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Coupling of unsaturated zone and saturated zone in radionuclide transport simulations

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ABSTRACT

In the management of radionuclide release in the environment, the unsaturated zone could be a natural barrier to delay or to stop the radionuclide migration through the environment and to protect the groundwater from radiological risks. Thus, a suitable scientific evaluation of any radionuclide transport problems related to groundwater may to take into account the processes affecting flow through the unsaturated zone. In this work, an approach that involves the interactions between unsaturated zone and saturated zone both from hydrogeological and radionuclide transport point of view is proposed. This approach was tested developing a case study on an Italian nuclear site. The behavior of unsaturated zone as protective barrier for the groundwater was highlighted and identified as a fundamental aspect in the development of environmental analysis concerning the radionuclide transport into the environment. Promising results were found to improve the design of a radiological monitoring network.

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1. Introduction

In the nuclear field, Safety Assessment involves all safety activities in order to manage a nuclear facility from the siting to the post-closure phase (International Atomic Energy Agency (IAEA), 2004; IAEA, 2009). In particular, as far as the radioactive waste management is concerned, the isolation of radioactive waste from the external environment has to be performed and investigated in order to avoid radiological risks for population and environment. Each nation involved in peaceful use of nuclear energy has a radioactive waste management strategy to safeguard population and environment (e.g. Sanders and Sanders, 2016). The modelling of radionuclide migration into the environment is one of the activities that allows to predict the dynamics of the radiological risk due to a nuclear facility operation, and its quantitative and qualitative impact on human beings and environment. The modelling can also be a supporting tool to plan the monitoring network, that is able to detect radionuclides in case of accidental release from a nuclear facility in order to make mitigation actions and/or to restore previous conditions.

Numerous studies on the environmental and radiological impact due to nuclear facilities can be found in the recent literature. Yim and Simonson (2000) reviewed performance assessment models for low level radioactive waste disposal facilities. Three different categories are identified. The first one concerns the near-field models, e.g. degradation of the facility, waste contained, and seepage of radionuclides into the surrounding subsoil. The second category involves the radionuclide migration from the subsoil to potential human exposure sites. Finally, the last category tracks the uptake, exposure, and dose equivalent due to transported radionuclides. Seher et al. (2016) investigated flow and transport processes in generic landfills that only contain nuclear decommissioning waste, through two different software SiWaPro DSS (Ingenieurgesellschaft and Dresden, 2007), and SPRING (Delta h, 2010). Skuratovič et al. (2016) investigated unsaturated zone at two radioactive waste disposal sites in Lithuania. In particular, they collected data and determined distributions of tritium and stable isotope ratio of oxygen and hydrogen in precipitation, unsaturated zone and groundwater. They underlined the importance of unsaturated zone as the first natural barrier to limit the spread of contaminants.

In this context, our study focuses on the groundwater as natural resource, which should provide water for human purposes, taking

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into account the possible effect of radionuclide migration in unsaturated zone and groundwater. In fact, from the hydrogeological point of view, the subsoil profile can be characterized by two zones, with different hydrogeological features: unsaturated zone, that is the part above the water table level, and saturated zone, which is the part below the water table level. In the management of radionuclide release in the surface environment, the unsaturated zone could be a natural barrier to delay or to stop the radionuclide migration through the environment and to protect the groundwater from contamination risk; moreover, understanding the contaminant dynamics in the unsaturated zone allows to protect the biodiversity and the agricultural use of this zone. Thus, a suitable scientific evaluation of any pollutant or radionuclide transport towards groundwater has to take into account the processes affecting flow through the unsaturated zone. Despite groundwater research has highlighted the importance of unsaturated zone, its representation has been often simplified during modelling due to the complexity, the computational demand and the lack of data necessary to characterize hydraulic properties (Keese et al., 2005). Another relevant challenge regards the need to integrate the modelling between the two hydrogeological systems. Different software have been used to model unsaturated zone and saturated zone, separately. The software simulating both unsaturated and saturated zone often oversimplify the modelling of the unsaturated zone. For this reason, in this study a literature research was carried out in order to identify which simulation tools are widely accepted and used by scientific community to model unsaturated zone and saturated zone, respectively. Thus, suitable software to perform separate studies was applied and tested on the unsaturated zone (Testoni et al., 2014), through HYDRUS 1D (Šimůnek et al., 2013), and on groundwater (Testoni et al., 2015, 2016), through MODFLOW (Harbaugh, 2005) and MT3DMS (Zheng and Wang, 1999). Then, these software were coupled in order to represent and model both zones as unique system, considering the effect of unsaturated zone on the transport in groundwater. This choice is confirmed by MODFLOW literature research. A promising approach to integrate the modelling between unsaturated zone and saturated zone has been suggested, to fill the gap in the integration of simulation codes for unsaturated and saturated systems, for safety assessment studies of nuclear facilities. The Variability Saturated Flow (VSF) process (Thoms et al., 2006), the Unsaturated Zone Flow (UZF1) package (Niswonger et al., 2006) and the HYDRUS package (Seo et al., 2007) are unsaturated zone modelling packages that can be coupled with MODFLOW, from the hydrogeological point of view. The performance comparison of these different tools was investigated by Twarakavi et al. (2008a), identifying the HYDRUS package for MODFLOW as the more promising ones. A coupled model simulates the effects of near-surface hydrological processes on groundwater flow by linking a groundwater model with a selected unsaturated zone model in space and time. This coupling makes it possible to estimate both qualitative and quantitative relationships between the two hydrogeological systems. In this work, a modelling approach that involves the interactions between the unsaturated zone and the saturated zone, both from hydrogeological (HYDRUS 1D-MODFLOW) and radionuclide transport (HYDRUS 1D-MT3DMS) point of view, is proposed. In addition to previous studies, the radionuclide transport was investigated taking into account unsaturated zone. This approach was tested developing a case study on an Italian nuclear site.

The aim of this paper is the assessment of radionuclide transport in the subsoil and groundwater, taking into account the unsaturated zone. In general, this zone is oversimplified or neglected in the studies of radionuclide transport for Safety Assessment purposes. We study the radionuclide transport in a real system constituted by unsaturated zone and saturated zone, by means of HYDRUS 1D and MODFLOW/MT3DMS software, respectively. This approach can be a useful tool which can support safety assessment studies of current or future nuclear activities.

2. Radionuclide transport: travel time and retardation factor

One of the most conservative evaluation of radionuclide migration through the subsoil is to assume that the solid matrix has no ability to slow radionuclide movement. Consequently, the radionuclides would travel in the direction and at the same rate of water. Due to the geochemical features of the soil minerals and to the chemical properties of the elements, this assumption is appropriate for certain radionuclides such as tritium and technetium, but is too conservative for other ones, such as americium and cesium.

The water and solute flow in unsaturated zone is characterized by three main parameters: water content, pressure head and hydraulic conductivity. The law that characterizes the dynamic of water and solute in unsaturated zone is the Richards' equation. Richards' equation describes the water flow in porous media, under assumption that air phase plays an insignificant role in the liquid flow process (Šimůnek et al., 2013). This zone is characterized by a water flow mainly in vertical direction. Equation (1) describes the Richards' law in a one-dimensional system:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K\left(\frac{\partial h}{\partial z} + \cos\alpha\right)\right] - S \quad (1)$$

where:

h is the pressure head [m];
θ is the volumetric water content [$m^3 \cdot m^{-3}$];
t is time [d];
z is spatial coordinate [m];
S is the sink term, the volume of water removed by the soil through plant uptake per unit time [d^{-1}];
α is the angle between the flow direction and the vertical axis (i.e. $\alpha = 0°$ for vertical flow, 90° for horizontal flow, $0° < \alpha < 90°$ for inclined flow);
K is the unsaturated hydraulic conductivity function [$m \cdot d^{-1}$] given by:

$$K(h,z) = K_s(x) \cdot K_r(h,z) \quad (2)$$

where K_s is the saturated hydraulic conductivity [$m \cdot d^{-1}$] e K_r the relative hydraulic conductivity [-].

Model of van Genuchten (Šimůnek et al., 2013) was assumed to describe the hydraulic properties of the unsaturated zone:

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{\left[1 + |\alpha_{air} h|^n\right]^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \quad (3)$$

$$K(h) = K_s S_e^l \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \quad (4)$$

where:

θ_r and θ_s are the residual and saturated water content, respectively [-];
α_{air} is the inverse of the air-entry value [1/m];
n is a pore size distribution index, and $n > 1$ [-];
m is an empirical parameter defined as $1\text{-}1/n$, [-];
l was estimated equal 0.5 for many soils [-];
K_s is the saturated hydraulic conductivity [$m \cdot d^{-1}$];
S_e is the effective water content, equal to $(\theta-\theta_r)/(\theta_s-\theta_r)$ [-];

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