Abaqus/Standard Simulation of Coupled Multi-physics Processes at an Underground Nuclear Waste Disposal Site

Abaqus Technology Brief

Summary

The integrity of a nuclear waste burial site must be maintained for several millennia. The physical processes taking place at an underground disposal facility include heat generation from residual radioactivity, groundwater seepage, heat transfer, and material swelling. These processes induce stress in the waste containment structure and must be understood in order to develop safe long-term disposal schemes. In this Technology Brief we show how the coupled multi-physics simulation capabilities of Abaqus/Standard can be used to analyze design options for nuclear waste burial.

Background

Spent nuclear fuel remains radioactive for centuries and underground burial is one of the most promising disposal methods. Different approaches for waste burial are being researched [1] and one of the main goals of any design is the prevention of leakage. The storage site location thus needs to be geologically stable and the waste needs to be encased in a material that can minimize any possible ground water contamination. Bentonite and similar clays are useful in this capacity, as they have low permeability and expand when their water content increases from an unsaturated state. This property helps maintain a good seal even when these materials become exposed to ground water.

A schematic diagram of a representative design for waste burial is shown in Figure 1. The spent nuclear fuel is placed in a canister, which is then encased in clay. This assembly is placed in an excavation in rock and is then sealed by a plug. A suitable depth in the surrounding rock is chosen based on local geological conditions.

Burial designs can be comparatively assessed by analyzing the likely outcomes of potential failure modes. The fully coupled temperature-displacement-pore pressure analysis capability in Abaqus/Standard can be used to perform such simulations.

Analysis Approach

The model under consideration is shown in Figure 1. The burial is at a deep location in the bedrock. The clay and canister are placed in a cylindrical hole which is covered by a plug of concrete, rock, or similar material. The open space above the hole represents the access tunnel. The finite element mesh is shown in Figure 2. An axisymmetric model is used for the present analyses, but a full three dimensional model can be used when more detailed analyses are required.

The burial hole diameter is 1.4 m with a depth of 7 m from the base of the tunnel. The canister is cylindrical with a radius of 0.35 m and a length of 3 m. The plug is 1 m in height and the remaining region of the hole is occupied by clay.

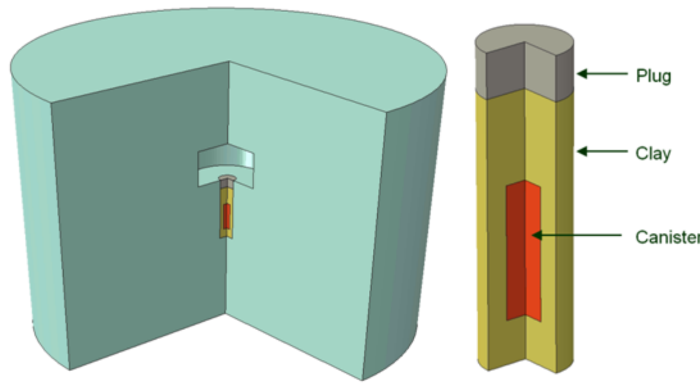

Figure 1: Representative design for underground nuclear waste disposal

Key Abaqus/Standard Features and Benefits

- Fully coupled temperature, displacement, and pore fluid flow analysis method for modeling the coupled interaction between heat transfer, pore fluid diffusion and stress
- Moisture swelling for modeling expansive materials
- Robust multi-physics contact interactions

The canister, rock, and the plug are modeled as linear elastic. The clay is assumed inelastic with a negligible friction angle and is therefore modeled using Mises plasticity. All four components are thermally conductive. Additionally, the clay and the plug permit pore-fluid flow. A sorption relationship that defines saturation vs. capillary pressure is specified for the clay and the plug. The expansion in the clay that results from water ingress is modeled using the moisture swelling capability. Frictional contact interactions are defined between all components and a tie constraint is used between the clay and the plug.

Analysis Procedure

The fully coupled temperature-displacement-pore fluid flow capability in Abaqus/Standard is used for the analyses. The model is restrained from movement normal to the outer boundaries. The clay and the plug are assumed to be partially saturated at the beginning of the analysis, with a saturation value of 0.3 at the top of the plug. The ground water level is assumed to be 3 m below the bottom of the hole in which the assembly is placed. The clay and the plug are considered to have a void ratio of 0.5 at the beginning of the analysis. The initial temperature is specified to be 30 degrees C in all regions of the model.

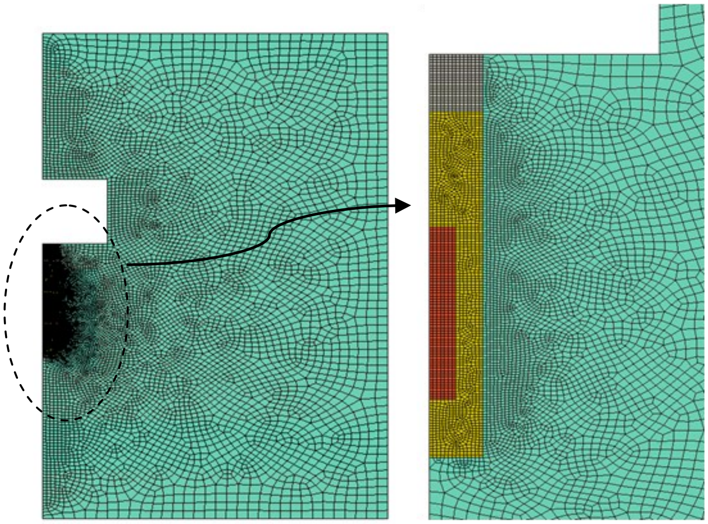

Figure 2: Finite element mesh. The complete model is shown on the left and an enlarged view near the canister is shown on the right.

The models do not include the interior details of the canister. The increase in canister temperature that arises from radioactivity is specified by temperature boundary conditions; the time variation is shown in Figure 3. Note that the temperature decreases slowly over several millennia after a relatively quick rise to 95° C.

Mixed boundary conditions, wherein the heat flux is a function of temperature, are defined on the top surface of the plug and over all boundary surfaces of the rock. This allows for the generated heat to dissipate away from the burial site.

Two cases are analyzed. Case 1 is the response due to temperature variation with no water ingress; i.e., no change to the ground water level. Case 2 then includes the effects of water ingress at the clay-rock interface. Both analyses are run for a period of 10,000 years.

For Case 1 the pore pressure at the top of the plug is restrained to its initial value of -100,000 Pa for the full analysis time. For Case 2 the water ingress is assumed to start at year 100 and continue to year 1000. During this time the height of the ground water level rises by 10 m. It increases at a constant rate starting from 3 m below the bottom of the hole at 100 years, reaching the top surface of the plug at 1000 years and then remaining constant. For both cases the pore pressure boundary conditions are specified using the DISP user subroutine.

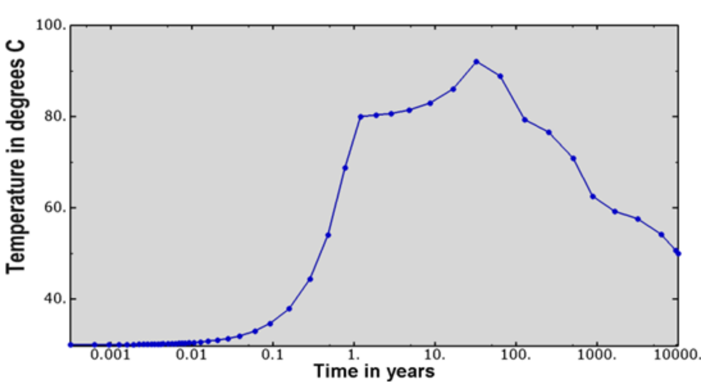

Figure 3: Prescribed canister temperature on a logarithmic scale

Results and Discussion

The Case 1 temperature distribution 32.5 years after waste burial is shown in Figure 4. The temperature in the canister reaches about 92 degrees C at that time, and a significant rise in temperature is observed to occur in the surrounding clay and rock. The contact pressure on the rock is shown in Figure 5 at time 4 years 10 months.

In the Case 2 model, the clay expands as it absorbs water and the confinement of the surrounding rock can lead to high stresses. These stresses can compromise the integrity of the design and need to be accurately estimated. Figure 6 shows the pore pressure in the clay as water ingress takes place and Figure 7 shows the associated changes in saturation.

Figure 8 shows the Mises stress in the Case 2 model at an intermediate stage of water ingress. High values of Mises stress are seen to occur at the interface between the fully saturated and partially saturated regions. The clay region that gets newly saturated expands due to moisture absorption and the region that has not yet reached a saturated state occupies a relatively lesser volume. This mismatch leads to the high Mises stresses in that region. The resulting stresses can then remain until the end of the analysis.

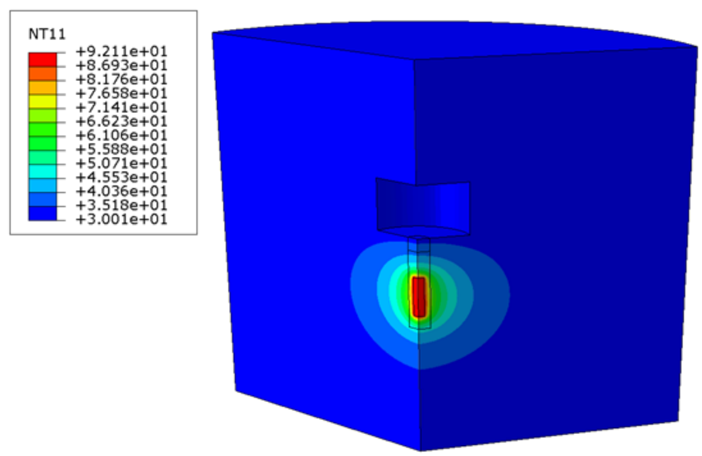

Figure 4: Temperature distribution in the Case 1 model at 32.5 years

Conclusion

In this Technology Brief we have shown that the contact and fully coupled temperature-displacement-pore fluid flow analysis capability in Abaqus/Standard allows for the simulation of long-term behavior of nuclear waste repositories.

Only a single model configuration, with one-long term analysis case and one failure mode case, have been presented. Further detailed analyses could include complete three-dimensional geometry, plasticity models specific to the clay barrier, inclusion of canister details, fluid permeation in the rock, and creep behavior.

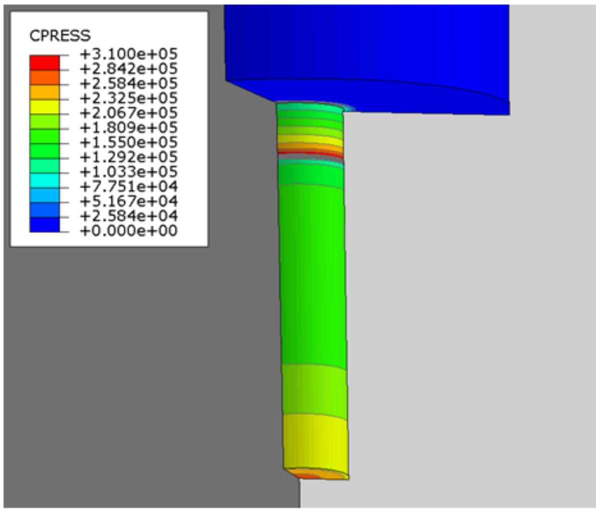

Figure 5: Contact pressure on rock hole faces, case 1, at 4 years 10 months

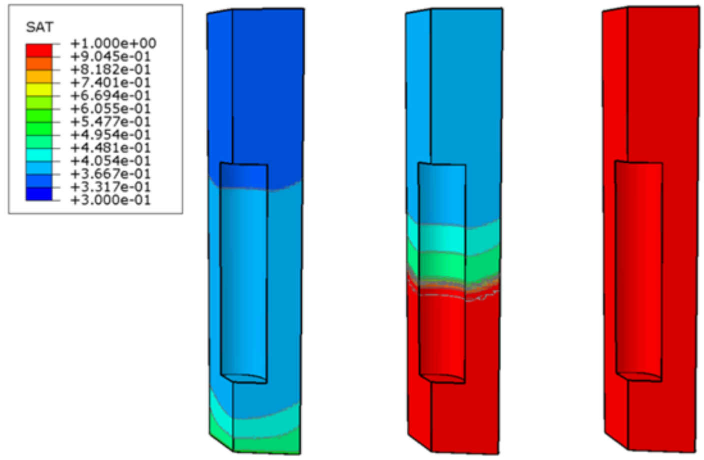

Figure 7: Saturation in the clay, case 2, at the beginning of water ingress (left), at an intermediate stage (middle), and at the end (right)

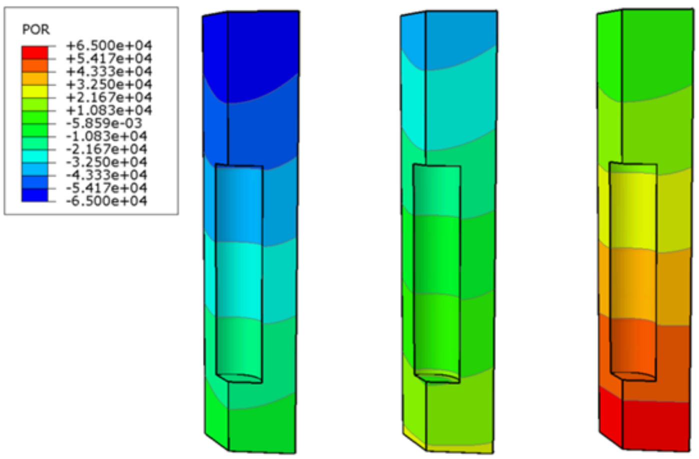

Figure 6: Pore pressure values in the clay, case 2, at the beginning of water ingress (left), at an intermediate stage (middle), and at the end (right)

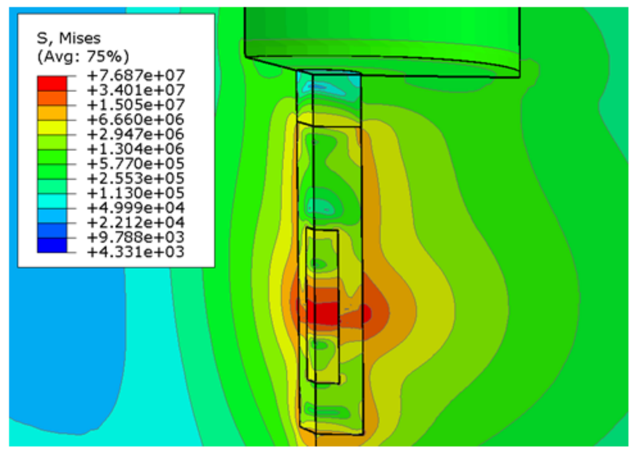

Figure 8: Mises stress, case 2, at an intermediate stage of water ingress

References

1. *THM Modelling of Buffer, Backfill and Other System Components - Critical Processes and Scenarios*, Åkesson, M., Kristensson, O., Börgesson, L., Dueck, A. and Hernelind, J.; Technical Report TR-10-11, SKB, Sweden, March 2010.

SIMULIA References

For additional information on the Abaqus capabilities referred to in this document please see the following Abaqus 6.13 Analysis User's Guide references:

- 'Coupled pore fluid diffusion and stress analysis,' Section 6.8.1

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