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# Implementing a fully-coupled thermo-hydro-mechanical model: Lessons learned from the application to radioactive waste storage

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ABSTRACT: The fully-coupled thermo-hydro-mechanical (THM) model presented in Haxaire et al. (2013) has been implemented in the finite element code PLAXIS 2D. An application to radioactive waste storage is conducted and analysed. It is inspired by the OPERA research programme, in the Netherlands (Verhoef & Schröder 2011). The study consists of a simplified scenario of galleries in a layer of Boom Clay at a depth of 500 m. The formulation and the implementation is stable and provides qualitative results in accordance with expectation. Further studies, in particular validations based on in situ experiments, will have to be conducted to demonstrate the ability of the model to be simulate the complex coupled THM phenomena inherent to radioactive waste storage.

## 1 INTRODUCTION

The model presented in Haxaire et al. (2013) has been implemented and released in the finite element code PLAXIS 2D (Plaxis 2015a). The code offers a full coupling between the thermal, hydraulic and mechanical phenomena, for unsaturated porous media. The implementation supports plane strain and axisymmetric problems. The calculations can be steady state, transient, semi- and fully-coupled. The pore fluid has one constituent, water, and allows phase change: the three available states are ice, liquid and vapour. The time integration scheme is fully implicit to ensure robustness and stability. Transient and steady-state analyses can be performed, with automatic time stepping procedures for the transient analyses to provide efficient analysis times. Downscaling of the time step is triggered if the convergence criteria is exceeded and upscaling is used as the calculation becomes more and more stable.

To evaluate the performance of the model and its implementation, a case study is presented. It is based on the research work conducted at TU Delft in the framework of the OPERA research programme (Arnold et al. 2015). The OPERA project is a five year project running from 2011 - 2016, where a substantial research programme is being carried out to lead towards the development of a generic safety case (Verhoef & Schröder 2011). The work carried out by TU Delft for the OPERA project initially assessed the thermal behaviour of the proposed repository and found that due to the long term (100 year) proposed interim storage the yielded temperatures were unlikely to exceed proposed limits. The THM processes close to the proposed repository were not assessed. In this paper, only the ability of the developed code to simulate the THM processes close to the proposed repository is illustrated. The complexity of the interaction between the THM phenomena, the near and far field scale difference, in addition to the large time scale, pushes the code to its boundaries, making thus an ideal application to test and benchmark the implementation.

## 2 CASE STUDY

The case study is inspired by one scenario developed by Arnold et al. (2015), but is simplified to illustrate the code performance. Figure 1 presents the geometry, mesh and the boundary conditions. The analysis is plane strain. It consists of a set of two 1.6 m radius galleries excavated at a 500 m depth in a Boom clay layer, with a spacing of 50 m (centre to centre). The mesh contains 2,298 fifteen-noded elements, with 18,729 nodes. The boundary conditions are applied to both galleries. A heat flux of 11 W/m$^2$ is applied to both tunnel outer circumferences to model the heat emitted by the radioactive waste canisters once in place. Five points of interest are chosen horizontally at the mid-height of the model, from the boundary of the canister (1.6 m) to the middle of the model (25 m).

## 3 SIMULATION

The mechanical behaviour is modelled using the hardening soil (HS) model (Plaxis 2015b), which was shown by Arnold et al. (2015) to be suitable to model the clay host rock behaviour. As this model does not contain a temperature dependence, the contribution of the temperature to the mechanical behaviour was via only thermal expansion. The Van Genuchten model was used for the soil water retention behaviour, where the soil desaturates. The material parameters are presented in Table 1, the full description of the parameters is given in Plaxis (2015b). The parameters utilised are based upon those given by Arnold et al. (2015).

The initial conditions are a homogeneous temperature of 295 K in the model, a hydraulic head of 400 m at the top of the model and 500 m at the bottom.

In terms of thermo-mechanical coupling, the influence of the temperature on the mechanical behaviour of the galleries is made through the thermal expansion, i.e. before calculating the constitutive stresses.

For this analysis, first, the excavation is calculated and then, the thermal load induced by the canister radioactive waste is applied.

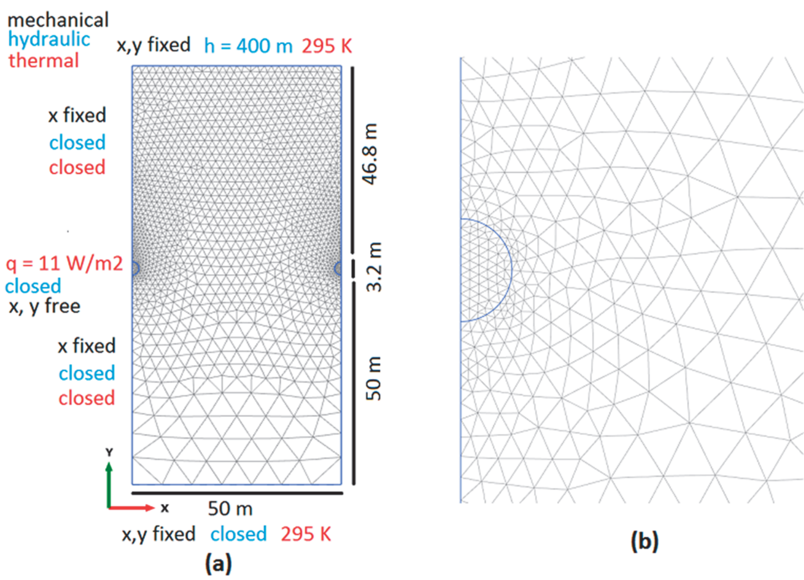


Figure 1. Model geometry and boundary conditions (a) and inset zoom on the left gallery (b).

Table 1. Thermo-hydro-mechanical parameters for the Boom Clay used in the case study.

| Mechanical | Unit | Value | Hydraulic | Unit | Value |
|---|---|---|---|---|---|
| $E_{50}^{ref}$ | [kN/m$^2$] | 145,300 | $S_{res}$ | [-] | 0.01629 |
| $E_{oed}^{ref}$ | [kN/m$^2$] | 145,300 | $S_{sat}$ | [-] | 1 |
| $E_{ur}^{ref}$ | [kN/m$^2$] | 435,800 | gn | [-] | 1.103 |
| Power (m) | [-] | 0.7 | ga | [1/m] | 2.650 |
| | | | gl | [-] | 2.5 |
| $e_{init}$ | [-] | 0.166 | $k_x$ | [m/s] | $10^{-12}$ |
| $c'_{ref}$ | [kN/m$^2$] | 300 | $k_y$ | [m/s] | $10^{-12}$ |
| φ' | [°] | 12.5 | | | |
| Ψ | [°] | 0 | Thermal | Unit | Value |
| $\nu'_{ur}$ | [-] | 0.3 | $c_s$ | [J/kg.K] | 1400 |
| $p_{ref}$ | [kN/m$^2$] | 100 | $\lambda_s$ | [W/m.K] | 1.4 |
| | | | $\rho_s$ | [kg/m$^3$] | 2000 |
| $K_0^{nc}$ | [-] | 0.7836 | $\alpha_s$ | [-] | 0.00005 |

# 4 RESULTS

## 4.1 *First phase: excavation*

Figure 2 presents the results after the excavation stage of the analysis. They focus on the left gallery, as the one on the right side of the model gives the same results, and the location close to the tunnel where displacements occur. The largest total displacement on Figure 2 (a) is 12.91 cm, or 8% of the radius of the gallery. This value was confirmed by a three dimensional calculation performed using PLAXIS 3D. Non zero values of the displacement field extend to 21 m below the galleries.

The total deviatoric strain on Figure 2 (b) exhibits the behaviour observed for the total displacement field: high displacements at the edge of the gallery, combined with an extended shear zone below the gallery. The maximum value obtained, 8.6%, is close to the total displacement ratio, confirming thus that the displacements are mainly caused by shearing.

The increase in effective mean stress presented in Figure 2 (c) is concentrated above and below the gallery, while the deviatoric stresses shown on Figure 2 (d) confirm that most of the shear is found at the horizontal edge of the gallery.

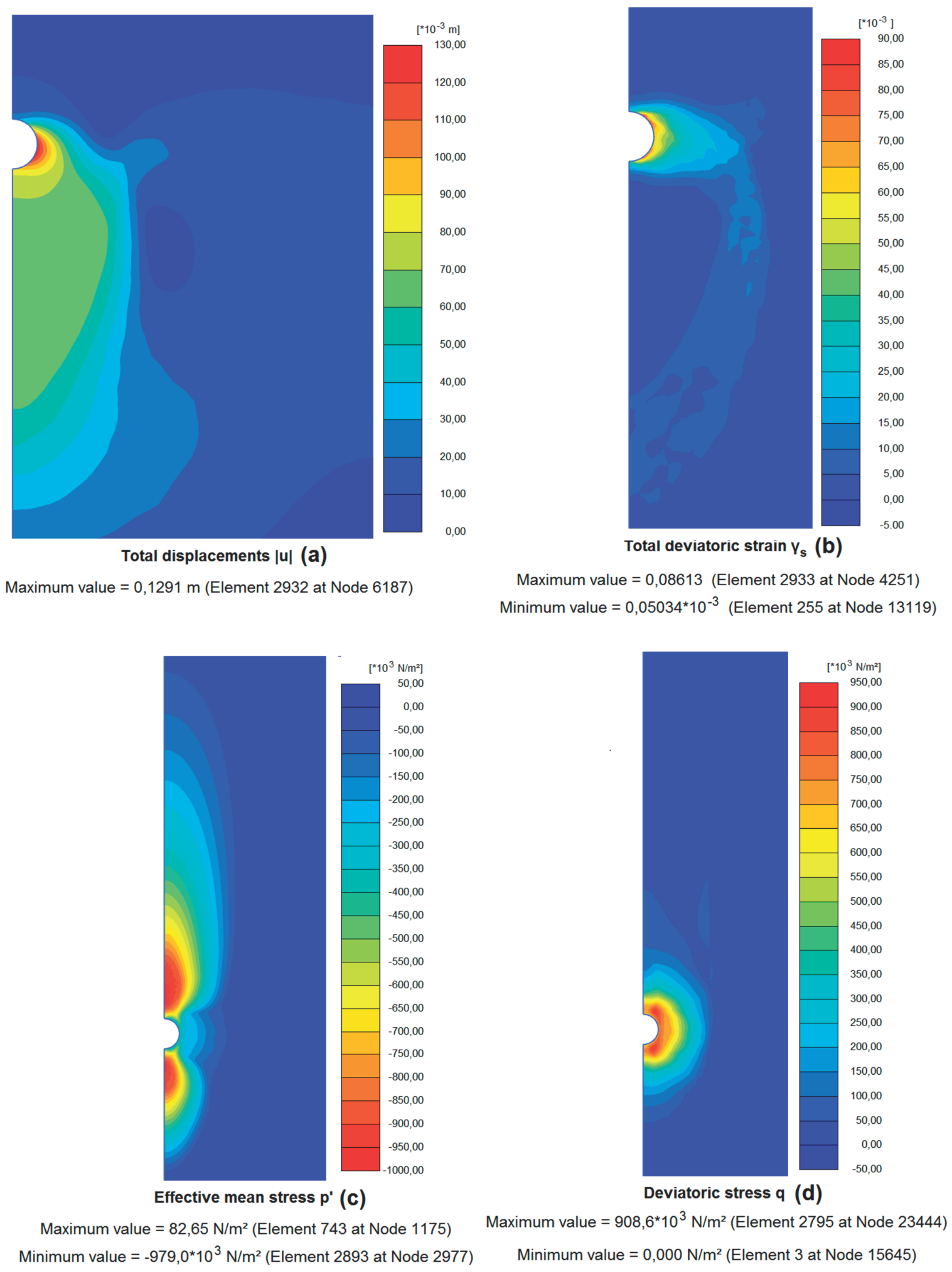


Figure 2. Mechanical results of the excavation (zoomed sections around the left gallery): (a) total displacements, (b) total deviatoric strain, (c) effective mean stress and (d) deviatoric stress.

### *4.2 Second phase: heating*

Figure 3 presents the evolution of the temperature over time applying a heat flux of 11 W/m$^2$. The position of the measurement points A, B, C, D and E is shown in Figure 4. The steady state is reached after approximatively 1.4e10 seconds, i.e. 444 years. The maximum temperature, obtained at the boundary of the gallery, at point A, reaches 360 K.

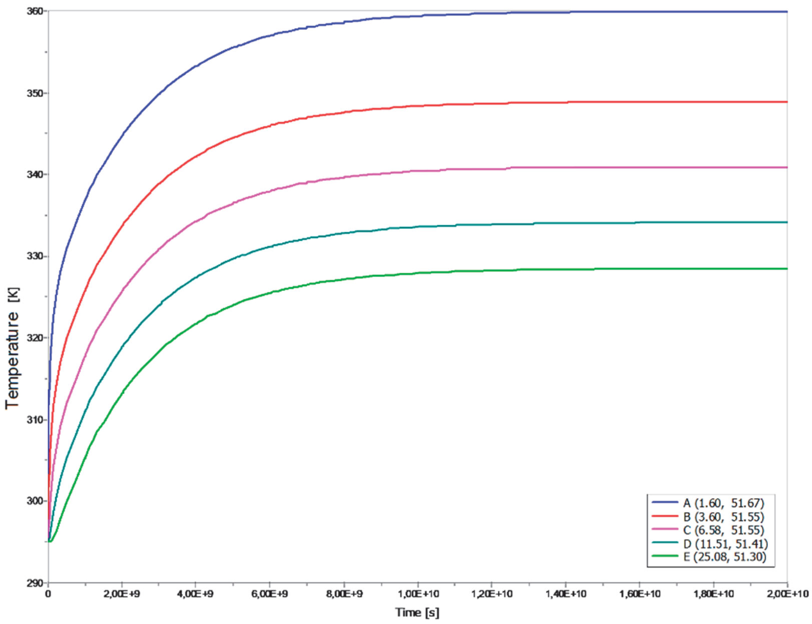


Figure 3. Evolution of the temperature from the boundary of the canister to the middle of the model.

Figure 4 presents the temperature and the heat flux in the model at steady state. Figure 4 (a) exhibits the interaction between the two canisters. The temperature at the middle of the model, at point E (25.08 m, 51.30 m), reaches 328.4 K. Figure 4 (b) shows that the heat flux, as expected, is null at the centre of the model, confirming the interaction between the two canisters at steady state.

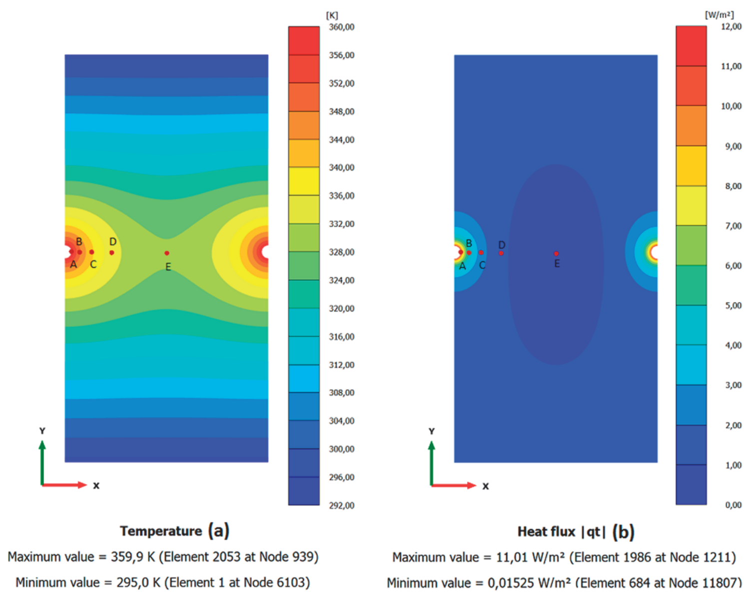


Figure 4. Temperature distribution (a) and heat flux (b) at steady state.

Figure 5 presents the evolution of the pore pressure close to the Boom clay-canister interface, after the start of the heating. We can see on Figure 5 (a) that, as expected, the heating increases the pore pressure: as the permeability is low, the water expands but cannot easily flow. The pore pressure initially increases rapidly due to the rapid temperature increase and then is subsequently controlled by the recharge effects of closing and backfilling the tunnel, returning to hydrostatic conditions (beyond the time shown in Figure 5). Figure 5 (b) confirms this result over the three points A, C and E. This confirms other simulation results such as those undertaken in the design of the PRACLAY experiment in Belgium (Li et al. 2010).

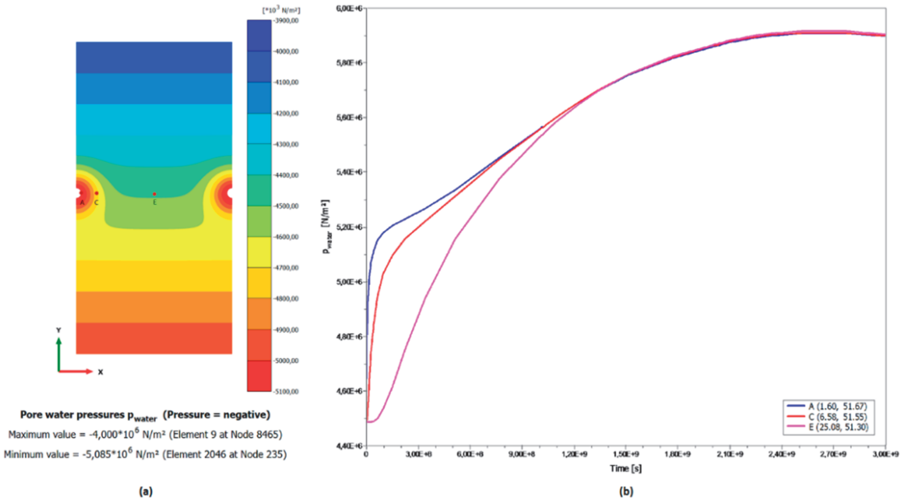


Figure 5. Pore pressure (a) after 282 days of heating and (b) from the left canister to the middle of the model until 95 years (with inverted pore pressure to emphasize the increase).

## 5 CONCLUSION

The current implementation of PLAXIS 2D's fully-coupled THM model has been shown to be able to simulate the THM effects of a radioactive waste repository. It can simulate a number of expected phenomena, leading to confidence in its ability to be used in further studies. In this paper, the effects of first excavating the galleries and then the installation of heat producing radioactive waste have been simulated. From this positive experience, more refined studies can be conducted, such as considering the excavation damaged zone, or the impact of vapour fluxes on the THM processes, as well as full validations based on in situ experiments.

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