Geomechanical modelling of the Dutch radioactive waste disposal facility accounting for uncertainties

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The current generic radioactive waste disposal concept in the Netherlands is designed to be situated in a Boom Clay stratum at approximately 500 m depth. The location of such a repository has not been decided and, as such, the design contains many uncertainties. The impact of these uncertainties are important to the feasibility of the repository design and construction, with respect to both stability and consequential financial performance. The objective of this study is to develop an approach that uses probabilistic methods to quantify uncertainties, and utilises PLAXIS to assess the geomechanical repository behaviour during and after construction. In addition, the new Thermal module in PLAXIS has been utilised to provide an initial assessment of the temperature changes in the Boom Clay. This research project was undertaken as part of the OPERA research programme.

1. Introduction

The current disposal concept for radioactive waste in the Netherlands is based upon the Belgian supercontainer concept and is designed to be situated in a Boom Clay stratum at approximately 500 m depth (Verhoef et al., 2014). The location of such a repository has not been decided and, as such, the design contains many uncertainties. The impact of these uncertainties are important to the feasibility of the repository design and construction, with respect to both geomechanical stability and consequential financial performance. In particular, the tunnel lining, initially estimated to be 50 cm thick (Verhoef et al., 2014), has been estimated to be up to 80% of the total repository construction costs (Barnichon et al., 2000).

The life-time of a radioactive waste repository may be categorised into five phases, which are schematically outlined in Figure 1 where different stages of the repository evolution are outlined. The current outline of the OPERA repository is shown in Figure 2. The design consists of a single level with the waste being segregated in specific zones. The main gallery, connecting the shafts with all disposal zones in the repository, is excavated in a single loop and will serve all transportation and access purposes. In Zones A and B, dead end disposal drifts with an envisaged length of 200 m are excavated perpendicular to the secondary galleries. The disposal galleries in Zone C are planned to be excavated directly from the primary gallery, with a length of 45 m. The deep geological repository concept consists of an Engineered Barrier System (EBS) and multiple natural barriers, in order to satisfy all containment and long-term isolation requirements for the disposal of radioactive waste.

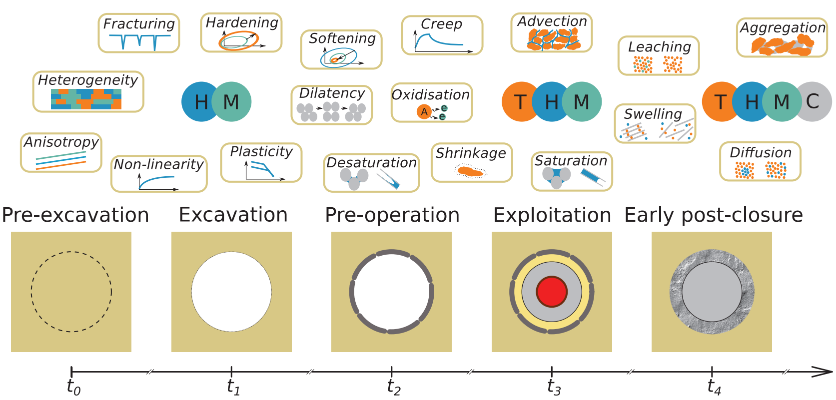


Figure 1: Schematic outline of life-time phases of a radioactive waste repository and processes influencing the repository performance

To construct and operate the repository, stability is required. For the tunnels, a lining is required for structural stability and to limit convergence due to the Boom Clay behaviour. Due to the plastic nature of the Boom Clay, a stiff lining was required, and therefore the use of pre-cast concrete segments was specified. A cross section of the tunnel for the disposal galleries is shown in Figure 3.

Assessments of the tunnel stability, including the possible gallery spacing, constitutive model selection and parameterisation, probabilistic analysis of uncertainties and an initial thermal assessment were undertaken. In the main, these analyses fit into the excavation and pre-operation stage and the thermal analyses fit into the early post-closure phase (see Figure 1). This work was undertaken as part of the

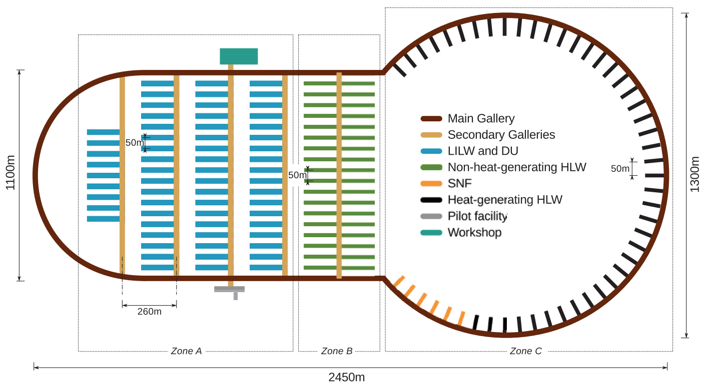


Figure 2: Schematic outline of the OPERA deep geological underground disposal facility in Boom Clay (after Verhoef et al., 2014). LILW is Low and Intermediate Level Waste, DU is Depleted Uranium, SNF is Spent Nuclear Fuel and HLW is High Level Waste

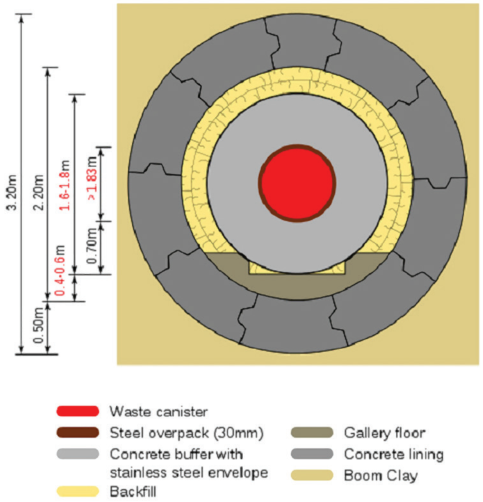


Figure 3: Cross section of the disposal galleries

OPERA research programme and specifically work package 3.1. The final results are available in Arnold et al. (2015).

2. Boom Clay behaviour

Boom Clay is a marine Oligocene shelf deposit from the Lower Oligocene Rupelian stage and builds with the Bilzen and Eigenbilzen Formations the Rupel Group. A detailed analysis of the geological extents and geohydrological setting can be found in Vandenberghe et al. (2014).

In general, Boom Clay can be considered as a non-linear (stress-dependent) material in terms of the stiffness, which may also be anisotropic in behaviour (e.g. Deng et al., 2011). While many studies on Boom Clay have been undertaken, there are little data from appropriate depths for the proposed repository. A number of boreholes have been made, including hydro-mechanical investigations. In addition, the underground laboratory in Mol at -223 m is a source of samples and in-situ data.

Deng et al. (2011) performed a series of triaxial tests at different over-consolidation ratios and the results are shown in Figure 4. From these tests it can be concluded that the soil behaviour is non-linear. The confining stress and the over-consolidation ratio are highly influential in determining the material properties, and the soil stiffness decreases significantly with axial strain.

A thorough investigation of material models and parameterisation was undertaken to select an appropriate model. For each material model, a single set of parameters was calibrated to best fit all three sets of test data. It was concluded that the Hardening Soil (HS) model was the most appropriate, due to its ability to simulate non-linear material properties and both dilation and contraction due to shearing. However, strain-softening behaviour could not be simulated, as the material model does not include such behaviour. Among the other models tested, the Modified Cam Clay model was able to include strain-softening, but the representation of other behaviour was poor. The best fit results for the three triaxial tests for which the model was calibrated are shown in Figure 4, alongside the experimental data, with the material parameters shown in Table 1. It is emphasised that a single set of parameters (Table 1) was used to give results for all tests.

To show the uncertainty/heterogeneity of the Boom Clay layer, a compilation of selected Boom Clay test data (in terms of the effective stress Mohr-Coulomb failure criterion) with respect to depth, is plotted in Figure 5. It is seen that a wide spread of data exists, with some depth trends apparent in the shear strength profile. A detailed statistical analysis of the small database of available data was carried out, with both depth-related statistics and cross-correlation between material properties being considered. This resulted in a depth dependent trend in measured material parameters, including the confidence levels of the fit and the standard deviation of the residuals (deviation) from the fit (see the example in Figure 6). Figure 7 presents the cross-correlation between the effective cohesion and effective angle of friction (in standard normal space). A clear negative correlation is shown to exist.

The analyses presented below utilise the parameters obtained from the triaxial tests shown in Figure 4. However, the clear depth dependency indicates the uncertainty in the parameters, therefore without further experimental data the results should be considered preliminary.

3. Assessment strategy

A probabilistic Reliability Based Design (RBD) framework was used in this project. The variables utilised are set up in a vector, X, along with their statistical distributions. In addition, a limit state, i.e. what part of the design you would like to optimise for, must be defined. In this case, the plastic radius of the tunnel was decided to be a single limit state, with a second being the stability of the tunnel lining.

A RBD module was developed based on the OpenTURNS library (OpenTURNS, 2014) which used PLAXIS as the geomechanical engine. A flowchart of the module operation is presented in Figure 8, where in Figure 8(a) the vector X is established, (b) the geomechanical model is run multiple times utilising selected combinations of the material properties, controlled by OpenTURNS reliability methods, such as the Monte Carlo Method or the First/Second Order Reliability Method (FORM/SORM), (c) outlines the assessment against the limit states and (d) is an output visualisation tool assessing the sensitivity of various parameters. After this point either more information can be used to constrain the analysis via optimisation of either the design or material parameter uncertainty (e), or the safety can be assessed (f).

The reliability methods used can have a large effect on the amount of computation required. For Monte Carlo methods, in general, a very large amount of computation is required, which is unfeasible for detailed geomechanical models, such as required here. FORM/SORM typically require significantly less, in this work it was found to be ~200 analyses, rather than ~25,000 for the Monte Carlo methods, which were initially tested with an analytical model (see Arnold et al., 2015). This level of computation proved to be unfeasible to use a detailed geomechanical engine, such as PLAXIS.

4. Results

A selection of representative results is shown below. For further results and detailed analysis, please refer to Arnold et al. (2015).

4.1 Deterministic tunnel stability model

In this section the deterministic response of the Boom Clay due to the excavation of a tunnel is investigated. This model is then utilised by the probabilistic module, by varying the HS model parameters. The results are presented in the following section.

Figure 9 shows the model domain, boundary conditions and mesh of the numerical model. The bottom boundary is fixed, with the left-side and right-side boundaries fixed in the horizontal direction and free in the vertical direction. The initial vertical effective stress in the domain was set to be hydrostatic with a depth of 420 m to the top of the domain (initially with an additional part of the domain, not shown on the figure). Initial horizontal effective stresses were computed using the *K0* procedure. Subsequently, the additional part of the mesh was removed from the initial domain to result in the 80 × 160 m model

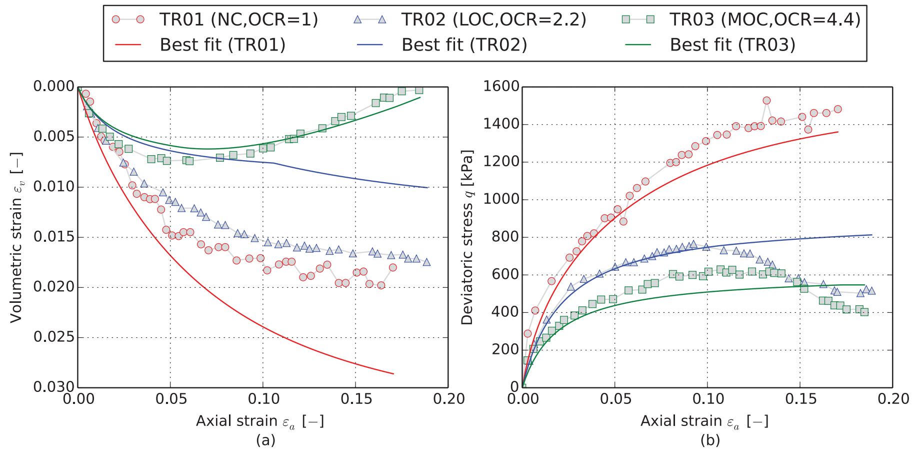


Figure 4: Results of three Boom Clay triaxial tests (after Deng et al., 2011) and best fit material model results, based on a single set of fitting material parameters (Table 1).

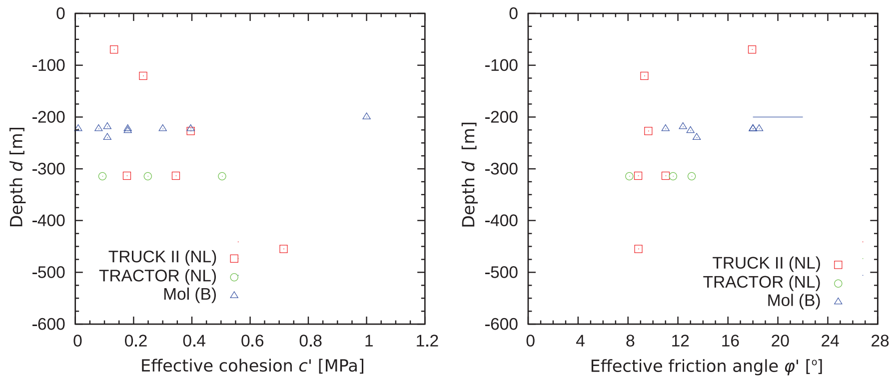


Figure 5: Effective cohesion c' and effective friction angle ϕ' of Boom Clay samples at different depths, locations and research projects: TRUCK II, TRACTOR and at the HADES in Mol

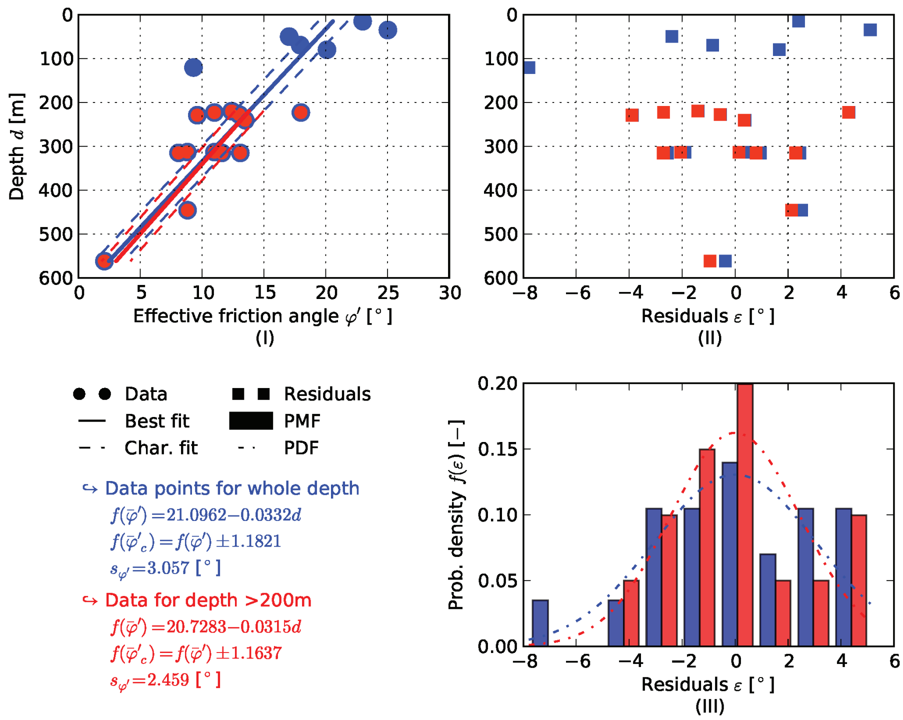


Figure 6: Statistical interpretation of the effective angle of friction

domain with a total vertical stress of 4.2 MPa applied along the top boundary. The domain was discretised using 15-node triangular elements and refined in the vicinity of the tunnel. In the basic HLW gallery set-up, the tunnel radius was 1.6 m, and the overcut (distance between the tunnel lining and rock) was 75 mm. The domain was discretised by 8554 elements with 68946 nodes. The tunnel construction process except for the overcut was not considered.

An example result of the plastic zone is depicted in Figure 10. As expected, it is seen in Figure 10(a) that the radial stresses decrease and the tangential stresses increase, causing hardening and shear failure. The plastic zone is shown in Figure 10(b), where, due to K_0 equals 0.9 in this case, the horizontal extent of the plastic zone is higher than the vertical extent. Here, the plastic zone extends about 12 m from the tunnel centre, with a small zone close to the tunnel where the material has reached the failure line.

An initial sensitivity analysis (not presented here, please see Arnold et al., 2015 for details), yielded results that the plastic zone would not be large enough to affect an adjacent tunnel and additionally the radial stress would not be high enough to cause instability in the tunnel lining. This yields the possibility to reduce the tunnel spacing and the lining thickness, if other performance criteria allow, such as changes in permeability or thermo-mechanical behaviour.

4.2 Probabilistic results

As previously stated, the location for such a repository has not been decided and, as such, the design contains many uncertainties. By carrying out a probabilistic assessment, the importance of the uncertainty in the material parameters can be assessed. In this case Figure 8 has been followed from (a) to (d). A metric to define the relation between the relative change in value of a parameter to the relative change in response it causes, can be defined. This is called an importance factor (Eq. 1), and can be defined as:

$$\alpha_i = \frac{\partial \beta}{\partial u_i} \qquad (1)$$

where α_i are the importance factors relating to each material property, i; β is the reliability index (the distance in standard normal space of the expected response to the critical point) and u_i is the material property transformed into standard normal space (e.g. Lemaire, 2009). This means that further research can be directed towards investigating this parameter and reducing its uncertainty.

As the amount of data available is small, a probabilistic reliability analysis was performed to investigate the impact of the various parameters. An example result, from a FORM investigation, showing the impact of different coefficient of variations (V = mean / standard deviation) for the E_{50}^{ref} parameter is shown in Figure 11. For the case of a medium coefficient of variation or Case 2, all coefficients of variation are equal to 0.125. In this case the response due to changes in the effective friction angle, ϕ', is shown to be the most sensitive, followed by the reference secant modulus, E_{50}^{ref}. When the coefficient of variation of E_{50}^{ref} increases from 0.125 to 0.2 (with all other coefficients of variation remaining the same), then this parameter becomes the most sensitive. In these cases the probability of the lining pressure exceeding 7 MPa (arbitrarily set in this case) were 1.4×10^{-6} for Case 1, 5.0×10^{-6} for Case 2 and 3.1×10^{-4} for Case 3, respectively. The small increase in probability of failure between Case 1 and Case 2 is indicative of the E_{50}^{ref} value not being the most important. However, the large increase in

Table 1: Boom Clay parameters for the HS model

Property	Symbol	Value from HS calibration
Reference secant modulus*	E_{50}^{ref}	8.53 MPa
Reference un-/reloading modulus*	E_{ur}^{ref}	20.94 MPa
Reference oedometer modulus*	E_{oed}^{ref}	11 MPa
Rate of stress dependency of stiffness	m	0.7
Un-/reloading Poisson's ratio	ν_{ur}	0.3
Dilatancy angle	ψ	0°
Effective friction angle	ϕ'	12.4°
Effective cohesion	c'	0.11 MPa

*Reference stress p_{ref} = 0.1 MPa

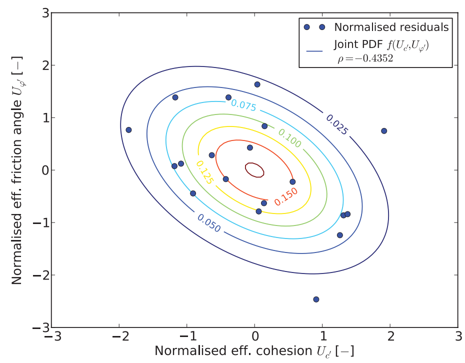


Figure 7: Correlation between normalised residuals of soil cohesion and friction angle of Boom Clay, sampled at different depths and locations, with the isochrones representing the bivariate joint probability density function

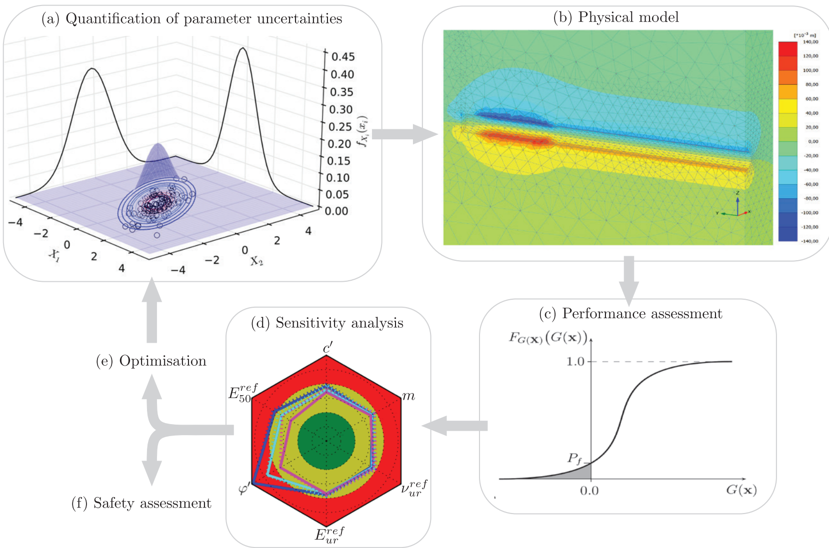


Figure 8: Flow chart schematically showing the employed RBD model framework

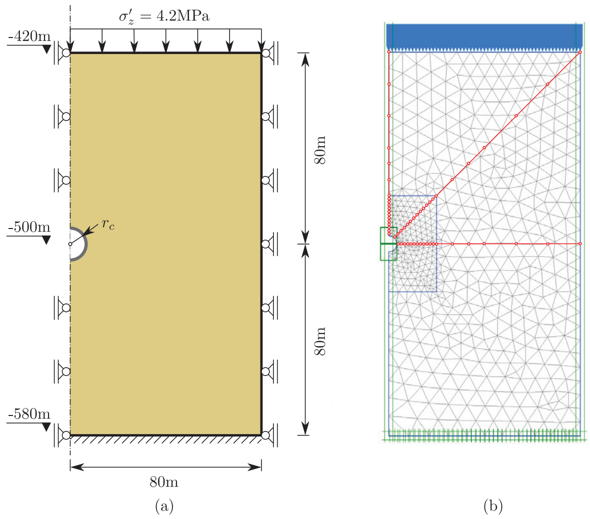


Figure 9: Base set-up for a deterministic two-dimensional plane strain analysis at 500 m depth: (a) Model domain and boundary conditions; and (b) Discretisation using 15-node triangular elements. Red lines represent the data output axes (horizontal, vertical, diagonal)

probability of failure in Case 3 is indicative of the E_{50}^{ref} parameters being the most important.

4.3 Thermal

An initial thermal assessment has been carried out using the new PLAXIS 2D Thermal module. The heat output of the radioactive waste has been assessed, per metre of the disposal tunnel, and included in a 2D model as a boundary condition. The heat output decays over the lifetime of the repository, and a stepwise boundary condition has been utilised.

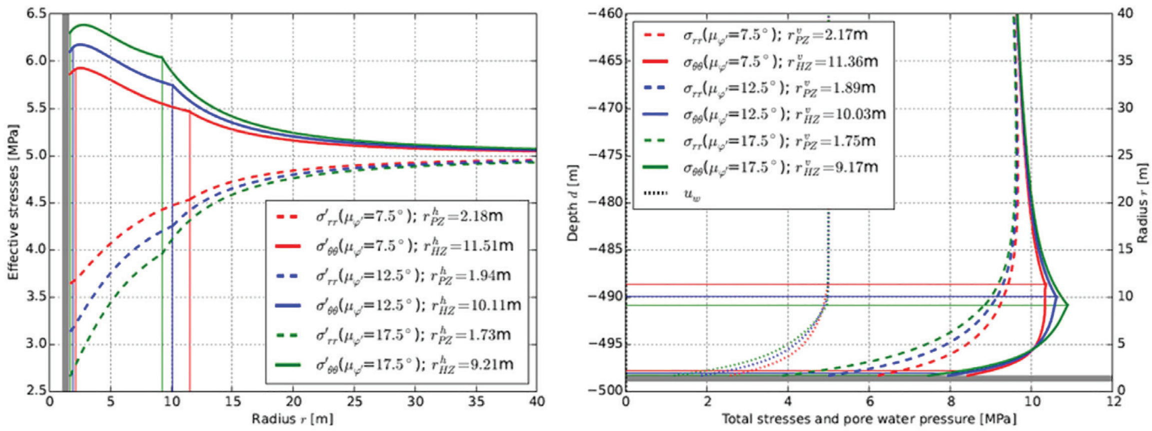
A 2D model has been adopted, as the disposal tunnels are long compared to their diameter. The corresponding model domain is shown in Figure 12a. The heat flux was applied to the tunnel surface. The side boundaries are 'no heat flow' boundaries due to symmetry, and the top and bottom boundaries are fixed. The initial temperature was 295K (~22°C). Sample results are presented in Figure 12b as a contour plot of temperature and quantitatively in Figure 13. It can be seen in Figure 13 that the predicted maximum temperature is ~335K (~62°C) at approximately 30 years, in the Boom Clay closest to the tunnel. For the following 30 years the temperature seems to remain approximately the same and decreases over time. Sensitivity analyses have been presented in Arnold et al. (2015) to account for uncertainties in the material properties. In none of the cases considered were the temperatures close to thermal limits that have been suggested, e.g. 100°C or 85°C.

5. Conclusions

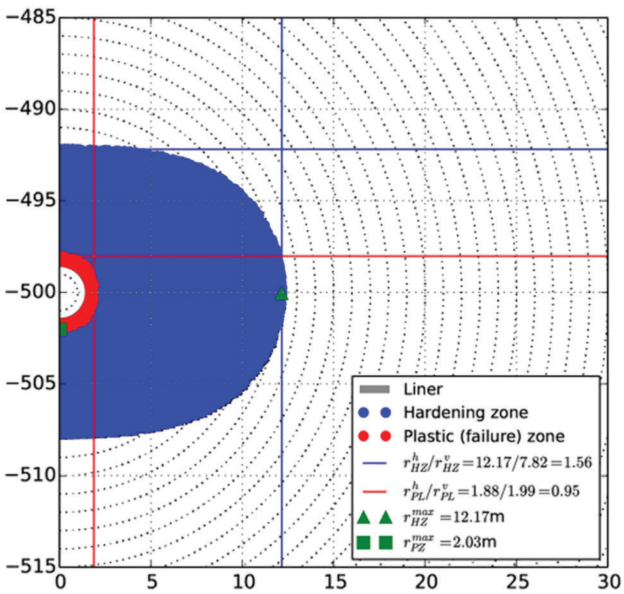
An investigation into the feasibility of the current OPERA repository reference design has been undertaken for individual tunnel galleries at realistic disposal depths, with respect to the Boom Clay geomechanical behaviour, during the excavation, and during the pre-operational and early post-closure phases. The full report is presented in Arnold et al. (2015).

The location for the repository has not yet been decided and, as such, the design contains many uncertainties. The impact of these uncertainties are important to the feasibility of the repository construction, with respect to both stability and consequential financial performance. An approach has been developed that uses probabilistic methods to quantify uncertainties, and utilises PLAXIS to assess the geomechanical repository behaviour during and after construction. In addition, the new Thermal module has been utilised to provide an initial assessment of the temperature changes in the Boom Clay.

The Hardening Soil model was chosen as the appropriate soil model, since many of the non-linear features of the Boom Clay can be simulated. Strain softening, however, could not be simulated, as this material model does not include such behaviour. This study suggests that the tunnel construction would remain stable, and stability would not be affected by an



(a)



(b)

Figure 10: Undrained response: (a) Radial and tangential stresses with a change in friction angle, (b) Gaussian integration points showing the extent of the Plastic Zone (PZ) and Hardening Zone (HZ) for the mean property values and an earth pressure at rest $K_0 = 0.9$

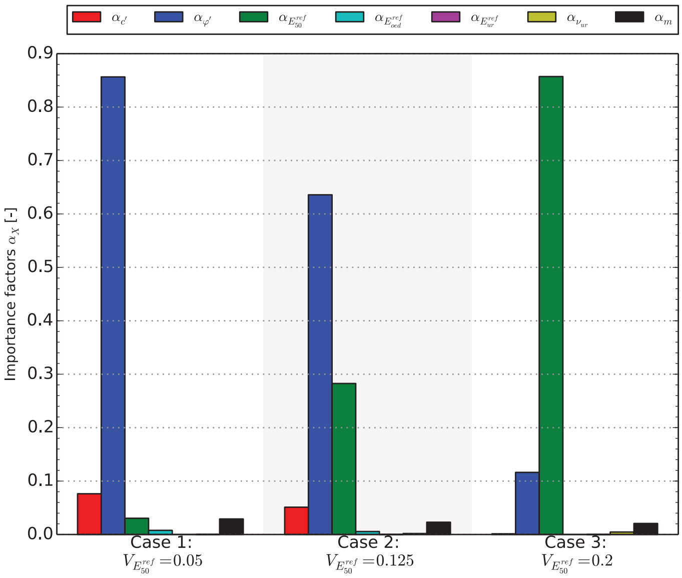


Figure 11: Importance factors α for the three coefficients of variation of E_{50}^{ref}

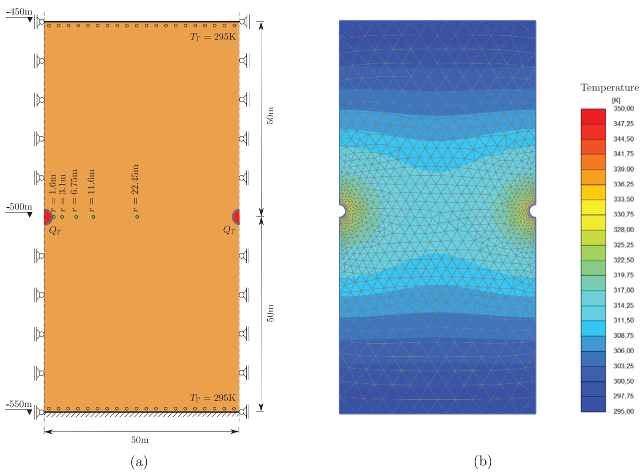


Figure 12: Two-dimensional thermal analysis: (a) Model domain with boundary conditions, (b) Contour plot of the temperature distribution from Scenario Mid at the peak temperature

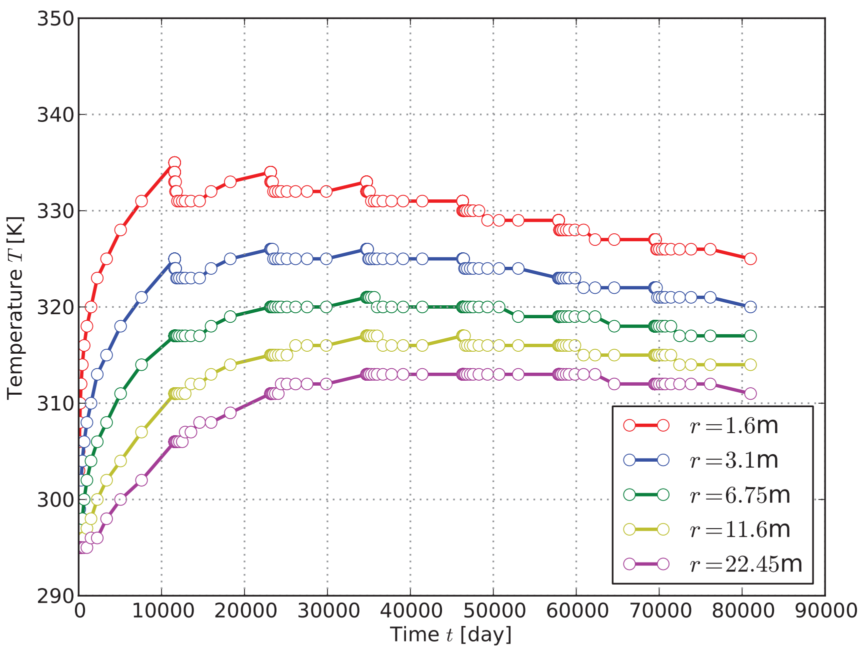


Figure 13: Thermal results in time at points 1.6 m, 3.1 m, 6.75 m, 11.6 m and 22.45 m along a horizontal line from the centre of the tunnel

extension of the plastic zone to adjacent tunnels, or via radial stresses on the tunnel lining. In addition, a thermal analysis indicates that temperatures would be unlikely to reach values that would be in excess of limits chosen. However, there was only a limited amount of experimental data at appropriate depths available. Therefore an investigation into the changes in material variation was undertaken. This approach can be utilised further when additional information becomes available and uncertainties can be reduced.

6. Acknowledgements

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