Building a staircase of confidence in groundwater modeling: a summary of ten years data collection and model development

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Surface radioactive waste disposal in northwest of Belgium – ten years of hydrogeological research

The study site (60 km²) is situated in north-eastern Belgium within the Nete river catchment with a fairly flat topography. Hydrogeology is defined by two aquifers of mainly clayey sands (the upper aquifer) and thick clay-rich semi-permeable Kasterlee Clay aquitard. The aquifer effective hydraulic conductivity is in range from 10⁻¹⁰ to 10⁻⁴ m/s, as it features alternating layers of heavy clay (d₅₀ < 4 μm) and coarse sand (d₅₀ > 200 μm). The upper aquifer consists (from top to bottom) of the Quaternary, Mol and Kasterlee Sands; the lower aquifer is composed of the clayey top and sands of the Davent Formation, the Dessel, Berchem and Voort Sands (Beerten et al. 2010). The lower boundary of the second aquifer is defined by the regional 100 m thick regional Boom Clay aquitard (K = 10⁻⁴ m/s, Yu et al. 2013).

Building a staircase of confidence

A stepwise approach to improve a groundwater flow model through data collection following sensitivity and uncertainty analysis has been adopted. In a period of ten years, two site characterizations were carried out with opening developing an increasingly more reliable groundwater flow model. Such stepwise reduction in conceptual model uncertainty and model parameter uncertainty, also called a staircase of confidence, was achieved by tailoring the data collection towards maximum reduction in model uncertainty.

First site characterization and initial model

The original hydrogeological model (Hardy et al., 2003) was based on scarce field data concentrated around the future repository. Approximately 25 borehole logs (on average 0.4 km² per km²) were used to determine the thickness of the Kasterlee Clay aquitard and 76 piezometers (on average 1.3 km² per km²) were available to calibrate the model. Interpolation of aquitard thickness resulted in several zones without data which, for convenience, were interpreted conservatively as zero-thickness zones (see left). Moreover, the hydraulic conductivity of the Kasterlee Clay aquitard was measured only as a single horizontal value only. The overall performance of the calibrated model based on groundwater heads in upper and lower aquifer was good (R² = 0.97 and RMSE = 0.25 for upper aquifer and R² = 0.89 and RMSE = 0.69 for lower aquifer).

Analysis of the initial model

Confidence in models requires more than just performance indicators such as R² or RMSE: confidence is obtained through multiple lines of evidence, including establishing a robust conceptual model. Structural model uncertainty addresses first and foremost the contiguity of the Kasterlee Clay aquitard, while a model-wide assessment of the aquitard geometry was also proposed. Decreasing model parameter uncertainty was directed primarily towards determinations of the hydraulic conductivity of the different hydrogeological units and in addition of piezometers at places most beneficial for model calibration. Sensitivity and uncertainty analyses performed with the initial model consisted of:

- identification of most sensitive parameters (including top boundary conditions);
- one-percent sensitivity maps (see right for an example with the most sensitive parameters).

Model parameter uncertainty due to limited calibration data

The second site characterization included 170 direct push cone penetration tests (CPT) uniformly distributed over the model domain (see right). The Kasterlee Clay was proven to be continuous in the entire model domain considerably decreasing the structural uncertainty. Decreasing model parameter uncertainty was achieved by:

- performing six long-term pumping tests and four additional piezometer development tests to obtain large-scale K estimates;
- installing additional twelve piezometer sites, representing 36 filter depths to better constrain the model during calibration;
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Second site characterization and update of the initial model

The spatial covariance derived from a CPT-based quasi-continuous CPT data. Weighted arithmetic and harmonic means where then used to upscale the K values to a 2 km vertical resolution to a single value for the entire aquitard thickness, followed by a 2D geostatistical interpolation to generate a spatially continuous K field. The resulting K range is 3.5×10⁻¹⁰ to 5.4×10⁻⁴ m/s with the vertical anisotropy ranging from 10 to 65/200. However, observed hydraulic gradients across the aquitard disqualified this approach.

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