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Numerical and polynomial modelling to assess environmental and hydraulic impacts of the future geological radwaste repository in Meuse site (France)

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ABSTRACT

This study aims to evaluate the hydraulic impacts of the construction of a deep geological radwaste repository planned by the ANDRA (French National Agency for Nuclear Waste Management) within the Meuse aquifer system in the east of the Paris basin. A three-dimensional numerical model of variably-saturated flow was developed with respect to the construction data of the Underground Research Laboratory (URL). The flow calibration process was based on the Latin Hypercube Sampling of uncertain hydraulic parameters and the polynomial regression analysis of hundreds of transient flow simulations. The minimization of the objective function led to a good matching of computed and measured time series of state variables. Results showed that the flow perturbation due to the construction of the future repository extends over 10 km around the site. After an operational period of 100 years, the repository post-closure re-saturation time is estimated to thousands of years.

1. Introduction

The ANDRA's deep geological repository of nuclear waste project (Cigéo) has driven numerous and intensive field investigation campaigns and groundwater modelling studies with the objectives of analysing and understanding the regional and local groundwater flow in the vicinity of the potential radwaste disposal of Meuse/Haute-Marne site. In this study, a three-dimensional numerical model of variably-saturated flow was developed: *(i)* to understand the local transient flow behaviour in the Oxfordian aquifer system during and after the construction of the access shafts to the Underground Research Laboratory (URL) in the Callovo-Oxfordian host formation; *(ii)* to predict the hydraulic perturbation during the construction and the operational period of the future repository infrastructure and to evaluate the extension of the unsaturated zones around this structure; and finally *(iii)* to estimate the repository post-closure re-saturation time of the geological/engineered system.

Variably-saturated flow models are very often used in petroleum and geotechnical engineering as well as in agricultural engineering (Diersch, 2014). In this study, they aim to represent the near surface flows and to estimate the extent of the unsaturated porous volume around the future repository access structures (ramps and shafts). Nevertheless, the modelling of a three-dimensional, long-term, variably-saturated flow at the regional scale remains a challenge. The resolution of the nonlinear Richards' equation (Richards, 1931) is very sensitive to space and time discretization (Paniconi and Putti, 1994) which implies a high computational cost. Moreover, the model has to be calibrated using historical data and then to be used for long-term predictions of the dynamic of the system which implies a large number of model runs and is thus time consuming.

With regard to the model results, the quality of the predictive simulations depends on the ability of the model to reproduce historical measures and observations. The calibration of the model aims to identify parameter values that produce the best-fit of data (Hill et al., 2013). Generally it is the most time consuming step in the modelling exercise especially for complex models involving a large number of parameters. Uncertainties affecting the concep-

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tualization of the model and the reliability of the data increase the time demand for calibrating the flow (Hill and Tiedeman, 2007; Refsgaard et al., 2007). Several methods of inverse modelling have been proposed and showed their efficiency for the estimation of model parameters (e.g. Carrera et al., 2005; Zhou et al., 2014; Poeter and Hill, 1997; de Marsily et al., 1999). Very often, these techniques are automated and provide the best set of parameters with the associated local sensitivity and uncertainty (Doherty, 2003), but do not provide information about the global parameter sensitivity. Furthermore, most inverse methods yield best-fit parameters by minimizing an objective function accounting for the difference between measured and simulated state variables (e.g. hydraulic heads) used to constrain the calibration of the model (Hendricks Franssen et al., 2009). However, the major difficulties when dealing with those methods arise in the case where the objective function admits several local minima, and high computational cost depending on the initial parameter values.

In order to reduce the computational cost needed to run a large number of variably-saturated flow simulations with an optimal resolution for large time and space scales and to converge to an acceptable calibration of flow, a surrogate model based calibration method was set up. It uses global sensitivity analysis (GSA) methods which allow to identify the most influent parameters (Saltelli et al., 2010; Deman et al., 2015). GSA can help to optimize the use of measured data for the calibration of numerical models (Younes et al., 2013). The quality of GSA depends also on the sampling procedure of parameters' uncertainty ranges (Helton and Davis, 2003). Furthermore, the method developed in this work is based on Response Surface Modelling RSM which allows to save time by using a mathematical proxy model to run a larger number of possible combinations of parameters instead of running the physical variably-saturated flow model. Fajraoui et al. (2011) used polynomial chaos expansion as a surrogate model in order to reduce the computation time required to predict mass transport and to identify the most influent parameters. Laloy et al. (2013) used generalized polynomial chaos theory to emulate the outputs of a regional groundwater flow model.

In this study, an efficient sampling method (Latin Hypercube Design, McKay et al., 1979) was used to cover the model's parameters distributions and to perform a sensitivity analysis GSA in order to point out the most influent parameters. The latter were then used to establish a polynomial model including linear, higher order and interaction terms to be used as a metamodel. Finally, inverse modelling was performed on an Objective Function (OF) polynomial regression model (Response Surface Model RSM) to estimate model parameters' values. The main advantages of using this RSM methodology are to measure the global sensitivity of the model outputs to input parameters and also to converge rapidly to optimal parameters by minimizing the global OF with reasonable computational cost.

The study is divided into five sections. In section 2, the site and URL data are described together with the hydrogeological settings of the area of interest. In section 3, the numerical groundwater flow model is outlined with the finite element mesh, the flow boundary conditions, and the mathematical model with the hydrodynamic parameters. Section 4 is dedicated to the sensitivity analysis framework based on the Latin Hypercube sampling method and to the establishment of the Response Surface Model (RSM). Section 5 deals with the application of the RSM to calibrate the transient flow induced by the URL construction and operation during the last eleven years (2001 to 2012). In the last section 6, the results of the predictive simulations to assess the hydraulic impacts of the construction and the operation period of the future repository are presented and discussed.

2. Description of the site

2.1. ANDRA's deep geological repository project (Cigéo)

For over twenty five years, the ANDRA (French National Radioactive Waste Management Agency) has been studying the feasibility of a radioactive waste disposal in the Jurassic-age Callovo-Oxfordian argillites (COX) in the eastern Paris basin (Fig. 1). Through multiple scientific projects and field investigations (e.g. geophysical surveys and drilling of deep boreholes) the host formation has been extensively studied (Delay et al., 2007b) together with the Oxfordian and Dogger limestone aquifer formations (Linard et al., 2011), respectively above and below the COX in order to characterize the layers geometry, state variables (e.g. hydraulic heads), and physical properties (e.g. hydrodynamic parameters).

After the first characterization studies, ANDRA began in 1999 the construction of the Meuse/Haute-Marne Underground Research Laboratory (URL) at Bure in order to investigate among others the in situ properties of the host formation. The URL consists of two shafts (i.e. principal access well PPA and auxiliary well PAX), and a set of experimental drifts at 500 m depth approximately (Delay et al., 2007a). The construction of the URL has been monitored in about ten deep boreholes and has yielded a large amount of data (i.e. geological, hydrogeological and geochemical). Hydraulic data are presented in section 2.3.

Later in 2005 and 2008, two nested zones were defined north and west of the URL to complete a new investigation survey: (*i*) the transposition zone ZT and (*ii*) the zone of interest ZIRA. In the ZT that extends over an area of approximately 250 km^2, the Callovo-Oxfordian formation is encountered at a depth of around 500 m, with a minimum thickness of approximately 130 m and a very low hydraulic conductivity (less than 10^{-12} m/s). ANDRA has carried out several investigation campaigns considering the chosen host domain and its surroundings and also carried out extensive site-descriptive modelling (ANDRA, 2012). The aim of the site-descriptive modelling is to develop a discipline-integrated description of the past and present conditions at the site, by analyzing, assessing, and modelling the data obtained from the investigation campaigns. ZIRA is an area extending over 30 km^2 selected for further investigations, and where will probably be emplaced four 500 m deep shafts with a diameter of 5 m and two ramps to access the future repository. The two access ramps of 4 km length and 6 m diameter are sub-horizontal with a slope of about 7° to join the shafts in the Callovo-Oxfordian host formation at about 500 m depth.

Prior to the construction and the operation of the future deep geological repository, ANDRA aims to analyze and to predict the hydraulic impacts which could be induced by the underground structures (shafts and ramps) linking surface installations to the radwaste disposal located in the clay formation at 500 m depth.

2.2. Regional hydrogeology

The geology of the Paris basin consists of a succession of sedimentary layers which hydraulically represent aquifers and aquitards or even aquicludes (Gonçalvès, 2002; ANDRA, 2005) reaching more than 3000 m of thickness at the centre of the basin. In 2012, ANDRA has developed an integrated regional-local hydrogeological model for the entire Paris basin to study the groundwater flow and mass transport behaviour in the multi-layered aquifer system (ANDRA, 2012). This model integrates data and knowledge that has been accumulated about the system over the last two decades. At the scale of the Paris basin the fully three-dimensional hydrogeological conceptual model consists of 27 layers from the Triassic