# Evaluating Performance of Artificial Capillary Barriers to Improve Root Zone Conditions Using HYDRUS

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## Abstract

An artificial capillary barrier (CB), which consists with a layer of gravels, has been used to improve root zone condition for crop production. However, it is not fully evaluated how much water can be saved if CB is installed. In addition, CB can be easily broken when it is not carefully designed. The long term stability of CB needs to be well understood.

The main objective of this study is therefore to numerically evaluate the performance of CB under crop cultivation using HYDRUS-1D program (Simunek, et al., 2008). While water retention properties of CB used in this study were determined in the lab, unsaturated hydraulic conductivity was first modeled with single-porosity van Genuchten-Mualem model. Numerical simulation was however unstable because of low hydraulic conductivity for CB. In this study, we then used dual-porosity model by Durner to increase unsaturated hydraulic conductivity significantly in a dry range, while effect on the water retention curve was kept insignificant. Adjusting hydraulic conductivity of CB with the dual-porosity model made numerical simulation very stable. Experimental results were well reproduced by numerical analysis which also account for root water uptake. This study demonstrated the usefulness of numerical simulation to evaluate the performance of CB.

## Cultivation Experiments

Komatsuna or Japanese mustard spinach (*Brassica rapa* var. perviridis) was cultivated in rectangular container, size of which is 24 x 36 x 23 cm. Three containers with CB and one container without CB (for reference) were use. The packing of CB layer was shown in Fig. 1. Fertilizers were mixed with the upper layer (Tottori dune sand) before seeding and liquid fertilizers were applied with irrigation water twice a week.

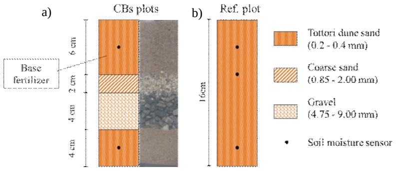



Fig. 1 The CB (a) and reference (b) layers

Table 1 The irrigation rates during cultivation experiment

| Experimental plots | CB | Irrigation (cm/day) |
|---|---|---|
| C15 | | 0.15 |
| C30 | ○ | 0.30 |
| C45 | | 0.45 |
| Ref | × | 0.30 |

Three different irrigation rates were used to the containers with CB, while an irrigation rate for the reference container (Ref.) was 0.30 cm/day (Table 1). To enhance germination, 0.5 cm of water was irrigated on the seeding day. The cultivation experiment was conducted in a temperature controlled phytotron with 25°C during daytime and 15 °C during nighttime. Volumetric water contents (VWC) were measured every hour using commercial soil moisture sensors, EC-5 (Decagon Devices Inc., USA) at the depths of 3 cm. and 14 cm (Fig. 1). The growth of Komatsuna was recorded until harvesting.

## Results

While the daily average VWC at 14-cm depth (which is under the CB layer) for all three CB cases did not increase much in the early stage, VWC at the same depth for Ref started to increase at Day 3 (Fig. 2b). This shows that the gravel layer in all three CB cases inhibited deep percolation and worked as CB. However, for C45, VWC at the same depth started to increase drastically at Day 8 because CB was broken (Fig. 2b). Because of the larger irrigation rate, excess water accumulated at the interface and CB was eventually broken. In the cases of C30 and C15, VWC in the lower sand layers increased gradually. It may be due to vapor transport through the gravel layer.

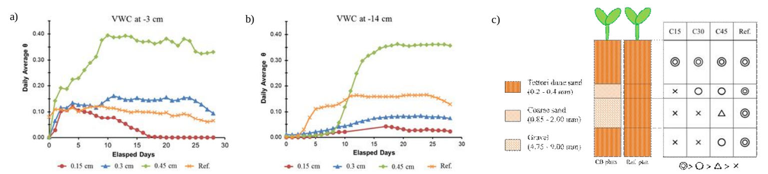



Fig. 2 Changes in daily average VWC at above (a) and (b) the CB layer with different irrigation rates and root distributions observed after harvesting

The height of the vegetable and the root length for C30 were the largest (Fig.3). it was shown that CB can inhibit irrigated water to percolate deeper. It was, however, also shown that if the irrigation rate is too small (C15), CB cannot improve root zone condition as all applied water can be lost through evapo-transpiration. If too much water is applied (C45), CB may be broken as excess water accumulates at the interface.

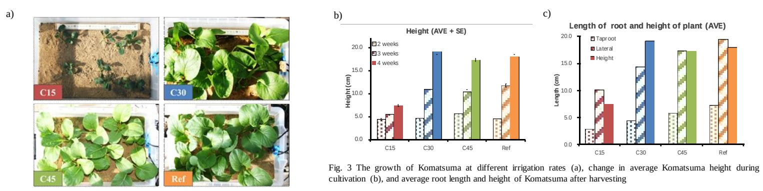



Fig. 3 The growth of Komatsuma at different irrigation rates (a), change in average Komatsuma height during cultivation (b), and average root length and height of Komatsuma after harvesting

## References

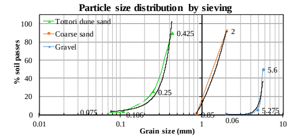
Durner, W., 1994. Hydraulic conductivity estimation for soils with heterogeneous pore structure. Water Resour. Res. 30: 211 –233.
Šimůnek, J., M. Th. van Genuchten, and M. Šejna, 2008. Development and applications of the HYDRUS and STANMOD software packages, and related codes, Vadose Zone Journal, doi:10.2136/VZJ2007.0077, Special Issue "Vadose Zone Modeling", 7: 587-600.
Van Genuchten, M.T., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. America J., 44: 892–898

## Hydraulic Parameters

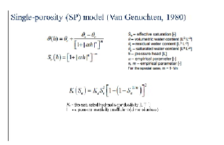
**Calculating empirical K by using Hazen (1892) equation**

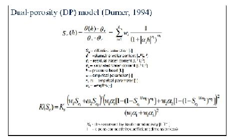
$$K = Cd_{10}^2$$

| | |
|---|---|
| **K** | hydraulic conductivity (cm/s) |
| **C** | Hazen coefficient |
| **$d_{10}$** | A grain diameter for which 10%of the sample will be finer than (the effective size) |




| Soil types | Hydraulic conductivity (cm/h) | $\theta_r$ | $\theta_s$ | $\alpha$ | n |
|---|---|---|---|---|---|
| Tottori dune sand | 72 | 0.016 | 0.384 | 0.030 | 6.665 |
| Coarse sand | 291.6 | 0.004 | 0.371 | 0.133 | 20.772 |
| Gravel | 828 | 0.005 | 0.204 | 0.204 | 15.524 |



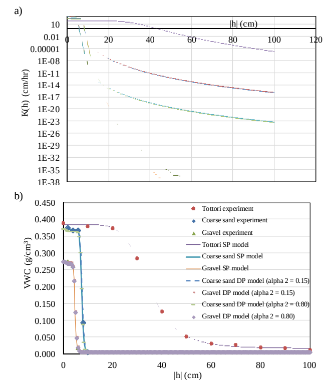




Fig. 4 The VWC and K(h) of Tottori, coarse sand and gravel calculated by using SP (Van Genuchten, 1980) and DP model (Durner, 1994)

K(h) estimated from the SP model for coarse sand and gravel are too small at lower pressure heads for numerical analysis (Fig.4a). The DP model was then used to increase K(h) of coarse sand and gravel (Fig. 4a). Parameters for the DP models were determined so that there was almost not effect on soil water retention curves (Fig. 4b). In this study, $w_2$ in DP was set 0.02.

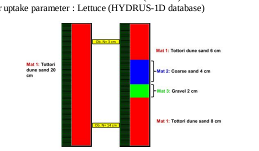
## Numerical Analysis

**Simulation conditions**

**Irrigation rates**: 0.15, 0.30, 0.45 cm/day for each CB systems, and 0.30 cm/day for Ref.

**Simulation parameter**

| | |
|---|---|
| Final time (Day) | : 28 Days |
| Soil hydraulic model | : Dual-porosity model for gravel and coarse sand |
| Lower boundary condition | : No flux |
| Upper boundary condition | : Atmospheric BC with Surface Run Off |
| Initial condition | : In Pressure head (-200 cm) |
| Root water uptake parameter | : Lettuce (HYDRUS-1D database) |



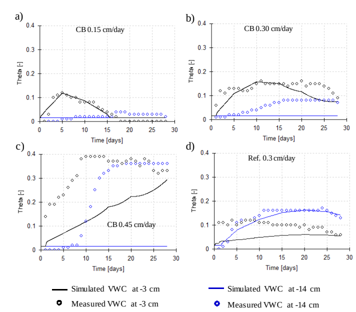




Fig. 5 The comparison of VWC between observed and simulated

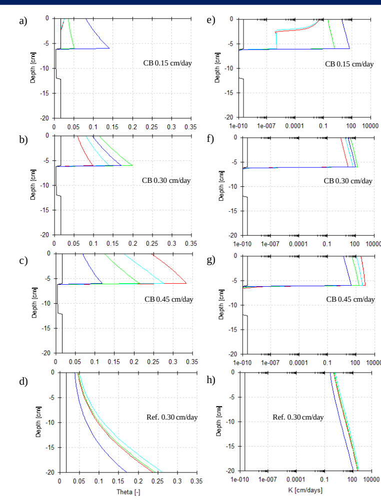



Fig. 6 The simulated VWC and $K(h)$ of CB and reference materials

Experimental data were well reproduced with HYDRUS except for C45 in which CB was broken during the experiment (Fig. 5). Results of numerical simulation however show that CB were well developed in all three cases(Fig. 6).

## Conclusions

By adjusting hydraulic properties, especially hydraulic conductivity, of coarse materials (e.g., gravel) with the dual porosity model, the performance of the capillary barrier can be well evaluated with HYDRUS-1D model. This study demonstrates the usefulness of numerical simulation in designing and evaluating the capillary barrier to improve the root zone during cultivation.