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Experimental and numerical evaluation of a ring-shaped emitter for subsurface irrigation

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ABSTRACT

A low-cost subsurface irrigation system can generate benefits for small-scale farmers who have scarce water resources. A ring-shaped emitter made from a standard rubber hose has been developed and introduced for subsurface irrigation in Indonesia. It is a low-cost irrigation technology based on indigenous materials and skills. To build a ring-shaped emitter of the original design, a rubber hose is bent into a ring shape with a diameter of about 20 cm, and then five 5-mm holes are drilled into it at even intervals. Next, the entire ring-shaped hose is covered with a permeable textile so that water can infiltrate in all directions around the buried emitter. Water is applied from a water tank connected to the emitter by adjusting the pressure head imposed at the inlet of the emitter. Although it has been successfully used in practice, the performance of the ring-shaped emitter has not been evaluated in detail. Additionally, because the ring-shaped hose is fully covered with the textile, it may be difficult to detect any malfunctions or repair it. To promote the ring-shaped emitter for subsurface irrigation among small-scale farmers in arid or semi-arid regions, it is important to design an emitter that is easy to maintain. This study proposes a reduction in the number of holes and a change of covering method. Because the number of experiments that can be carried out to evaluate the performance of alternative ring-shaped emitters is usually limited, numerical simulations can be performed in addition to experiments. The main objectives of this study thus were 1) to experimentally investigate the water movement around a buried ring-shaped emitter and 2) to numerically evaluate the effect of modifying the design of the ring-shaped emitter on soil water dynamics around the emitter. Numerical simulations were carried out using HYDRUS, one of the most complete packages for simulating variably-saturated water flow in two- or three-dimensional domains. HYDRUS simulations in a fully three-dimensional domain were performed using the soil hydraulic parameters that were optimized against experimental data collected during experiments with the original ring-shaped emitter. Simulation results confirmed that reducing the number of holes does not significantly affect the water availability in silt for model plants, such as tomato and strawberry, and that covering the entire emitter is not necessary. Partially covering the emitter allows one to maintain the emitter much more easily compared to the original fully-covered emitter.

1. Introduction

Some of the modern irrigation technologies designed for large-scale farming with complex and expensive devices tend to fail when introduced in rural areas of developing countries where farming is generally practiced on a much smaller scale. In these areas, maintaining complex irrigation systems can become a roadblock to promoting modern technologies because there may not be enough well-trained engineers and it may be difficult to find parts to repair these systems. Therefore, the use of indigenous skills and materials is crucial to introducing irrigation technologies in such communities.

Subsurface irrigation with a ring-shaped emitter (Saefuddin et al., 2014) is one of the irrigation techniques recently developed and introduced in rural areas of Indonesia for cultivating annual and perennial crops (e.g., Sumarsono et al., 2018). An emitter made from a rubber hose is economically affordable, especially for small-scale farmers. After a rubber hose is bent into a ring shape with a diameter of about 20 cm, five 5-mm holes are drilled into it at even intervals. An entire ring-shaped hose is then covered with a permeable textile so that irrigation water can be distributed through the permeable textile in all directions around an emitter. When used in the field conditions, a number of ring-shaped emitters can be connected to a pipeline which delivers water from a water source, such as a reservoir, a water tank, or a faucet. A constant pressure head can be maintained at the inlet when

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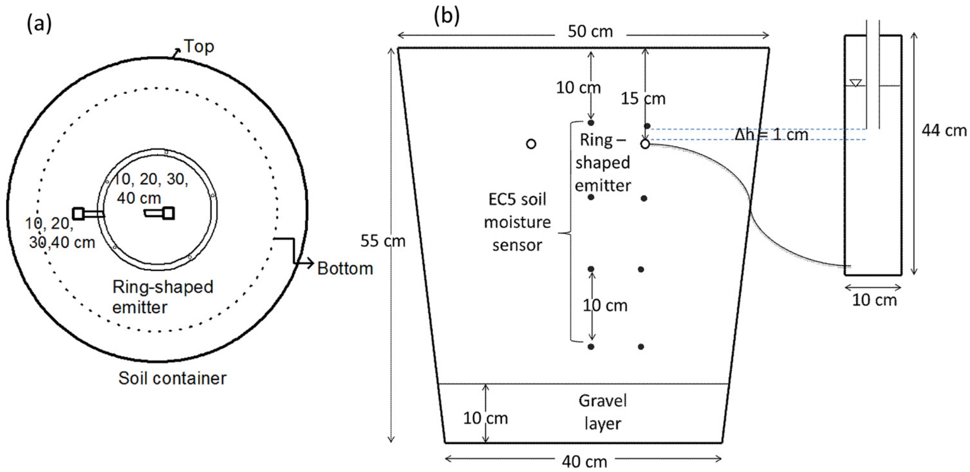

Fig. 1. Top view (a) and cross-section (b) of the soil container used in the laboratory experiments with a ring-shaped emitter.

the emitter is connected to a water tank. Sumarsono et al. (2018) applied 25-cm pressure head to the buried ring-shaped emitter to cultivate annual and perennial crops.

Although ring-shaped emitters have been successfully used for cultivating, for example, melon on an island of Indonesia where precipitation is limited (Saefuddin et al., 2014), its current design and operation are purely empirical. Understanding soil water movement and the spatial extent of the wetted volume around an emitter is crucial to achieving optimum operation of subsurface irrigation with a ring-shaped emitter and to modifying its design to improve usability and water-use efficiency. In addition, the current design of the ring-shaped emitter does not allow one to easily detect malfunctions because the emitter is fully covered with a permeable textile. As a result, it is not easy to repair it quickly.

For faster promotion of the technology, it is important to have a design that is easy to maintain. It has not yet been evaluated whether the number of holes can be reduced and/or whether it is possible to cover emitters only partially with a permeable textile. Because the number of experiments that can be carried out is usually limited, numerical simulations can be used instead to evaluate the performance of ring-shaped emitters of various designs and under different soils and environmental conditions. Using numerical simulations, a design that is more robust may be developed.

In this study, the HYDRUS (2D/3D) model (Šimůnek et al., 2016) was used to simulate soil water movement during subsurface irrigation with a ring-shaped emitter. The model is referred to simply as HYDRUS in the reminder of the manuscript. A number of past studies confirmed the suitability of HYDRUS for simulating water movement during subsurface irrigation. For example, Skaggs et al. (2004) compared HYDRUS-simulated water contents for a subsurface line-source drip irrigation with observed field data for three different emitter discharge rates. Kandelous and Šimůnek (2010b) used HYDRUS to evaluate laboratory and field data involving water movement in clay loam from point water sources buried at different depths and with different discharge rates. Kandelous et al. (2011) validated HYDRUS to simulate water movement from a subsurface drip irrigation system by comparing simulated results with measured soil water contents in several field experiments.

The main objectives of this study were 1) to experimentally investigate the water movement around a buried ring-shaped emitter during irrigation, 2) to validate the capacity of HYDRUS to simulate such water movement, and 3) to numerically evaluate the effects of modified designs of the ring-shaped emitter on soil water dynamics during irrigation. Laboratory experiments were first carried out to monitor changes in the soil water content at different positions during irrigation using the buried original ring-shaped emitter with five drilled holes that were fully covered by a permeable textile. While the emitter was developed to aid plant cultivation, the laboratory experiments were carried out without any plants in this study to avoid any difficulties associated with plant root water uptake. The collected experimental soil moisture data were used to calibrate HYDRUS. The calibrated model was then validated by comparing its prediction against additional experimental data.

The third objective was achieved by simulating changes in the soil water content around buried emitters of different designs. As an indirect quantitative proxy for evaluating the three-dimensional wetted volume around the buried emitter, corresponding root water uptake rates were computed. When water around the emitter is not uniformly distributed, the roots around the buried emitter may not be able to uptake water at an optimum rate because some parts of the root system are under stress. The root water uptake rate, therefore, can be used as an indirect indicator of how buried ring-shaped emitters of different designs performed compared to the original ring-shaped emitter.

2. Materials and methods

2.1. Laboratory experiments with the ring-shaped emitter

The laboratory experiments were carried out using a container (50 cm in diameter at the top, 40 cm in diameter at the bottom, and 55 cm in height) filled with air-dried soil (Fig. 1). Two soil types, silt and sand, were used in the experiments. Soils were packed in 5-cm increments at the predetermined bulk density of 1.41 g cm^{-3} and 1.52 g cm^{-3} for silt and sand, respectively. A 10-cm thick gravel layer was installed at the bottom of the container. For each experiment, the original ring-shaped emitter was installed at a depth of 15 cm. The emitter was connected to a Mariotte tank (10 cm in diameter and 44 cm in height) to control the water pressure head applied at the inlet (referred to as the inlet pressure). In this study, a constant pressure head of either 1 cm or 5 cm was maintained at the inlet of the buried emitter for 10 h to apply water through the emitter. Although a much higher pressure head was imposed at the inlet in field cultivation practices (e.g., Sumarsono et al., 2018), either 1 cm or 5 cm was used in this experiment to avoid a positive back pressure at the outlets (Shani et al., 1996; Lazarovitch et al., 2005). During the experiments, the volume of water in the Mariotte tank was recorded every 30 min to obtain the water application rate (i.e., the emitter discharge rate).

The ring-shaped emitter used in this study was made from a rubber water hose. The hose, which had a 1 cm inner diameter, was bent into a ring shape with a diameter of about 20 cm. There were 5 small holes with 0.5 cm in diameter drilled at even intervals on one side of the ring. The entire ring was covered with a permeable textile so that applied