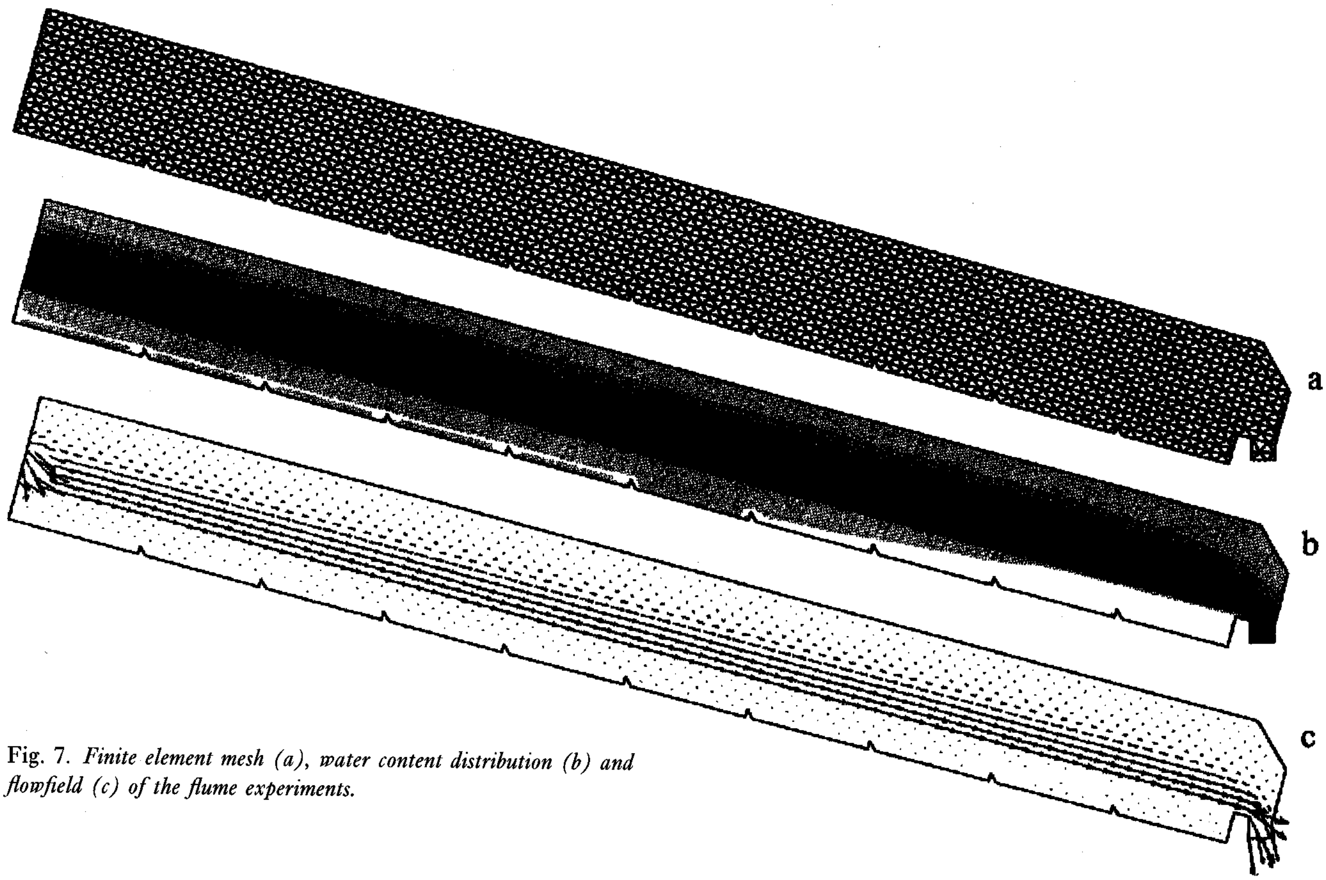

Fig. 7. *Finite element mesh (a), water content distribution (b) and flowfield (c) of the flume experiments.*

with element boundaries. When dealing with capillary barrier systems, this feature tends to smooth gradients at the layer interface. Therefore, a version was used, in which the soil properties are evaluated at the element (Šimůnek, personal communication).

BOUNDARY CONDITIONS

Numerical simulations of the flume experiments were performed as transient cases, until changes in storage and boundary fluxes were insignificant and a steady state solution was achieved. Hysteresis in the soil properties was not taken into account, because only imbibition processes were studied in these experiments (see Fig. 5). Further experiments, however, reveal an influence of the wetting/drainage history on the flow regime and this has to be considered in transient simulations.

Boundary conditions were chosen to be as close as possible to the experimental setup in the test flume. In the numerical model, water was applied at the left side corresponding to an imposed water injection by Neumann type source nodes. At the discharge end of the fine layer, a unit-gradient boundary condition was prescribed so that the flux conforms to the product of the unsaturated hydraulic conductivity and the gravitational gradient. The discharge of the block layer was implemented by 10 Dirichlet type nodes coinciding with the ten subdivisions at the bottom of the flume (see Fig. 4).

MATERIAL PROPERTIES AND PARAMETER ESTIMATION

Determinations from laboratory core samples of the saturated water content θ_s, water retention curves and the saturated hydraulic conductivity for the materials used at the test site "Monte Scherbelino" were conducted and then fitted to the van Genuchten–Mualem model (van Genuchten, 1980) to obtain hydraulic soil parameters α, n and θ_r. The parameters for the fine layer were consistent with those expected from a medium sand, but the capillary block showed an extreme step-type retention function due to the drainage performance of such coarse material. In view of the difficulties in the core sample determination of hydraulic properties of such coarse material, the hydraulic soil parameters for the coarse layer were estimated from the flume experiments. Preliminary studies revealed the dominant influence of the parameter α (inverse air entry value), which controls quite sensitively the shape of the unsaturated conductivity function. The calibration was performed at a dip angle of 10% until the modelled discharge in the capillary layer and the pressure distribution characterized by the suction at the interface conformed reasonably well. After the calibration run the parameters were fixed. The corresponding water retention and unsaturated conductivity functions are presented in Fig. 2.

RESULTS

The simulated moisture distribution is presented in Figure 7b; dark shading corresponds to high saturations. As expected from the flume experiments, at steady state the pressure distribution in the fine layer is hydrostatic and the saturation decreases with distance from the interface. In the capillary block, the saturation is uniform due to gravitational drainage. The flowfield presented in Figure 7c shows almost complete lateral flow above the coarse layer with the exception of the injection and discharge boundaries.

Several runs at different injection rates and various dip angles according to the flume experiments were performed with these fixed parameters. The good agreement between the experiments and the simulations is shown in Figure 8 for the discharge (a) and for the pressure at the interface between the layers (b). The performance of the flow regime when increasing the input rate (which can also be interpreted as increasing the updip length of the cover) is remarkable. Below a critical state, almost all the water is diverted laterally until a point is reached at which capillary forces no longer exclude water from entering the block. From this point on, additional water cannot be diverted in the fine layer and seeps through to the block and thence to drainage.

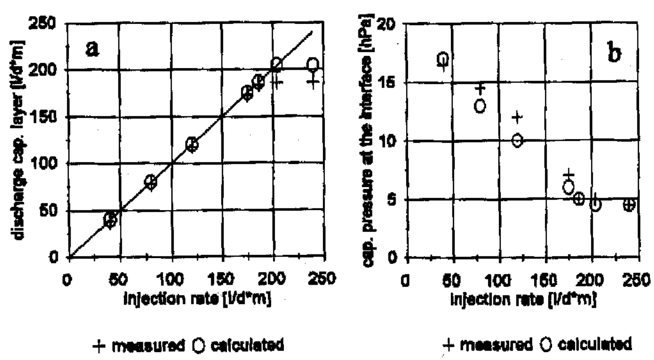

Fig. 8. *Comparison between measured and computed discharge (a) and capillary pressure at the interface (b).*

Conclusions

Capillary barriers have proved their ability to prevent rainfall infiltration into waste deposits in laboratory experiments as well as in large scale test sites under natural climatic conditions. The most important property of a capillary barrier is the diversion capacity, to which other design characteristics like length and dip angle must be adjusted. The diversion capacity is very sensitive to the shape of the unsaturated hydraulic conductivity function in the low pressure range of the used materials. To obtain a contrasting texture between the two layers, relatively coarse sands need to be used in the coarse layer. For such media, it is extremely difficult to obtain accurate hydraulic soil parameters from traditional soil core measurements. The agreement of the present flume experiments with field results implies that these experiments at a scale of several meters represent the relevant flow processes rather more accurately. The most relevant property of a capillary barrier, the diversion capacity, can be measured precisely by flume experiments. However, the transfer of laboratory results to field applications requires temperature effects to be taken into account.

The present numerical studies suggest that the lateral and vertical discharge rates as well as the pressure distribution in the fine layer can be simulated with an acceptable degree of precision. A numerical model in combination with flume experiments enables, without time-consuming experiments, assement of the effect of different design parameters such as the dip angle on the diversion performance.

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