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ROLE OF SOIL-ROCK INTERACTION ON RECHARGE INTO FRACTURED ROCK

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ABSTRACT

Groundwater recharge is an important but often a highly uncertain boundary condition when modeling groundwater flow in bedrock. Here the distribution of water infiltrating through the soil overburden into the underlying fractured bedrock is studied for different infiltration rates, drainage conditions and soil-rock permeability contrasts. Both the soil layer and the fractured rock are described with van Genuchten characteristic curves. The fractured rock is first represented as a homogenous deterministic continuum, then as a stochastic continuum with a spatially correlated hydraulic conductivity field. The flow simulations are performed with TOUGH2. The results from the stochastic simulations show that the recharge flux into the rock domain is concentrated into some distinct high-conductivity flow paths. In cases with large drainage rates unsaturated zones can develop even below the water table. This happens in areas with large conductivity contrasts. This desaturation results in lower effective conductivities and smaller fluxes in some parts of the rock in spite of the initially higher absolute hydraulic conductivity.

INTRODUCTION

Groundwater recharge is an important factor in the evaluation of groundwater resources, for example in assessing impacts of underground construction work or of other water withdrawal activities. Recharge forms also the upper boundary condition for groundwater flow and transport models, which usually makes the results from these models very sensitive to the applied recharge. A vital problem is that groundwater recharge is difficult to quantify (de Vries and Simmers, 2002). Recharge to the water table is often possible to estimate from water budgets, at least as a large-scale temporal mean value. However, the so-called inter-aquifer recharge, such as that from a soil aquifer into the underlying bedrock, is much more difficult to quantify. A large proportion of water infiltrating at the soil surface does not became recharge at the water table. Furthermore, often only a small part of water that has reached the water table will eventually enter the underlying bedrock aquifer. Factors affecting recharge include weather patterns, vegetation, local topography, properties of the soil overburden and the underlying rock and depth to the water table (Alley et al., 2002).

In this study, recharge flux through the soil overburden into the underlying fractured bedrock is investigated for various infiltration rates and soil-rock permeability contrasts. Simulations are performed for a hypothetical soil-rock profile consisting of a soil layer overlying fractured rock. Soil is always taken as homogeneous, but two different approaches are used for the heterogeneous rock: (i) Monte Carlo simulations using a heterogeneous model along with a stochastic representation of the hydraulic properties and (ii) a deterministic homogeneous model using effective mean values of these properties.

MODEL DESCRIPTION

Conceptual Model

The two-dimensional model domain used to simulate the soil-rock system is 50 m in the horizontal direction and between 10.5 and 13 m in the vertical direction (Figure 1). The thickness of the soil layer is 3 m and the upper boundary as well as the soil-rock interface are sloping from left to right with an inclination of 5%. No-flow boundary conditions are applied to the left boundary of the domain as well as to the right boundary of the rock zone. The objective is to represent flow conditions at a recharge area with predominantly vertical flow into the rock.

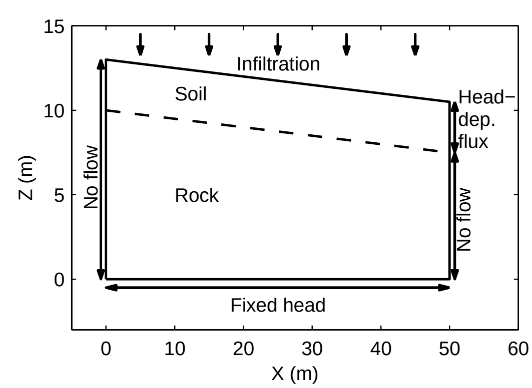

Figure 1. The model domain and types of boundary conditions used in simulations.

A constant fixed head boundary condition is used at the lower boundary. This specified head value is varied to simulate different drainage conditions that could arise e.g. from different underground construction activities. Lateral drainage in the soil zone is simulated using a head-dependent flux boundary condition at the right hand side:

$$q_x = C(h - h_0) \,, \qquad (1)$$

where q_x (m/s) is the lateral flux over the boundary, h is the hydraulic head at the boundary, h_0 is a reference head, and C (1/s) is hydraulic conductance. The reference head is fixed to a level 2.5 m below the level of the soil-rock interface at the boundary. The hydraulic conductance, C, is chosen to correspond to the conductance of a 50 m long column of soil material. This boundary condition could be seen as drainage to, for example, a stream with constant head, located downstream from the boundary. The upper boundary condition is a spatially uniform and constant infiltration rate through the soil surface over the entire model domain. Infiltration rates of 200 and 150 mm/year are used.

Properties of Soil and Rock

The hydraulic properties of the domain are selected to represent those of a medium-textured soil and typical fractured crystalline rock as encountered in Sweden. The properties of the soil medium closely represent those of a sandy loam at the NOPEX Site north of Uppsala, Sweden (Lundin et al., 1999). The soil material is modeled as a homogenous porous medium with deterministic properties.

For the rock, properties typical for fractured rock are used. A continuum model is used to represent the flow of the fractured system. We thus assume that at the support scale used in the stochastic simulations (0.5m) the rock behaves as a continuum and can be approximated by means of a continuum conductivity tensor. The absolute hydraulic conductivity, K_s, is assumed to be log-normally distributed and spatially correlated. A standard deviation of log(K_s) of 1.5 and a correlation length of 2 m can be considered reasonable for the support scale used. It should be pointed out that we use a numerical discretization of the same scale than the support scale of the stochastic heterogeneity.

To describe the capillary pressure-liquid saturation and relative permeability-liquid saturation relations the van Genuchten (1980) characteristic curves are used for both the soil and the rock

$$K = K_s S_e^{1/2} \left[1 - \left(1 - S_e^{1/m} \right)^m \right]^2 \,, \qquad (2)$$

$$P_c = -\frac{1}{\alpha} \left(S_e^{-1/m} - 1 \right)^{1-m} \,, \qquad (3)$$

where S_e is the effective saturation defined as

$$S_e = \frac{S - S_r}{1 - S_r} \,. \qquad (4)$$

For the rock medium the values of the residual saturation, S_r, and of the fitting parameters α and m are taken from a model of an unsaturated fracture continuum at Yucca Mountain at 0.25 m element scale (Birkholzer et al., 1999). The capillary strength parameter α is assumed to be correlated to the heterogeneous saturated hydraulic conductivity according to Leverett's (1944) scaling rule:

$$\frac{\alpha_{ref}}{\alpha} = \sqrt{\frac{K_{ref}}{K_s}} \,. \qquad (5)$$

Here α_{ref} is the value of the parameter α at the reference saturated hydraulic conductivity, $K_{ref} = 10^{-8}$ m/s. With this correction we take into account the fact that for the same water saturation higher capillary pressures need to be exceeded to drain small pore spaces (corresponding to small conductivities) than large ones.

The parameter m in equations (1) and (2) can be related to the spatial distribution of fracture apertures and is here assumed to be a deterministic constant. This is the same as to assume that the variability of fracture apertures is statistically homogeneous (Birkholzer et al., 1999).

Numerical simulations

The TOUGH2 code (Pruess et al., 1999) is used to solve the governing equations for unsaturated flow. In this case only flow of liquid water is considered, and therefore the TOUGH2 module EOS9 is used. Harmonic mean weighting is used at element interfaces for both the absolute saturated conductivities and for the saturation dependent mobilities, following the recommendations by Pruess et al. (1999).

The model domain is discretized into square elements with a side length of 0.25 m in the homogeneous case and 0.5m in the heterogeneous case. The discretization is coarser in the stochastic model due to computational limitations. The realizations of the stochastic conductivity fields are generated as unconditioned sequential Gaussian simulations using the GSLIB software package (Deutsch and Journel, 1998). An exponential variogram model is assumed.

Different contrasts in hydraulic conductivity between the soil and rock domains are considered. In the deterministic model this ratio is varied while the stochastic simulations are carried out for one ratio only, assuming two orders of magnitude difference in conductivity. In both cases, the pressure at the lower boundary is varied to represent different drainage conditions. For each set of boundary conditions hundred Monte Carlo realizations are simulated in the stochastic cases. Convergence of the output statistics is usually achieved after 50 to 80 realizations.

AN EXAMPLE SIMULATION RESULT

A characteristic result from a stochastic simulation is shown in Figure 2. The results show a recharge flux in the rock domain that is concentrated into some distinct high-conductivity flow paths. The example is for a case with a large drainage rate into the rock. In other words, a low value has been specified for the pressure at the lower boundary. In such cases unsaturated zones develop also below the water table in some areas with large conductivity contrasts (Figure 3). Consequently, small water fluxes are observed in areas with high absolute hydraulic conductivity but correspondingly low water saturations and effective water conductivities. (Figures 2 and 4). This phenomenon is not captured in the homogenous simulations where the entire rock domain below the water table remains saturated.

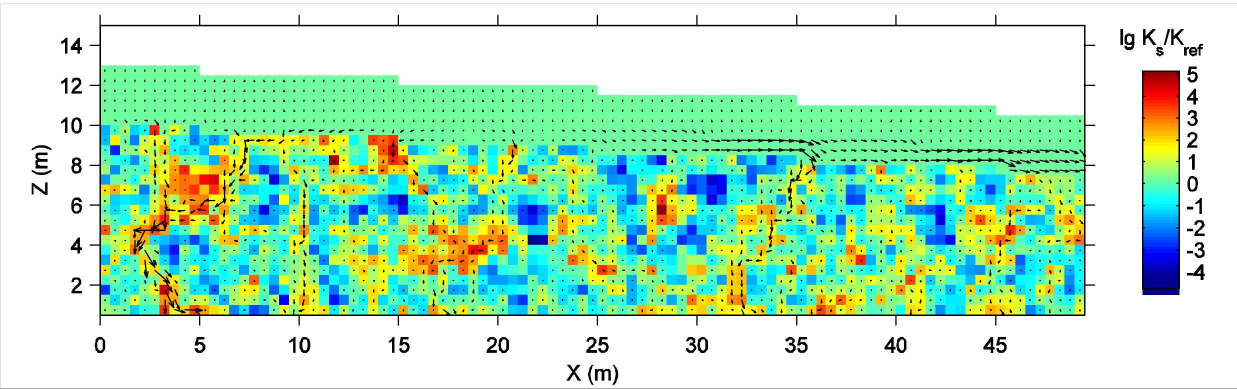

Figure 2. Resulting fluxes from the example stochastic realization. The color of the elements shows the logarithm of the saturated hydraulic conductivity divided by the geometric-mean conductivity.

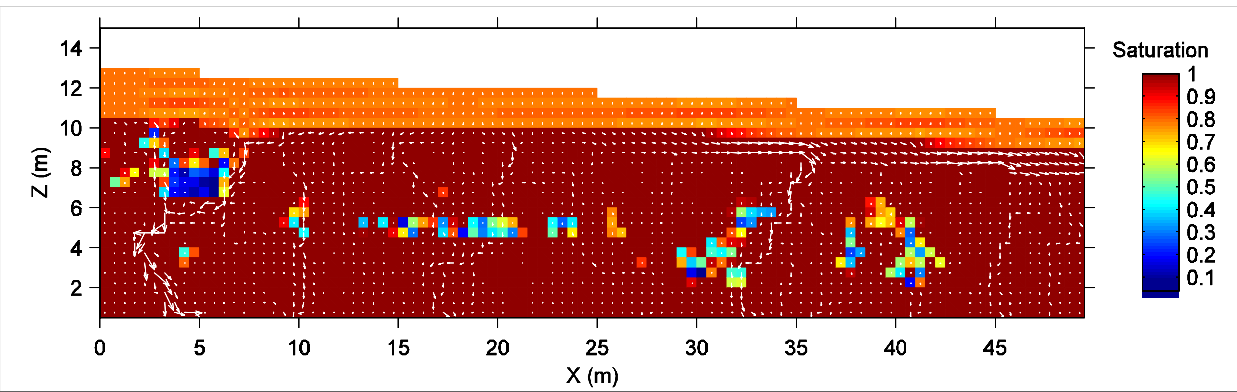

Figure 3. Resulting liquid saturation from the example stochastic realization. Fluxes are indicated with arrows.

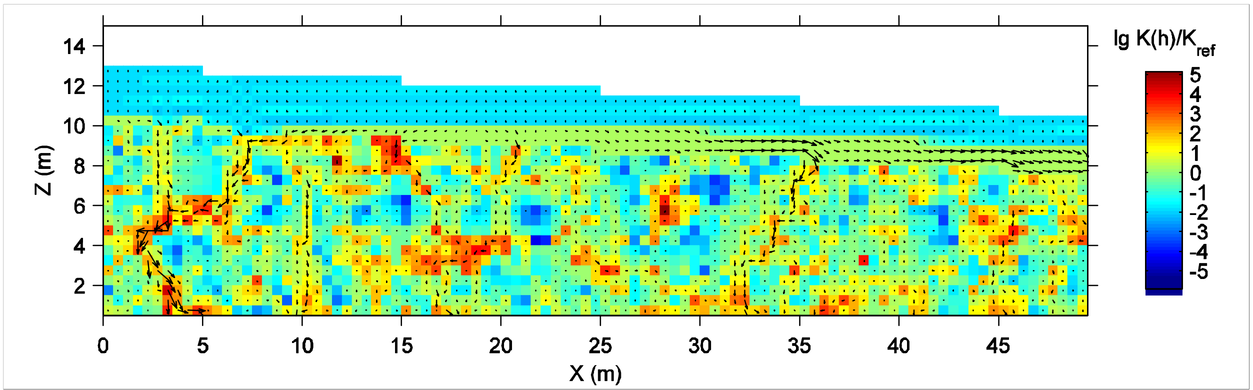

Figure 4. Resulting effective unsaturated hydraulic conductivity field from the example stochastic realization. The color of the elements shows the logarithm of the effective conductivities divided by the geometric-mean conductivity. The flux field is indicated with arrows.

The total flux over the soil-rock interface show large variations between the different realizations. A synthesis of the multiple realization results is presently underway.

CONCLUDING REMARKS

The results from this study can be used to evaluate the importance of rock heterogeneity on estimates of recharge into fractured rock. The results stochastic heterogeneous simulations can be compared to those from homogeneous effective mean value analyses that would be more typically used when deriving such estimates. An analysis of the results is presently underway, but one of our hypotheses is that the unsaturated zones that are observed in the heterogeneous results do influence the final recharge estimates. Detailed result of this study will be presented in a paper under preparation.

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