Experimental study of solute transport in the vadose zone of fractured rock

B. Čenčur Curk
M. Veselič

IRGO - Institute for mining, geotechnology and environment, Slovenčeva 93, SI - 1000 Ljubljana

The main goal of this research was the study of solute (pollutant) transport in fractured and karstified carbonate rocks, particularly in the unsaturated (vadoze) zone. In recent years, numerous detailed studies have been carried out with the objective of studying the safety of depositing radioactive waste into rock (Abelin *et al.*, 1991; Cacas *et al.*, 1990). At these sites research mainly focused on the understanding of the hydromechanics of rocks, solute transport and heat transfer in fractured igneous rocks, i.e. in very poorly permeable rock, while carbonate rock has been less researched (Veseliè, 1995).

Fractured and karstified rocks, and above all their voids geometry and topology, are very heterogeneous and complex, which results in complicated hydraulic, mechanical, thermal and chemical processes and the varying of their parameters. Therefore detailed studies of these processes have to be performed on a detailed scale, on experimental field sites for example (Čenčur Curk, 1997c).

Experimental design

One locality for an experimental field site was chosen in carbonate rock at Sinji Vrh in Slovenia, where structural analysis of discontinuities and tracer tests were performed. The experimental field site consists of surface outcrops and an underground tunnel 10–13 m below (Fig. 1). In the research area there is a fault zone at the crossing of the tunnels. In this zone the limestone is dolomitised and contains 35% $CaCO_3$ and 65% $MgCO_3$. The rock in the dead end and access tunnel is almost pure limestone containing 99.5% $CaCO_3$. The main fracture and fault strike of the surface rocks and within the tunnel is NNE-SSW (295/80 and 115/85), the subordinate dips are 85/40–90, 185/85, 140/80. The dip of limestone strata is 230/14-50. From the structural analysis and fracture mapping we were able to properly position injection holes, which were positioned above the tunnel crossing (Fig. 1). The holes were drilled only through the soil cover to avoid fracture flow disturbance within the rock and to avoid interaction between tracer and soil. A special construction for collecting water penetrating through the rock was developed. The construction enables the sampling of the water seeping from the ceiling of the tunnel in segments along the tunnel. The length of each

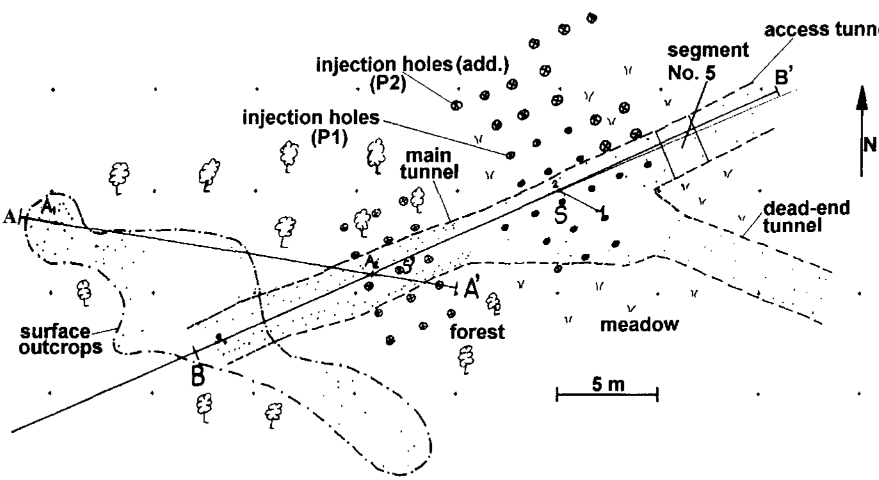

FIG. 1. The experimental field site at Sinji Vrh - the position of the surface outcrops area and research tunnel.

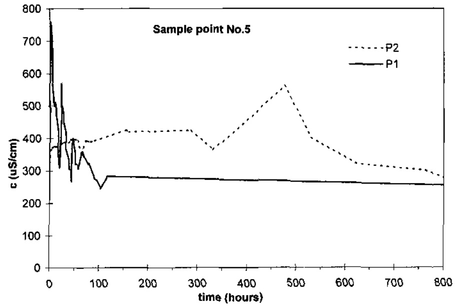

FIG. 2. Specific electric conductivities of water samples at sample point No. 5 for two tracer tests (P1 and P2) in variable saturated rock.

segment is 1.5 m and the total number of segments is 28.

Before the tracer tests were carried out, laboratory experiments had been performed, comprising relations of flow to permeability, porosity, active rock surface, representative elementary volume (REV), rock and tracer types, rock saturation and sorption (Čenčur Curk *et al*, 1997a).

Two preliminary tracer tests with NaCl for the purpose of determining the parameters of vertical flow through variably saturated fractured rock were performed. Saturation rates were not measured, however due to snow melting in the first experiment (P1) it was very high, while the second experiment (P2) was carried out in a dry season with very low saturation rate.

Results and conclusions

In the first experiment (P1) the tracer has appeared only in two segments (No. 4 and 5). The tracer appeared almost immediately after the injection and the maximal concentration appeared after two hours (Fig. 2). This phenomena was due to a very high rate of saturation. The peak values after the first tracer breakthrough occurred because the meadow above the tunnel was additionally watered (time 20 and 55 h). Subsequently it started to rain (time 58 and 103 h). It must be noted that only the addition of new fresh water (either from watering or raining) results in additional rinsing of pollutants, provoking a temporary rise in their concentration. We believe that the tracer is probably retained (and gradually rinsed) below the surface soil cover rather than in small fractures of the overlaying rock mass cover. This fact will be verified in laboratory tests in unsaturated conditions.

This experiment indicated only one fast conduit where water runs faster than in the total conductive part of the rock. In our case the main flow structure was a fracture in the access tunnel (Čenčur Curk *et al.*, 1997b). This fact is not enough to design a flow in fractured rock in general, but we should be aware that such direct and fast paths exist in karst and are very important in determining potential pollutant locations. This experiment was the first evaluation of flow conditions in the research area.

For the second tracer test (P2) additional injection holes were drilled (for a total number of 29) in order to obtain also the influx caused by rock stratification. The tracer appeared in more segments approximately three weeks later. This confirms the fact that in almost dry stages of the unsaturated zone the water first fills up the voids (fractures) and only then the flow starts. In the case of 'dry' rock also the smallest voids have to be filled up with water, after that greater voids fill up and so the percolation threshold is reached.

The experiments in wet and dry time periods were very interesting for determination of the differences between tracer recovery (mass through flow), residence time and flow velocity. Two preliminary experiments showed the characteristics of vertical flow and verified the suitability of the injection holes on the surface. This data was the basis for planning the principal experiment which is in progress. In this experiment eight tracers will be used. Each tracer will be injected in a group of holes in order to obtain a more precise determination of flow paths and their characteristics. In this experiment concentrations of each ion (Ca, Mg, Na, K, Li, Cl, B, etc.) will be measured in order to determine the processes of ion exchange (tracer - rock, tracer - tracer interaction).

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