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Understanding the behavior of intersections excavated at the URL of Andra: a feedback concerning three intersection experiments

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Abstract

For more than 20 years, Andra, the French nuclear waste management agency, has built and operated an Underground Research Laboratory (URL) in Bure, in the Eastern part of France. The URL allowed the study of the behavior of underground structures in situ in the Callovo-Oxfordian (COx) claystone at a depth of 500 m in prevision for Cigéo, the French project for High-Level Waste (HLW) and Intermediate-Level Waste Long-Live (IL-LLW) Deep Geological Repository.

A step-by-step approach is being implemented at the Andra's URL concerning a dedicated research program for intersections. It aims to optimize their design regarding their shape, diameters, excavation sequences as well as the final lining design. The approach is both technological and scientific, allowing to validate the robustness of the current Cigéo intersections concept, and consolidating its future design specifications.

The paper presents the construction and behaviour of three different intersections. Two of them are T-shaped and one is X-shaped. The T-shaped crossings were both excavated first along the direction parallel to the minor horizontal principal stress and then along the direction of the major horizontal principal stress. For the X-shaped intersection, the order is the opposite. The intersections were always created by first excavating an initial drift and then digging the next drifts from this existing one. The hydro mechanical behavior of the rock is monitored before, during and after excavation. Boreholes were used to monitor deformation and water pressure, taking into consideration the "lessons learned" from previous drifts and intersections. A focus is done on the induced fractures zone around intersections detected by a network of cores and their evolution as the different branches are excavated. Finally, we present results from different numerical simulations to showcase the main findings of the models and the evolution of intersections in the longer term.

Keywords

Nuclear waste storage, intersections, geomechanics, research program

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1 Introduction

The safe storage of nuclear waste is a problem of the upmost importance to guarantee the safety of the environment and of future populations. Andra, the French nuclear waste management agency is in charge of designing and constructing Cigéo, the French project for High-Level Waste (HLW) and Intermediate-Level Waste Long-Live (IL-LLW) Deep Geological Repository. For that purpose, it has built and operated an Underground Research Laboratory (URL) since 2000 in Bure located in the middle of the Callovo-Oxfordian (COx) claystone layer at 500 m depth (Armand et al., 2013, 2014, 2016; Conil et al., 2018; Delay et al., 2014; Guayacán-Carrillo et al., 2016; Vu et al., 2023; Wileveau et al., 2007; Yven et al., 2007; Zhang et al., 2019).

One of the key elements of the future repository are the numerous intersections that will connect the drifts to each other. In order to optimize the design of the intersections of Cigéo a series of experiments are being carried out at the URL to better characterize their geomechanical behaviour. In this paper we present the ongoing efforts that have been initiated on three different intersections excavated since 2021 to determine the best shape, diameters, excavation sequences as well as the final lining design. Figure 1 shows a view of the URL and of the location of these intersections. The GT1-GER is an "X" shaped intersection meaning that is has four perpendicular branches. It was excavated first along the direction parallel to the major horizontal principal stress and then along the direction of the minor horizontal principal stress The GVA3-GRE and GVA3-GMA intersections on the other hand are "T" shaped with only three perpendicular branches. They were excavated first along the direction parallel to the minor horizontal principal stress. The intersections were always created by first excavating an initial drift and then digging the next branches from the existing one.

In this article, we start by presenting the geometries, excavation steps and supports used at the three junctions of interest. We then show the instrumentation that has been installed at the GT1-GER intersection to monitor the hydro mechanical behavior of the rock before, during and after its excavation. Data from an 11 m long horizontal extensometer is presented and analyzed to give a sample of the data that is recorded thanks to this investigation. An analysis of the geological data gathered around the GVA3-GMA is also given based on cores from a network of wellbores and a first model of the induced fractured zone is presented that shows its evolution as the third branch is excavated. Finally, we present different numerical models that have been developed to reproduce the data collected at the URL and used to predict the evolution of intersections in the longer term.

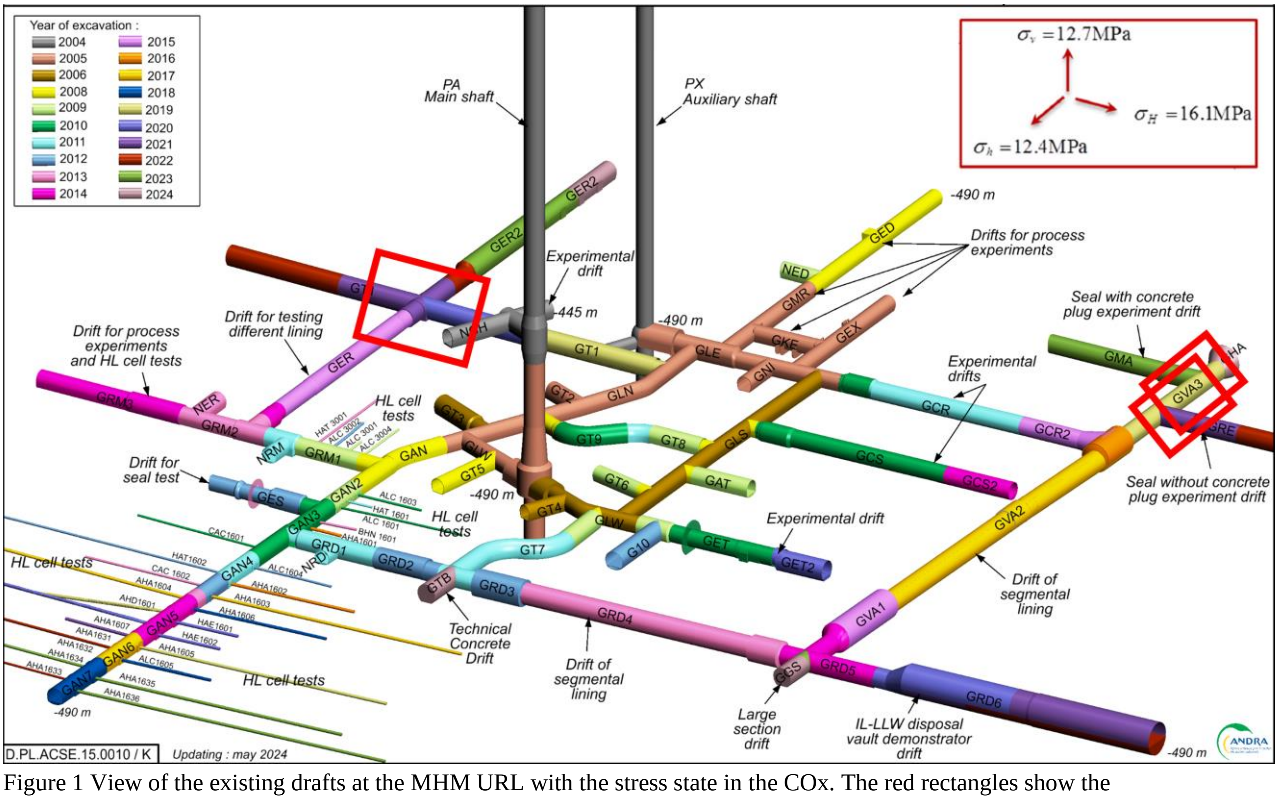

Figure 1 View of the existing drafts at the MHM URL with the stress state in the COx. The red rectangles show the intersections of interest for this study (GT1-GER top left, GVA3-GRE and GVA3-GMA are both on the right of the figure).

2 Intersections at the URL

2.1 Designs of "T" and "X" shaped intersections

All three intersections were excavated full face in one go using a pneumatic hammering machine combined with rock bolts, shotcrete and sliding arches every one meter as support in these 5.7 m diameter drifts. On the sides of the galleries, the bolts used were metallic while the ones at the face were fiberglass to allow an easier over-excavation. At the intersections, sliding frames were used (Figure 2) that have the shape of crossing cylinders of the same diameter. They are made of rigid H-shaped steel beams that can slide over one another at specific locations. The beams are clamped together to provide static friction so that a particular level of stress has to be reached for the beams to slide over each other.

The main difference between the "X" and the two "T" intersections are the directions in which they were first dug and the time the initial drift was left idle before a branch was added. In the case of the four branches intersection GT1-GER, the GT1 drift was excavated over its full length from October 1st, 2020, to March 18th, 2021. The symmetric steel frame was installed at the intersection from March 25th, 2021, to April 28th, 2021. The excavation of the two 6 m long GER branches were dug from the GT1 in quick succession from August 30th, 2021, to September 17th, 2021, for the first one and from September 23rd to October 22nd, 2021, for the second one. There was thus almost six months between the end of excavation of GT1 and the creation of the GER branches.

For the "T" shaped intersections, they were both excavated from the GVA3 drift. GVA3 was dug over its full length from May 14th, 2019, to November 14th, 2019. The steel frames were installed afterwards between November 19th and December 20th, 2019. The first 10 m of the GRE drift were dug from June 2021 to August 2021 while GMA was excavated from February 2023 to mid-March 2023. This means that GRE was started one and half years after the end of GVA3 while there was more than three years for GMA. Most of the convergences induced by the creation of a new gallery occur in the first three months following its excavation thus we assume that even though the idle times are different for the three intersections, they are all still comparable.

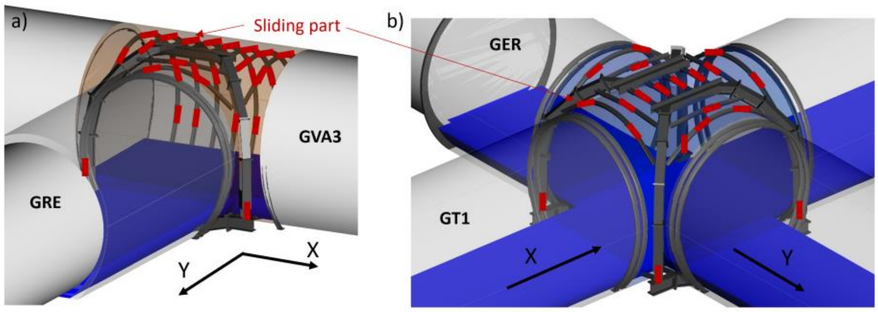

Figure 2 3D views of the sliding steel frames put in place in a) T-shaped intersections and b) X-shaped ones. The red rectangles show the places where the frames can slide. The x and y axis show the directions in which the drifts were dug, with the x being excavated before the y.

2.2 Experimental setups

Of the three junctions studied, the GT1-GER is the most densely instrumented (Cornet et al., 2021). Figure 3 shows all the sensors all the wellbores that have been drilled to gather data on the behaviour of the intersection. The goal was to determine the shape and extent of the induced fracture networks around the intersection but also to collect data on the hydro-mechanical behavior of the COx claystone as well as the support structures at and in the vicinity of the junction.

Before the digging even started, wellbores were created around the future intersections and five multi-packer completions measuring pore pressure were installed. In addition, two inclinometers, one extensometer and two reverse-head extensometers were also put in place. This allowed us to monitor the initial state of the formation and see how the rock was impacted by the creation of the intersection. After that, the GT1 drift was excavated in full and additional investigations were made during this process. In particular, the convergence of the drift was monitored in several sections, geological surveys were conducted of the unsupported front and short (3 m long) extensometers were place in the COx claystone. A full description of the instrumentation of the junction is given in Cornet et al. (2021).After the GT1 was completely dug up to PM100, the sliding steel frame was installed at the intersection and more wellbores were created. They were all cored on their entirety and these cores provide the base data to determine the shape and extent of the induced fracture networks. Some of the wellbores were instrumented with extensometers or pore pressure sensors to monitor how the rock in the very immediate vicinity of the galleries behave during the creation of the intersection. Additionally, the steel frame received vibrating wires, two optical fibers using fiber Bragg gratings and potentiometers to measure its deformation and the displacements of its sliding parts as the two extra branches are dug. The excavation of the GER from the GT1 main gallery was monitored standardly using geological surveys, convergence measurements and short extensometers. Two years after the intersection was completed, additional geological boreholes were drilled in order to characterize the fracture networks at final stage.

The other two intersections, namely GVA3-GRE and GVA3-GMA, were also monitored during their creation but to a lesser extent. For them, the focus was on characterizing their induced fracture networks which means that many geological wellbores were drilled before and after their excavation, but fewer completions were installed to record the hydro-mechanical behaviour of the junctions.

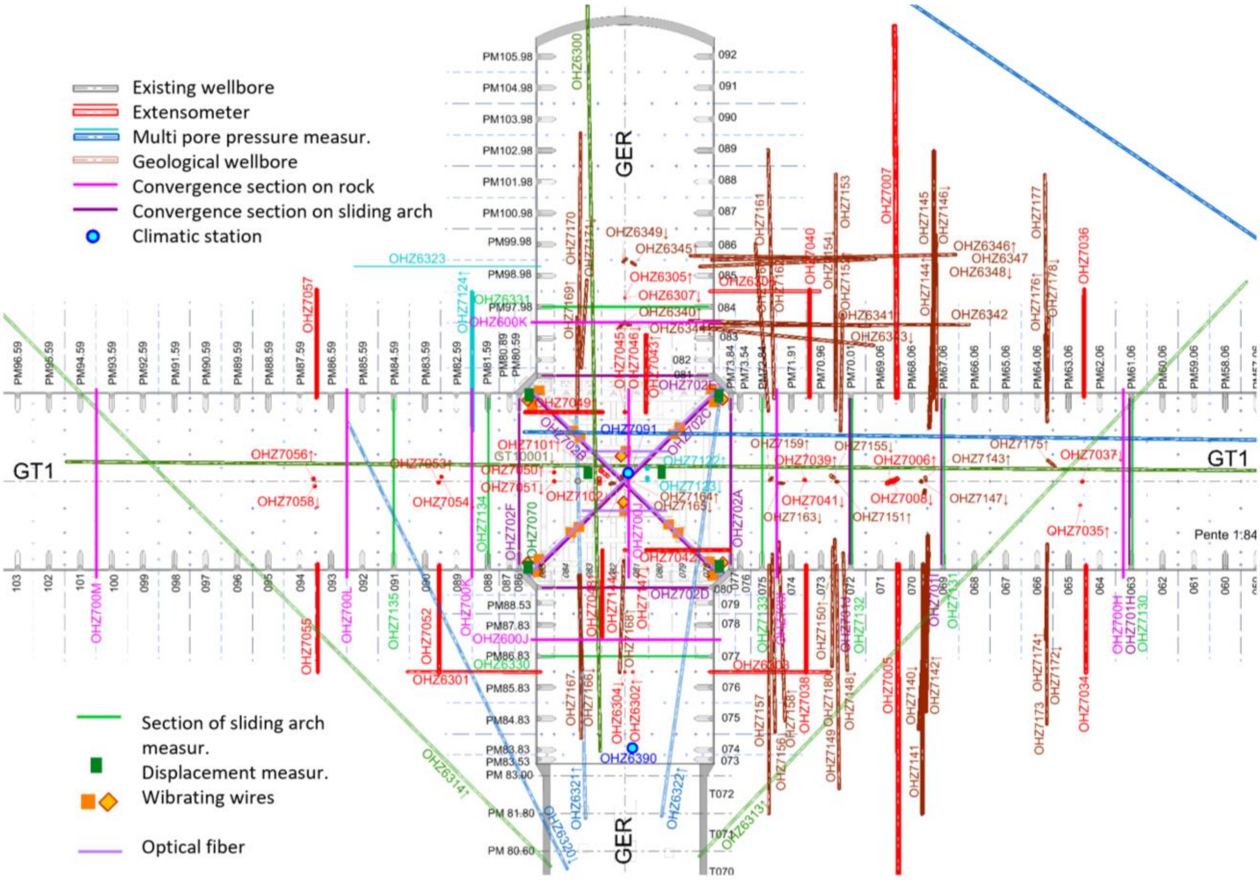

Figure 3 View from the top of all the sensors and investigations carried out at the GT1-GER intersection. All the wellbores are shown as well as the position of the sensors in the galleries.

3 Investigations results

3.1 Data recorded

To give an example of the data recorded, Figure 4 shows the deformations measured between different bases by an 11 m long horizontal extensometer starting from GT1 and running parallel to the GER drift (Figure 3). The extensometer was installed at the end of the excavation of the GT1, and the first three months show the typical response for a single gallery parallel to the major principal stress direction σ_H with the deformations being the largest for the shallowest bases. Once the two branches of the GER are excavated, however, the largest deformations are recorded between 3 and 4 m depth. This is unusual at the URL for this kind of gallery and shows that the creation of the intersection has induced fractures in a pattern that is different from the case where only one gallery would be present. This observation was cross-checked with data gathered from the multi pore pressure measurement completion running parallel to the extensometer. Permeability tests were carried in the same depth range and shows an increase in permeability between 3 and 4 m depth confirming a denser fracture network at this depth. The extension of the GER drift from November 2022 is also clearly seen on the data and induces more deformations between 3-4 m and 4-5 m depth than the 0-2 m interval that was initially the most fractured one. This illustrates the necessity to carry out experiments in real conditions to properly define the amplitudes of the phenomena like gallery convergence that will be very important when dimensioning the support structures of the intersections in Cigéo.

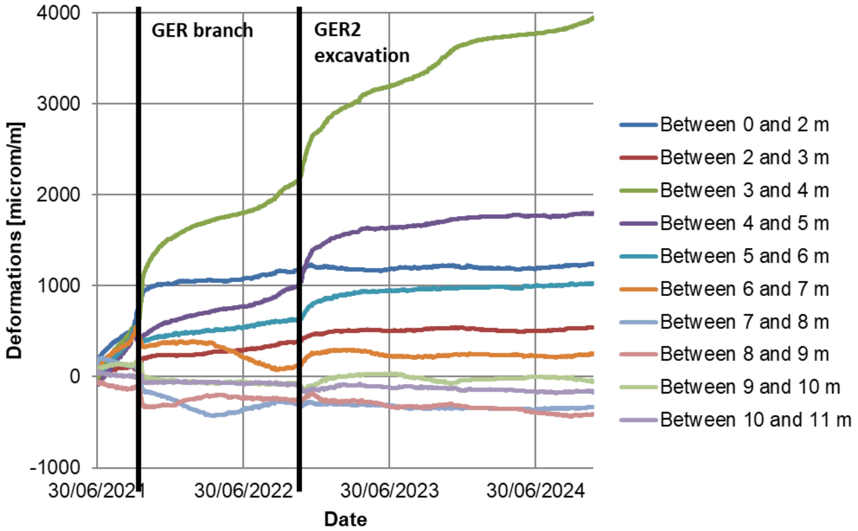

Figure 4 Deformations as a function of time recorded by the different bases of the OHZ7007 11 m long horizontal extensometer installed in GT1 to monitor the COx in the vicinity of the GER drift (see Figure 3). The vertical black lines mark major excavation events.

3.2 Induced fracture networks

One of the main objectives of the investigation of intersections is to determine the fracture network induced by their excavations. To that end, both geological surveys of the excavation fronts and cores from wellbores have been collected and analysed. Figure 5 shows all the geological data gathered around the "T" shaped GVA3-GMA junction. Data has been gathered both before the GMA drift was created and after. The first analysis of the joint survey and core data tends to show that the fractures around the intersection are predominantly dominated by the fractures created by the excavation of the first gallery of the junction, the GVA3 gallery which is parallel to the minor principal stress. The digging of the GMA creates a zone in the immediate vicinity of the GMA close to the intersection where there is a complex interaction between the fracture networks of the GVA3 and the GMA. At a distance of one diameter from the intersection, the facture network in the GMA is the one expected for a gallery parallel to the major principal stress showing that the impact of the intersection is very limited in space (less than one diameter of influence on the side where the GMA was excavated, and no influence was visible on the other side).

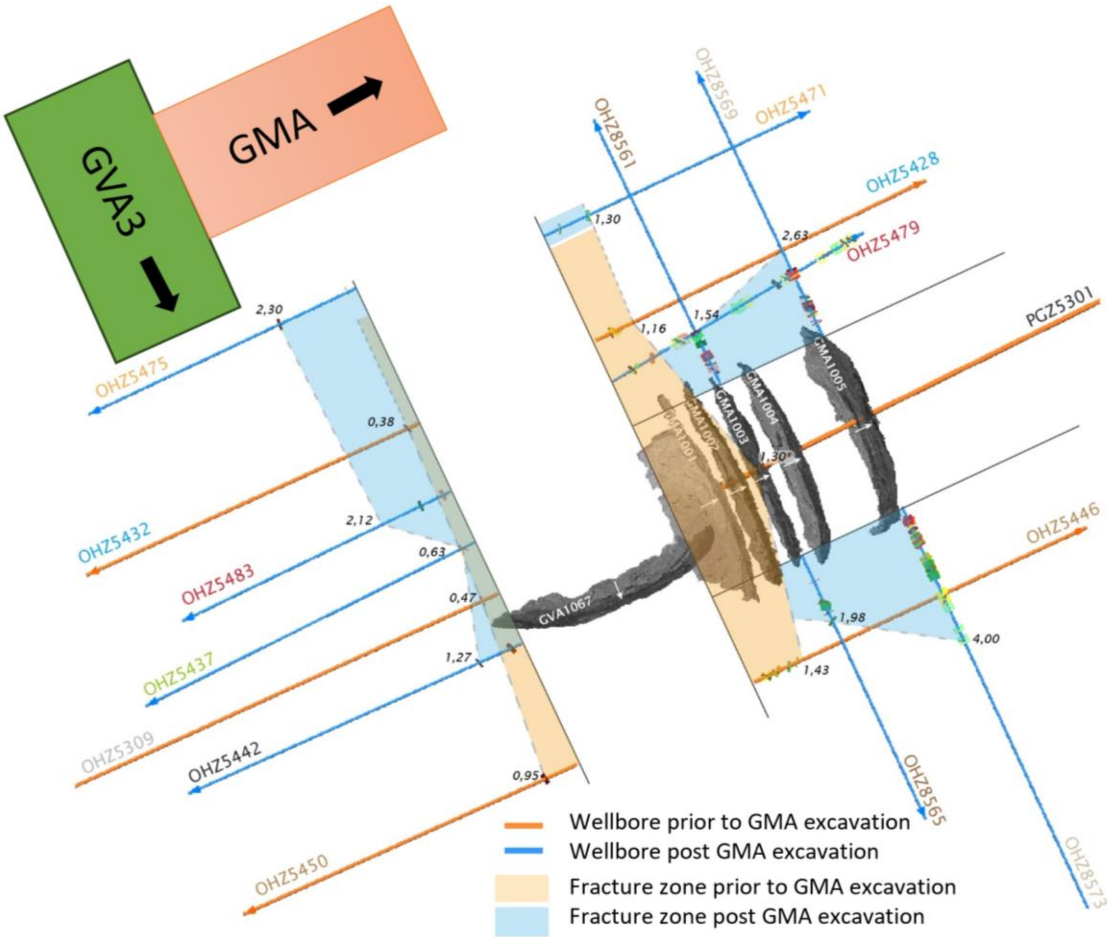

Figure 5 Top view of the geological data gathered at the GVA3-GMA intersection. Wellbores are shown in orange and blue depending on whether they were drilled prior or after the excavation of the GMA gallery. The corresponding fractured zones are also shown in light orange and blue. Fractures are represented as winglets in the boreholes. 3D scans of the excavation front are also shown in grey. The two drifts are represented schematically with their direction of excavation in the top left.

4 Numerical modelling

The last step of the research program for intersections is to carry numerical modelling to first reproduce the results observed in the URL, second to extrapolate the results in the long term or/and to other geometries and excavation steps and third to dimension the support of the Cigéo junctions.

Currently, a lot of effort is put in modeling the mechanical and hydro-mechanical behavior of existing intersections of the URL. The data recorded (example: Figure 4) is used to benchmark the numerical codes. An anisotropic Drucker-Prager elastoplastic law with shear strength hardening combined with the fabric tensor method has been used lately to model in three dimensions the effect of excavation on the plastic zone of the claystone (Figure 6) (Rapanakis et al., 2024). The model shows that the volume of influence of the intersections on the galleries does not exceed two of their diameters. It was however unable to reproduce the observed over fractured interval between 3 m and 4 m depth. In another study, two different approaches have been considered to model in 3D the mechanical behavior of intersections during excavation and then extrapolated to 200 years. One approach was explicitly defining the fractured zone around the intersections and using an isotropic Mohr-Coulomb model for plasticity coupled with a Norton law for viscosity with different plastic parameters inside and outside the fractured zone. The other approach was phenomenological and did not predefine the fractured zone using a Hoek and Brown isotropic elastoplastic law with a Lemaitre type viscosity. The convergences at 200 years for the first approach were computed to be twice the ones of the second approach. The stress in the various parts of the steel frames were also found to be larger in the first approach compared with the second one. Using different models and approaches allows to define an envelope of likely outcomes which are very important to dimension the future intersections of Cigéo.

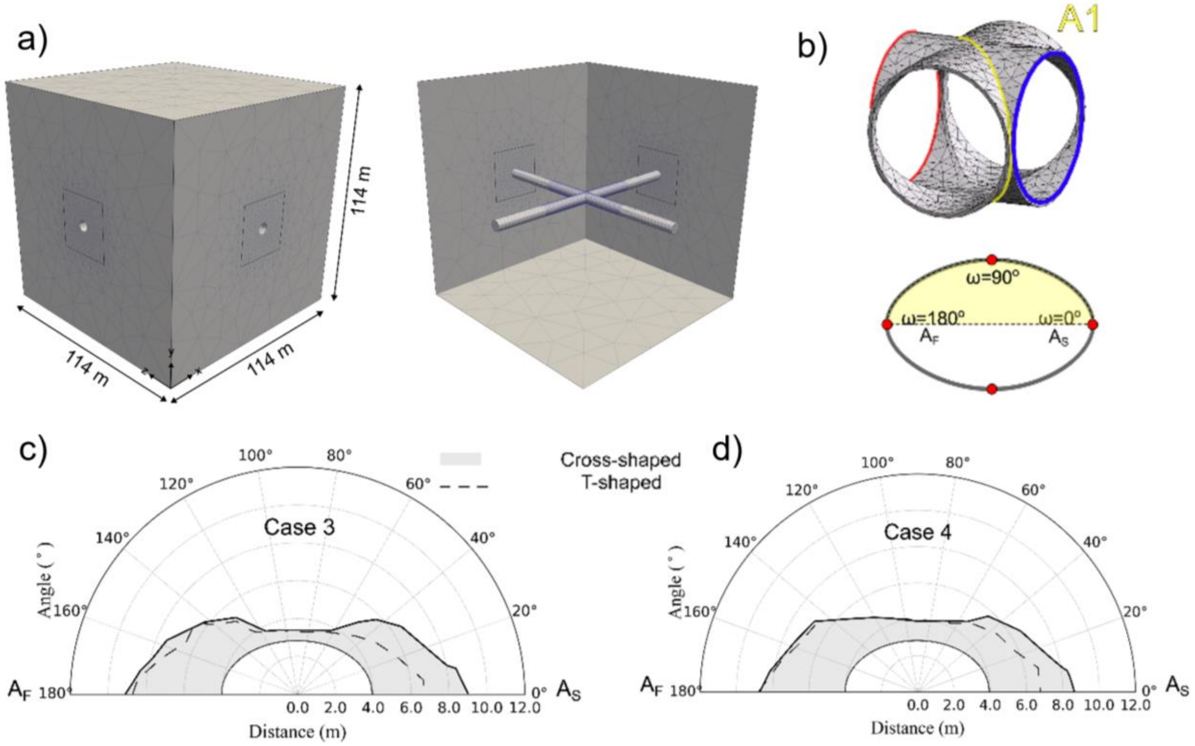

Figure 6 3D mechanical numerical model for intersections using an anisotropic Drucker-Prager elastoplastic law. Modified from (Rapanakis et al., 2024). a) View of the mesh for the model. b) Zoom on the mesh at the junction on which a yellow cross section A1 is highlighted. c) and d) plastic zones at the elliptic section A1 in the case of “T” and “X” or cross shaped intersections depending on whether the first gallery was excavated along the major c) or minor d) principal stress direction.

5 Conclusion

Andra has submitted a demand to start constructing Cigéo, the French project for High-Level Waste (HLW) and Intermediate-Level Waste Long-Live (IL-LLW) Deep Geological Repository. Cigéo will have many intersections, and it is important to properly caliber the support needed for them to optimize the global cost of the project.

In this light, a research program is being carried out at the URL to better characterize the behavior of intersections located in the COx claystone at 500 m depth. Both “T” and “X” shaped junctions are considered with the initial gallery being parallel either to the major principal stress direction or to the minor one. The research program consists first of creating several intersections and of monitoring them. Three junctions are particularly studied with two of them being “T” shaped (GVA3-GRE and GVA3-GMA) and the other one being “X” shaped (GT1-GER). In this article, we present the instrumentation installed to monitor GT1-GER as it is the most densely surveyed intersection. The instrumentation focuses on recording parameters related either to hydrological processes (like pore pressure or permeability) or to mechanical ones (convergences, deformations, displacements). The data recorded by an extensometer is presented and its results are analyzed in correlation with the excavation history of the drifts. Another major goal of the research program is to determine the fracture zones induced by the excavation of the intersection. A first analysis of the geological data for the GVA3-GMA junction is presented which shows that that the fracture network is predominantly influenced by the one created during the excavation of the first gallery. Finally, the different numerical 3D models that have been investigated to reproduce the mechanical behavior of the intersections have been presented. They are first benchmarked on the available data before being extrapolated either on longer times or to different geometries.

In the near future, the careful analysis of the data recorded at the URL on the junctions will continue and more efforts will be put to develop better and more representative numerical models.

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