Compressible Arch Segments for the Cigéo Access Ramps, Drifts and Vaults - A Field Test- 17011

Jean-Michel Bosgiraud*, Gilles Armand*, Jean Simon**
*ANDRA, 1 rue Jean-Monnet, 92298 Châtenay-Malabry Cedex, France
** CMC, 2401 avenue d'Uriage, 38410 Vaulnaveys-le-Haut, France
jean-michel.bosgiraud@andra.fr

ABSTRACT

Andra is currently implementing the detailed engineering phase of the step-wise design development of Cigéo (the French HLW and IL-LLW Deep Geological Repository). Various technical issues are at stake, including the requirements linked to "Reversibility / Retrievability", at different stages of the repository life cycle (from its construction start-up to its final closure and monitoring). These reversibility requirements have a significant impact on the way Cigéo is designed, will be progressively developed, operated, later closed and monitored. On a shorter term, one must demonstrate that the waste container retrieval operations are technically safe and feasible. In that sense, the structural dimensioning of the ramps and mains, as well as that of the IL-LLW disposal vaults, is critical, since the concrete liner supporting the rock walls must last over a period of some 100 to 150 years (lapse of time during which retrieval operations are likely to take place).

The present paper starts with a description of the geomechanical conditions prevailing in the Callovo-Oxfordian (COX) claystone formation (aka the argillites). The structural dimensioning of the IL-LLW disposal vault liner, as calculated at the end of the basic engineering phase is indicated. The thickness values obtained so far have led to considering an alternative design in which a compressible material is positioned between the concrete liner intrados and the rock walls: in such situation, the "creeping effect" of the rock is mitigated, for a time, by the compressible material (nearly a perfect elastoplastic material), hence reducing the stress level exerted inside the concrete liner. This situation enables to significantly reduce the liner thickness and provides potentially significant saving in the construction of the works concerned (preliminary sensitivity results are given).

The following part of the paper is then focused on a practical case story: a technological demonstration (still ongoing) of a tunnel boring experiment, implemented underground (in a dedicated drift of the Meuse Haute Marne URL infrastructures, at scale 1:2 of the Cigéo drifts/vaults). In this excavation and construction experiment, the tunnel boring machine (TBM) lays (via an erector) "classical" concrete arch segments (forming a ring) in a first portion of the drift and "compressible" ones (the compressible material is positioned on their extrados) in a second portion of the drift. The technical demonstration objective is two-fold: the capacity to lay compressible arch segments with a TBM is checked, their structural behavior (with time) is compared with that of "classical" ones.

The way the compressible material is produced and then fixed on the arch concrete segment is also documented, c/w a description of the complementary testing campaign to be carried out on a test bench (on surface) of a concrete ring (at a scale 1:2 of Cigéo) formed of compressible arch segments.

This paper concludes with a timeline of the experiment. Should the results obtained provide some perspectives of technical and economic improvement (i.e. saving vis-à-vis the "classical" solution) a decision could be taken by Andra to incorporate this alternative solution in the "design freeze" of Cigéo underground infrastructures. The positive outcomes of this technical test campaign would also pave the way for specifying the Cigéo TBM characteristics (dimensions and handling equipment), scheduled for manufacturing order around 2020.

BACKGROUND

The French geological repository project (aka Cigéo) is located on the eastern boundary of the Paris Basin, at the fringe of the Meuse and Haute-Marne departments. Andra locally started in 2000 (with the shaft sinking operations) the construction of an underground research laboratory (called the Bure URL), in the framework of its general research program (Delay et al, 2007 (1)) aimed at proving the feasibility of a reversible deep geological disposal of radioactive waste (HLW, IL-LLW). The Bure URL drifts are used to study the Callovo-Oxfordian claystone layer (i.e. the host rock formation, aka the argillites) between 420 m and 550 m in depth.

The main objective of the first research phase (2000 to 2005) was to characterize the confining properties of the clay through in situ hydrogeological tests, chemical measurements and diffusion experiments and to demonstrate that the construction and operation of a geological repository would not introduce pathways for radionuclides migration.

The ongoing research program (started in 2006) following the "Technology Readiness Level" (TRL) scale is now more dedicated to technology improvements and demonstration issues of the different disposal underground components (drifts, seals, disposal cells and vaults), even if characterization and monitoring activities are still ongoing.

In rock mechanics, at the main level of the URL (located at 490 m), construction and evolution of disposal cells of different sizes are studied for emplacement of HLW and IL-LLW packages. A step by step approach is carried out, based on comparison of HM behavior of parallel drifts excavated/supported by different construction methods (Armand et al, 2015 (2)). These various configurations give insight of the influence of construction method on the excavation damaged zone (EDZ) extent and evolution and also on the progressive loading of the support, which are key issues to design the Cigéo disposal drifts and select the most suited excavation methods (it has an impact on the excavation time, the structural dimensioning of the drift/vault liners and on their life duration, which is not less than 100-150 years for the IL-LLW vaults, taking into account the retrievability requirements).

Figure 1 shows the drifts and shafts network at the Meuse Haute URL. Two shafts provide access to two levels of drifts at depths of 445 and 490 m. The shafts with the connecting drift at -490m (in between the two shafts) ensure also ventilation and security. At the main level of the URL the orientation of the experimental drifts has been determined according to the orientation of in situ stress field which also correspond to the major orientation of the drift in the repository. The major stress (σH) is horizontally oriented at NE150° (Wileveau et al, 2007). The vertical stress (σv) is nearly equal to the horizontal minor one (σh). The ratio $\sigma H/\sigma h$ is close to 1.3

and varies with depth and the rheological characteristics of the respective layers.

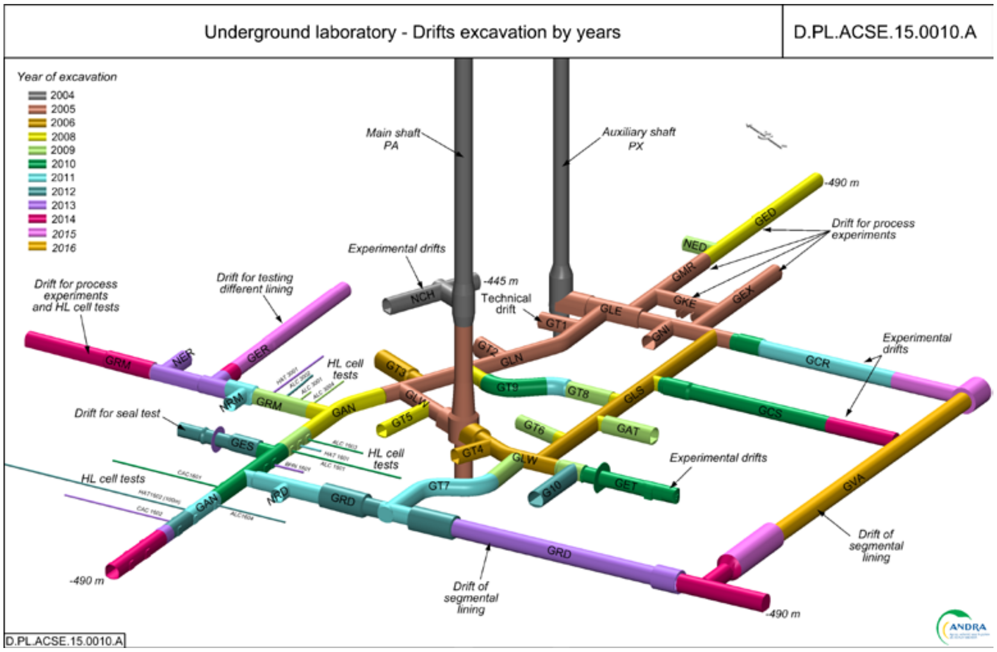

Figure 1: Bure URL drift network

Figure 2 shows a 3D architectural view of the Industrial Centre for Geological Disposal, Cigéo (to be located some 5 km from the Bure URL). Surface facilities will be split in 2 parts: one area taking care of the nuclear activities at large (receiving the primary waste packages via a rail terminal, commissioning the primary waste packages, re-packing them into disposal packages) and one area dedicated to the excavation (mining) activities (workshops, cement plant, storage, drainage basins, excavation muck “dumping area”, etc.) A ramp will be used to transport the disposal packages down to the main level of the disposal zones (at 500 m of depth). Shafts will be mainly used for all the activities related to excavation/support works, ventilation and workers transportation. The main underground disposal area will be split in two parts dedicated to the different types of waste packages. IL-LLW or HLW (Bosgiraud et al, 2010 (3)) will respectively be emplaced inside a 9 to 11 m outer diameter vault and inside a steel cased micro tunnel of 0.7 m internal diameter.

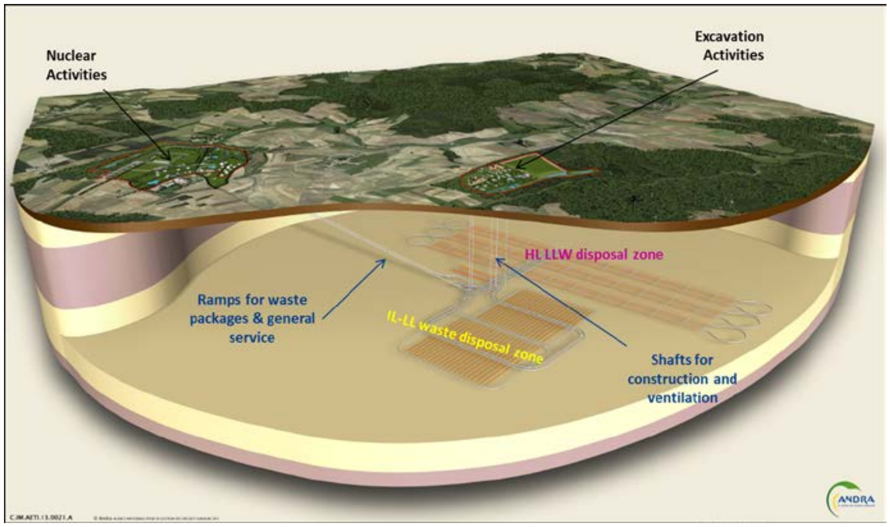

Figure 2: 3D architectural view of the Industrial Centre for Geological Disposal (Cigéo)

At time of writing, the excavation method selected for the construction of the 2 ramps (declines) and the first part of the horizontal mains in the argillites is the TBM technology, c/w the erection of concrete segments forming the support liner. It means that the TBM technology and the liner dimensioning must be compatible with the geomechanical properties of the argillites and the concrete liner life duration requirements (retrievability possible over 100-150 years).

Disposal Vault Concept for IL-LLW

Before emplacement, IL-LLW will be grouped into precast concrete cubic shape robust containers. The concrete containers will be stacked (trolley stack technique, pre-stacking technique…) in large diameter horizontal tunnels (vaults between 9 to 11 m OD). In the current concept, the vaults of IL-LLW are comparable to drifts and lined with thick concrete lining (alternatively with compressible concrete segments) to limit deformations over 150 years. Ventilation of IL-LLW repository cells has to be maintained as long as they are not closed, that is why vaults are parallel and connected to an air outtake drift. The forecast length of the disposal vault is around 500m. Figure 3 shows the IL-LLW disposal vault concept (in operation).

At the present state of design (basic engineering), based on an excavation method using a road header, with a preliminary installation of bolts and an application of a 25cm shotcrete support, followed some 10 to 12 months later by the casting of a rigid SCC liner, the total thickness of an 9m OD vault concrete wall is some 100 cm of concrete. This is a significant volume of concrete, and there is room for improvement, via innovative solutions such as the "Compressible Arch Segments" (in such a case, the use of a TBM technology for the construction of the IL-LLW disposal vaults is an open option).

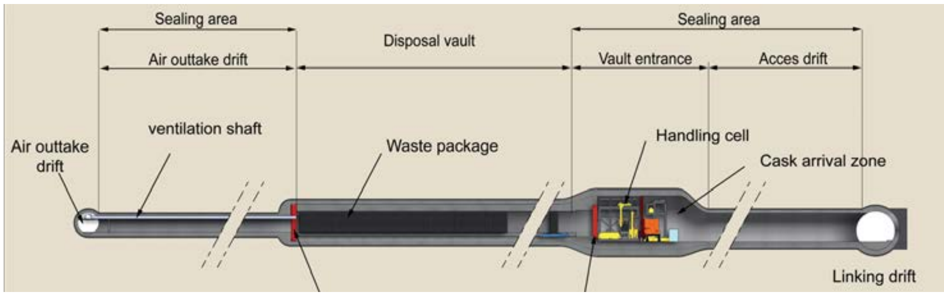

Figure 3: IL-LLW Disposal Vault concept (longitudinal section)

Contribution of the Bure URL to the Cigéo design

The understanding of drift behavior is associated with the design of the IL-LL Waste disposal vaults and access drifts (mains) in the argillites. A significant program of experiments is ongoing at the Bure URL to characterize the response of the rock to different drift construction methods (Armand et al, 2015 (4)). In situ experimental strategy for the study of drift behaviour is based on the following activities:

- Using the URL for observing real behavior of drift under different conditions (depth, size, geometry, ventilation, temperature…). Each drift excavation in the URL is a rock mechanics experiment in itself,
- Sequencing of drift construction to highlight the role of support/excavation method on the HM behavior (support loading, EDZ…) starting with "flexible" support up to rigid support,
- Using parallel drifts to compare the different behavior (Figure 1) of drifts excavated with different methods,
- Using “mine by experiments” (boreholes emplaced before the excavation) to study the HM behavior (at short and long terms).

In the Cigéo concept IL-LLW vaults are oriented as per the major horizontal stress. That is why at the beginning most of the URL drifts were also oriented along the major horizontal stress (Figure 1: drifts GET, GCS, GCR, GRD, and GRM). As of 2015, drifts GER and GVA were/are excavated respectively with a road header technique and with a TBM technology. The new data collected will be compared to those initially acquired in the GED/GAN drifts and will provide the same level of knowledge for drifts parallel to the minor horizontal stress.

The third portion of the GVA drift is the underground work in which the “Compressible Arch Segment” technology will be tested in mid-2017.

THE COMPRESSIBLE ARCH SEGMENT CONCEPT

Description of the Compressible Arch Segment

Andra and CMC (a Consulting Company) have jointly developed an original product, called VMC (US patent pending). The invention relates to the creation of tunnels and drifts, in particular to the construction elements of such tunnels/drifts. When a cavity is excavated in the ground, the equilibrium of the ground is modified and the latter exerts more or less intense thrusts which tend to close the cavity thus formed, this phenomenon being called "ground convergence". The VMC concept discloses a ground convergence damping system fitted on the extrados of concrete segments forming the tunnel/drift liner support.

Figure 4 shows a prototype of a “VMC” compressible arch segment made of a regular reinforced concrete segment (some 43cm thick), coated (at the extrados) with some 13cm of compressible material (called hereafter “shells”).

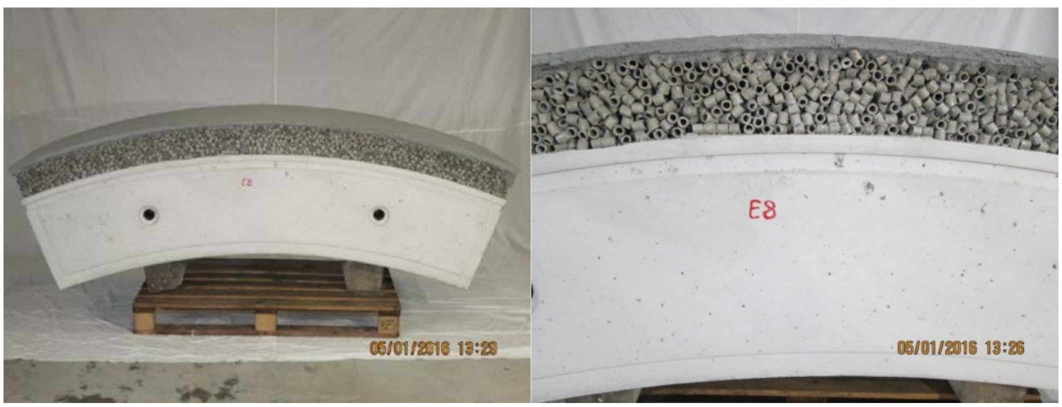

Figure 4: VMC prototype (left) and its compressible material coating (right) for GVA test drift

The shells are a ceramic material, produced from the host rock clay (argillites) excavated at the Bure URL (cf. Figure 5): this material is chemically inert, has no calorific load and is easily available. The clay based ceramic was chosen as a material more adapted that a high-density polyethylene foam, which is not stable and can disaggregate in time, resulting in a loss of its mechanical compression and deformation properties. Furthermore, such foam of synthetic material may be polluting.

Figure 5: Ceramic shells produced from argillites (i.e. from raw material excavated in the Bure URL)

The shells are agglomerated ("glued") by a cement grout to the concrete arch segment extrados, forming a layer covered by a 1 to 2 cm thick mortar to provide a protection during the handling of the arch segments (i.e. their transport and later during their erection underground by the TBM). The VMC concrete segment fabrication takes place in an ordinary concrete segment prefabrication plant; as such the VMC device is not industrially different in its use and production from a classical concrete arch segment. For the demonstration tests (scale 1:2) in lab and in the Bure URL, the drift is about 6 m of outer diameter which leads to a smaller segment consisting of 40 cm of concrete, 13 cm of shells and 2 cm of mortar cover layer. The 13 cm thick layer of shells is enough for the experiment and the URL lifetime.

Functioning Principle of the Compressible Arch Segment

As already mentioned, the main role of the compressible layer is to damp over time the convergence (creeping) effect exerted by the formation on the arch segment structure. If this damping function is effectively assured, a significant saving can be reached when dimensioning the structure. Collateral advantages are induced by the reduction of the excavation diameter: a smaller TBM is needed while the volume of excavated material is also reduced (besides, the use of a TBM saves time by reference to the traditional excavation method using a road header). A first structural pre-dimensioning of the IL-LLW vault liner composed of compressible arch segments provides the following figures: a layer 20cm of compressible material covering a 45cm thick concrete segment, i.e. a significant saving by reference to the "classical" structure (100cm).

The challenge is to make sure that the compressible material will effectively stay in the "Plastic Plateau Zone" (cf. Figure 6) during the requested life time of the structure (retrievability must be possible over some 100-150 years).The high porosity of the material conducts to an important compressibility without increase of the normal stress. It is therefore important to characterize this material as per the deformation due to rock convergence.

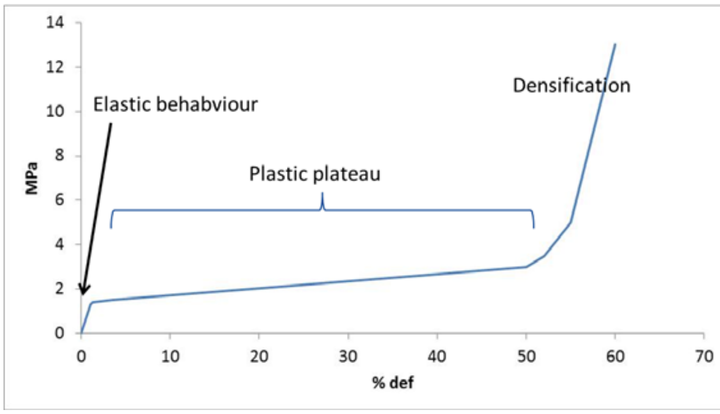

Figure 6: Conceptual Behaviour of a Compressible Material

Oedometric tests

Various geotechnical tests have been/are being carried out to optimize the granular size of the shells (ratio length-thickness-diameter), and the quantity of cement slurry needed to agglomerate them, while staying compatible with the practical arch segment fabrication and handling constraints.

Figure 7 shows a first series of geotechnical tests on the shells, while Figure 8 illustrates a practical test of arch segment handling (on an arch segment prototype), where the "robustness" has been checked. Due to the shell size, large experimental apparatus have to be used. First triaxial tests have been performed under low confining pressure on shells without any cement slurry (Fig 7a). Oedometer tests have been performed with different cement slurry densities (Fig 7b) in order to determine a satisfactory composition so as to get the required properties in terms of plastic behavior (level of the plateau and length of the plateau).

(a)

(b)

Figure 7: Geotechnical test (a) triaxial test on ceramic shells, (b) oedometer tests carried out with the ceramic shells and concrete

Figure 8: First tests carried out to check VMC resistance to handling

EXPERIMENTAL TEST CAMPAIGNS

During the year 2017, two major test campaigns are scheduled:

- The compressible arch segments fabricated (at scale 1:2) of Cigéo will be installed around mid-2017, in situ at the Bure URL (in the third portion of the GVA drift). Some of them will be instrumented and monitored over a decade, to check their structural and geometrical behaviour with time;
- A concrete ring formed of the same (instrumented) compressible arch segments as those installed at the Bure URL will be tested in a surface workshop (with hydraulic jacks) with an even loading and later with an uneven loading (reflecting the host rock convergence rates and the anisotropy of the loading, depending of the orientation of the drift versus the in situ major stress).

The second campaign will provide structural information to cross-check the stress/deformation values with those predicted during the preliminary sampling calculation undertaken to dimension the arch segments.

The first campaign will provide (with time) information/confirmation about the progressive loading of the concrete structure and a good set of data to compare the compressible arch segments behaviour with that of classical concrete segments which will be installed in the first portion of the GVA drift.

CONCLUSIONS

The confirmation in 2017 of the technical feasibility of installing in situ “Compressible Arch Segments” with a TBM is an important milestone in the validation of this construction solution as a potential optimization of Cigéo design (at least for the construction of the ramps and first horizontal mains).

The study of the structure/rock interference over a decade at the Bure URL will also be a precious element to validate the use of the compressible arch segments for the construction of the IL-LLW disposal vaults.

An additional step in this R&D work is so far missing: the anticipated savings (on the liner structure, on the TBM size, on the volume of excavated material) must be now accurately determined, while the ceramic shell production (and the cost of coating the arch segments) need to be more precisely assessed. This task is also scheduled in 2017.

REFERENCES:

(1). Armand, G., Plas, F., Bosgiraud, J.-M., 2015. "The contribution of Andra's Underground laboratory to selection and developpement of excavation techniques for the underground structures of Cigéo radioactive repository project". Tunnels et espace souterrain, n° 250, p.251-268 ;

(2). Bosgiraud, J.-M., Guénin, J.-J., Delort, D., Roulet, A., Glénet, O., 2010. "Technical Milestones for Emplacing Vitrified Waste Canisters into Horizontal Disposal Drifts in a Clay Host Formation". WM 2010 Conference, March 7-11, 2010, Phoenix, AZ, paper 10019;

(3). Delay, J., Vinsot, A., Krieguer, J.M., Rebours H. and Armand, G. 2007. "Making of the underground scientific experimental programme at the Meuse/Haute Marne URL, North Eastern France". Phys. & Chem. of the Earth, 32, 2-18 ;

(4). Wileveau, Y., Cornet, F.H., Desroches, J. & Bluemling, P. 2007. "Complete in situ stress determination in an argillite sedimentary formation". Physics and Chemistry of the Earth, vol. 36, 1949-1959.