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WORK PACKAGE 6

DELIVERABLE D6.3

CS perspectives with a focus on predictive simulations and models applied to assessment cases (tasks 5.3 and 5.4 of WP5):

The Beacon Project – A Summary for Civil Society

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Abstract

For long-term disposal of radioactive waste in repositories clay is often chosen and used for different purposes. It can be used as a buffer material surrounding the waste containers and for closing tunnels that are part of the repository after the waste has been emplaced. Clay is chosen because it has the quality to swell when water from the surrounding bedrock reaches it. The intention is to introduce clay barriers in the repository so that water flow, and the transport of material in the water, is limited.

In the Beacon project an effort has been made to better understand how it is possible to model how the clay in radioactive waste repositories behaves after the repository has been closed. Partners in the project are seven companies/organisations responsible for implementing repositories and a larger number of research companies/organisations, some of them technical support organisations to implementors or radiation safety regulatory bodies. The project has been coordinated by the Swedish implementor, Svensk Kärnbränslehantering AB (Swedish Nuclear Fuel and Waste Management Company), SKB.

This report summarises the work carried out and the results of the Beacon project in a form that should be readily accessible to the civil society (CS). The report is the final deliverable Work Package 6 (WP 6) on dissemination to CS that has been led by MKG, Miljöorganisationernas kärnavfallsgranskning [Swedish NGO Office for Nuclear Waste Review].

The report first describes the context of the Beacon project in developing the safety case for radioactive waste repositories. The report then describes the objective of the five Work Packages 1-5 (WP 1-5) in the project and how the work packages connect to one another. The report continues by describing the work carried out in the work packages and the results of the project are briefly described. The report concludes with some final comments on the achievements of the project.

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1 Introduction

The Beacon project is a research project financed by the European Commission. The project started in June 2017 and has been ongoing for five years and ends with a final workshop in London on 17-19 May 2022. At the conference a special effort will be made to make it possible for representatives of civil society (environmental NGOs and local communities with radioactive waste management projects to take part and learn more about the project and its results.

This is the final report of Work Package 6 (WP 6) of the project. WP 6 has been led by has as a task the dissemination of the work and results of the project to the civil society (CS) and has been led by MKG, Miljöorganisationernas kärnavfallsgranskning [Swedish NGO Office for Nuclear Waste Review]. The report will be used to support the CS participation at the Beacon final conference.

The Beacon project studies the behaviour of clay materials that are proposed to be used in repositories of different types for radioactive waste. Clay can be used as a buffer material around containers that the waste is put into. Another use is for closing tunnels that are part of the repository after the waste has been emplaced.

The clay used is most often chosen because it has the quality to swell when water from the surrounding bedrock reaches it. The intention is to introduce clay barriers in the repository so that water flow, and the transport of material in the water, is limited.

The Beacon project studies the swelling of clays and more specifically tries to model how the clay swells. The clay sometimes tends to swell unevenly, or inhomogeneously, and it is a challenge to model this in an accurate way.

Partners in the project are six companies/organisations responsible for implementing repositories and a large number of research companies/organisations, some of them technical support organisations to implementors or radiation safety regulatory bodies. The project has been coordinated by the Swedish implementor, Svensk Kärnbränslehantering AB (Swedish Nuclear Fuel and Waste Management Company), SKB.

The project has five work packages numbered 1-5 (WP 1-5) focusing on different aspects of the project. The next section describes the context of the Beacon project in developing the safety for radioactive waste repositories. In section 3 there is a description of the objective of the five work packages 1-5 (WP 1-5) in the project and how the work packages connect to one another. The section ends with a brief description of the work and results of the WP 6 on dissemination to civil society[1]. In section 4 the work carried out in the work packages WP 1-5 and in section 5 the results of the project are briefly described by work package. The report concludes with a summary on the achievements of the project.

The Beacon project also has an Expert Advisory and Review Board (EARB) that has commented the work done in the project in four reviews[2].

[1] In addition, there are two work packages, WP 7 for dissemination and WP 8 for coordination.

[2] The members of the EARB are Klaus-Jürgen Röhlig (TU Claustal), Wilfried Pfingsten (PSI), Nadia Mokni (IRSN), Jinsong Liu (SSM) and Frédéric Bernier (FANC).

2 The Beacon project in context

In many countries, also in the European Union, there has been a production of radioactive waste that needs to be safely and securely managed in the short term, as well as in the long- term. The most long-lived and highly radioactive waste comes from electricity production in nuclear reactors. This waste must be isolated from humankind and nature for hundreds of thousands of years. Larger amounts of more short-lived and less radioactive waste come from the operation and decommissioning of nuclear reactors and other nuclear activities, and to a lesser extent from medical and industrial sources.

For the disposition of the radioactive waste in the long term the most proposed way forward is disposal in geologic repositories. There are a few operational repositories, mostly for the least long-lived and less dangerous radioactive waste. The challenge is to find environmentally safe solutions of how to best move ahead regarding the long-lived and more dangerous wastes.

In different planned projects for final disposal of radioactive waste, clays of different kinds are to be used. Clay is a material that can be difficult for water to move through, and this is the main characteristic that makes it attractive as a barrier material.

By using clays as a barrier to surround canisters containing radioactive waste in a repository it is possible to delay surrounding water from reaching them. This means the canisters will be less affected by corrosion and the risk of leakage of radioactive material. The clay will also delay the spread of radioactive particles if the canisters start to leak.

Using a clay barrier around waste containers, often called a clay buffer, can also protect the canister physically if there are forces that affect the radioactive waste repository. Such forces can be due to earthquakes or movement of the surrounding bedrock due to effects of a possible future ice age.

Clay materials as a barrier are also considered for use to seal the tunnels and shafts that have been used while constructing the radioactive waste repository and for transporting the waste down.

Some clays swell if they are exposed to water. Bentonite clays are one example. As the clay swells it fills up the space around it. And, as it swells more and more against the surroundings and against the waste containers the clay can become even more difficult for water to pass through it. The characteristic of swelling clays, such as bentonite, make them especially attractive for use as barriers in repositories for radioactive waste.

It is important to be able to know how the clay in a repository will swell after the containers of radioactive waste have been placed in the repository. If the clays do not swell properly or if they swell unevenly, it is possible that the long-term safety will not be as high as planned.

It is therefore important to be able to predict how bentonite clays swell when they are used in a repository. Many experiments have been made throughout the years, both at smaller scales in ordinary laboratories and at larger scales in underground laboratories that have repository conditions. The results of the experiments have been used to create models with the ambition be able to predict how the clay will swell.

There is now a relatively good understanding of how bentonites swell. Still, more work needs to be done to understand the details, for example how clay can swell evenly. That clay swells in an even fashion, or as it also called with homogeneity, is important to avoid the uneven build- up of pressure around a canister of radioactive waste. Such uneven pressure can damage the canister. If clay swells unevenly, it can also increase the risk that the clay is eroded by flowing water, for example the tunnels in a repository for radioactive waste.

Experiments have been made in smaller scale in laboratories and in larger scale, in underground laboratories, to try and understand the swelling of clays. But to be able to predict how clays behave over time in real repository environments and that it will work as intended is essential. Modelling is one way to understand if the predicted swelling is good enough to provide a credible analysis for a safety case.

The Beacon project focuses on modelling the swelling of bentonite clay in buffers, tunnels, plugs, and seals. The project has as an overall objective to develop and test tools in the form of models to understand how swelling bentonite clays behave as barriers – the mechanical evolution – in a repository.

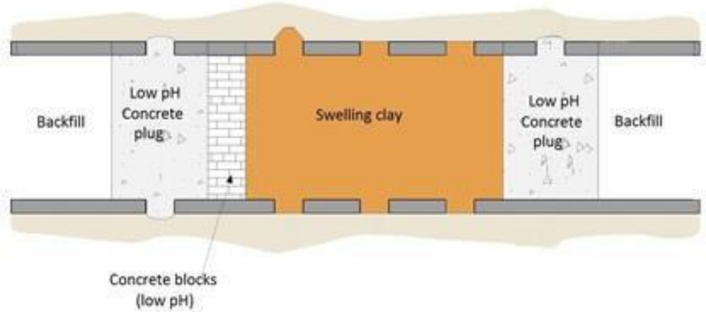
The driver for the Beacon project is repository safety, and the demands of waste management organisations, that have the responsibility for management and disposition of radioactive waste, to verify that the material selection and initial state design fulfil the long-term performance expectations. There is thus a need for the tools developed in the Beacon project to be able to show that the repositories have the theoretical prerequisites to be safe.

When a repository for radioactive waste is filled with waste, the initial state refers to the period at installation of the bentonite clay barrier. However, long-term performance and the safety case rely on the barrier systems to develop for a period for saturation and evolution of the so-called hydro-mechanical state to a final state, which can take from 10 to thousands of years. It is this final state that is used as a basis for the calculations which will underpin a safety case.

In current and future applications for licenses for repositories, the radiation safety regulators will expect applicants to have a sufficient predictive capability of the barrier evolution from the installed initial to the final state used for the safety case. The regulators will expect that modelling tools and physical experiments are sufficiently good enough to predict how the bentonite clays in a repository will swell to give long-term safety.

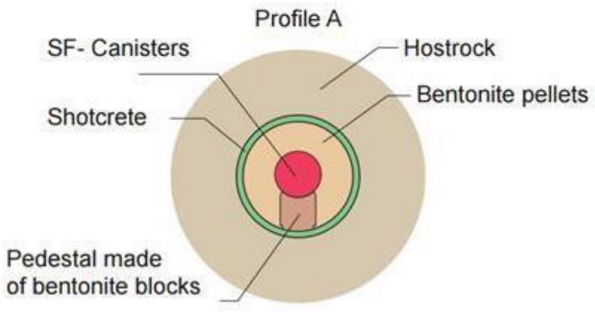
From previous experience, three representative cases where there are uncertainties about how clay swells, and where knowledge from the project could be utilised are:

a) a so-called “tunnel plug” in the design for a repository concept for high-level radioactive waste that the French radioactive waste management organization Andra have developed



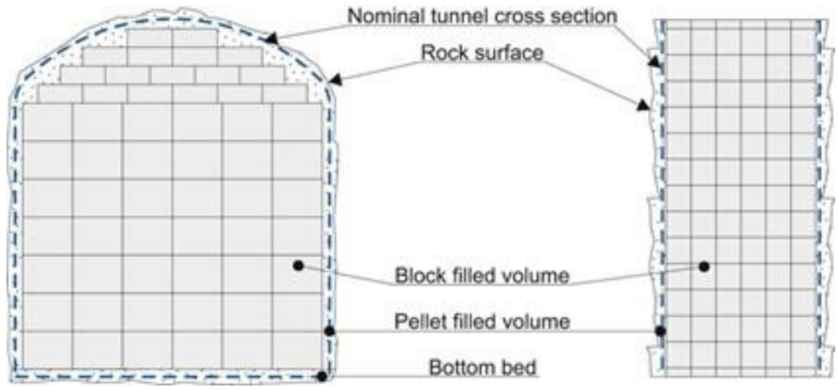
Tunnel plug in the Andra concept

b) a so-called “disposal cell” from the repository concept for high-level radioactive waste that the Swiss radioactive waste management organization Nagra have developed



Disposal cell in the Nagra concept

c) the so-called “backfill” of deposition tunnels in the KBS-3 method deposition tunnel that the Swedish radioactive waste management organization SKB have developed for the disposal of spent nuclear fuel



KBS-3 tunnel backfill

These three representative cases also became the assessment cases that were used towards the end of the project to apply the knowledge developed in the project to real-life cases. The three cases cover a broad range of issues, and the project results should be applicable to other concepts and systems as well.

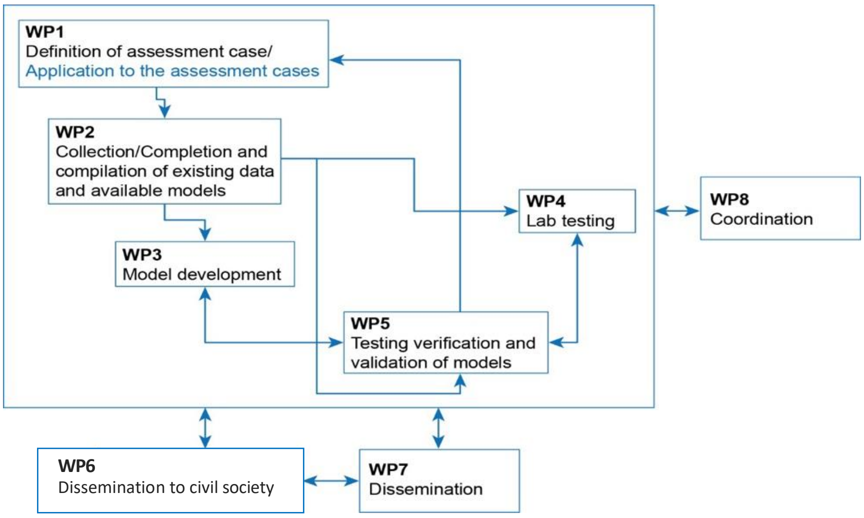
3 The organisation and structure of the Beacon project

The Beacon project is a five-year research project financed by the European Commission. The project started in June 2017[3]. The project ends with a final workshop in London on 17-19 May 2022. The project has been coordinated by the Swedish implementor of radioactive waste repositories, Svensk Kärnbränslehantering AB (Swedish Nuclear Fuel and Waste Management Company), SKB.

Taking part in the project are also six other implementors: SÚRAO (Czech Republic), Posiva (Finland), Andra (France), Nagra (Switzerland), ENRESA (Spain) and RWM (now NWS UK).

The project research has been carried out by a large number of research companies/organisations, some of them technical support organisations to implementors or radiation safety regulatory bodies. They are: Universitat Politècnica de Catalunya (UPC), Gesellschaft für Anlagen- und Reaktorsicherheit (GRS), Czech Technical University in Prague (CTU), Charles University in Prague (CU), French Atomic Energy and Alternative Energy Commission (CEA), VTT Technical Research Centre of Finland, University of Liege, Federal Institute for Geosciences and Natural Resources (BGR), Karlsruhe Institute of Technology (KIT), Lithuanian Energy Institute (LEI), Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Clay Technology, École polytechnique fédérale de Lausanne (EPFL), Imperial College London (ICL), Quintessa, Natural Environment Research Council (NERC) and University of Jyväskylä (JYU).

In the project there have been five "work packages" that are numbered 1 to 5 (WP 1-5) that are the components where the main work was carried out. How the work packages connect to one another is described in the figure below.



The organisation of the Beacon project

[3] The project was originally intended to be for four years but was extended for one year due to the Covid-19 pandemic.

3.1 The work packages 1-5

Work package 1 (WP 1) was called “Definition of assessment case/Application to the assessment case” and involves the waste management organizations in the project. The objective of WP1 was initially to define the important issues concerning the mechanical properties of bentonite and to define how these should be treated. The result were several specified assessment cases with focus on long term performance and/or repository engineering that was used as test cases for modelling. When results from the modelling of the assessment cases were available from Work Package 5 (WP 5) at the end of the project, WP 1 could use them to evaluate the findings with respect to the design and/or performance of the bentonite barriers of the three assessment cases.

Work package 2 (WP 2) was called “Collection and compilation of existing data and available models” and worked in the beginning of the project to create a knowledge base of existing information of importance for the upcoming work. All partners in the project were represented in WP 2 and the key objective was the sharing of knowledge and experience. The partners provided the work package with information and results from earlier assessments, design considerations, experiments, and modelling tasks. An important task of WP 2 was to collect and compile data from ongoing and decommissioned large-scale experiments in underground hard-rock laboratories, since no such tests were to be done within the Beacon project. The assessment cases defined in WP 1 were first passed to WP 2 to check for previous experience with similar cases. WP 2 in a sense, also served as the foundation for all work performed with WP 3-5.

A strong driver for the Beacon project was the understanding there were limitations in the predictive capability in the numerical models used before the project, even though such modelling work had been done for many years. The issue of homogenisation of bentonite clay and how the clay swells is challenging both from a conceptual and a numerical point of view. The purpose of work package 3 (WP 3) that was called “Model development” was therefore to identify and resolve the shortcomings of the existing models. The work in WP 3 was initially based on the information from WP 2, and it was done in close cooperation with WP 5 as the project progressed.

Although there was a substantial experimental database available for the project that was collected and documented by WP 2, it was considered necessary to perform additional experiments to support the model development in WP 3 and the model testing in WP 5. The experimental work was coordinated in work package 4 (WP 4) called “Laboratory testing”. WP 4 consisted of experienced experimental groups that had the flexibility to adapt the experimental work necessary to support the needs of WP 3 and WP 5.

The core component of the Beacon project was work package 5 (WP 5) called “Testing, verification and validation of models”. The main effort in the project was performed in this work package. The overall objective of WP 5 was to simulate the assessment cases defined by WP 1. To do this, the available models had to be tested first on results from laboratory experiments and later on results from large scale field tests to gain confidence in their predictive capability. In further steps the predictive capability of the models was tested, by means of “blind” predictions of experimental results provided by WP 4. Finally, the models were to be used to evaluate the assessment cases.

3.2 The Work Package 6 on dissemination to civil society

The role of Work Package 6 (WP 6) in the Beacon project has been to provide material in support of the dissemination work of the project[4].

In the first report of WP 6 a scoping effort was carried out and reported[5].

In the second report from WP 6 an effort was made to focus on providing information on the work and results of WP 5 that works with the testing and verification of models[6].

The present report is the third deliverable D6.3 that towards the end of the project provides a summary of the project intended for CS, especially for the participation of CS representatives at the Beacon final workshop. WP 6 organised the participation of several representatives from CS at the workshop and this is described in deliverable D6.4[7].

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[4] In the original contract with the European Commission WP 6 was intended as a WP for CS interaction but this was changed by demand from the commission in a renegotiation of the grant agreement so that the task of WP 6 instead had the task of CS dissemination. Originally a number of CS experts and a scientific expert chosen by them were involved in WP 6, but with the change of focus the interest in participation decreased. The CS experts were Johan Swahn, József Kóbor, Yves Marignac, Nadja Železnik and the scientific expert was prof. Roland Pusch.

[5] "Scoping of the Beacon project, initial civil society (CS) perspectives and enhanced work plan for years 2-4", Deliverable D6.1, Johan Swahn, Roland Pusch, József Kóbor, Yves Marignac, Nadja Železnik, May 2018 (revised February 2020). The original report for deliverable D6.1 was rewritten after input from European Commission after the demand that the work of WP 6 should only be dissemination and not interaction.

[6] "CS perspectives with a focus on verification and validation of models, and comparing models with situations close to disposal conditions (task 5.1 and 5.2 of WP5)", Johan Swahn and Nadja Železnik, Deliverable D6.2, January 2021.

[7] "CS broader participation at Beacon Final Workshop", Johan Swahn, Deliverable D6.4, May 2022.

4 The work carried out in the work packages 1-5

The actual work in the Beacon project is carried out in the five Work Packages 1-5 (WP 1-5)[8]. In this section the work is described.

4.1 Work Package 1 “Definition of assessment case/Application to the assessment case”

In work package 1 (WP 1) on “Definition of assessment case/Application to the assessment case” the first task was to make an initial report called “Beacon - Bentonite Mechanical Evolution: State-of-the-Art Report (deliverable D1.1)”. The report was produced by having a questionnaire completed by the implementors in the project and gives information of how they presently handle clay issues when they analyse the safety of a repository. The report allowed the groups that make models (WP 3) and the experimentalists in the project (WP 4) to better understand what the whole project was aiming at.

WP 1 had no further tasks until towards the end of the project. In a report in August 2020 WP 1 provided three assessment cases for WP 5 to attempt to model during the last year of the project[9]. The assessment cases were described in section 2, i.e., the Tunnel plug in the Andra concept, the Disposal cell in the Nagra concept and the KBS-3 method tunnel backfill.

At the end of the project WP 1an evaluation the results of the project and lessons learnt from the different work package in a report called “Final assessment report (deliverable D1.3)”. The report ends with an evaluation of what new information the modelling of the three assessment cases gave and what further issues still could be addressed.

4.2 Work package 2 “Collection and compilation of existing data and available models”

At the beginning of the project WP 2 on “Collection and compilation of existing data and available models” led a concerted effort by all the partners in the project to collect information on experiments that had been carried out, and on clay modelling that had been done, and that could provide input to the project. To assist in this work an open workshop was organised at the kick-off meeting of the Beacon project in Kaunas in Lithuania in June 2017.

The information was collected in a database and published in a report called “Review of data and models on the mechanical properties of bentonite available at the start of Beacon (deliverable D2.2)”.

WP 2 had no further tasks until towards the end of the project when the work package in a report called “Identification of captured knowledge of bentonite mechanical evolution gained over the duration of the Beacon project (deliverable D2.3)” summarised the key learning from the experimental and modelling work undertaken in the project as well as providing an updated database.

[8] In addition, apart from WP 6 on CS dissemination there are two work packages, WP 7 for dissemination and WP 8 for coordination.

[9] The report “Assessment Cases for the Evaluation of the Degree of Heterogeneity” is not a project deliverable.

One important result of the work of WP 2 is that there is now a database of bentonite experiments accessible on the Beacon project web site[10].

4.3 Work package 3 "Model development"

The work package 3 on "Model development" consisted of 14 modelling partners that formed nine modelling groups in the project. The groups started the project using models they had previously developed. In order to be able to compare and develop their different models the groups in the work package at the beginning of the project completed a special questionnaire to describe how their particular models worked. The result was the first report from WP 3 called "Description of the constitutive models available at the start of the project. Conceptual bases, mathematical description and model capabilities and shortcoming (deliverable D3.1)".

The modelling groups in WP 3 have been working in work package WP 5 doing modelling to see if they can model the results of a number of chosen experiments. This is described below. WP 3 also produced two reports describing the development and improvement of the modelling work, one mid-way through and one towards the end of the project. The final report of the WP 3 was called "Description of the constitutive models developed in the project. Conceptual bases, mathematical description and model capabilities: Assessment of predictive power (deliverable D3.3)"

4.4 Work package 4 "Laboratory testing"

Work package 4 on "Laboratory testing" also consisted of many groups that are experimental. The eight groups from six countries have carried out a number of new experiments to provide new results that the modellers in WP 3 can work on. Time was first spent on defining which experiments were to be carried out so the modellers would have a broad choice to choose from. The experiments were then carried out and reported in a first report mid-way into the project with a report called "Bentonite mechanical evolution – experimental work for the support of model development and validation (deliverable D4.1/4.2)".

A final report of the experimental work in the project was published as "Experimental work on bentonite evolution in the frame of BEACON – final report of WP4 (deliverable D4.3)".

Several experiments were selected for modelling cases in the work packages WP 3 and WP 5.

4.5 Work package 5 "Testing, verification and validation of the models"

The work package 5 on "Testing, verification and validation of the models" was the most central work package in the Beacon project. In this work package the modellers from WP 3 tested their models on different cases. During most of the project they tested their models against experimental data from experiments that had been carried out before the Beacon project started. Towards the end of the project, they also modelled with data from the experiments done in WP 4 and finally the assessment cases chosen by WP 1.

From the results of the early work of WP 2 with the long list of previous experiments on clay, two lists of experiments were made on which the modellers tested their modelling skills. The first list was composed of three smaller laboratory tests and the second list of large-scale

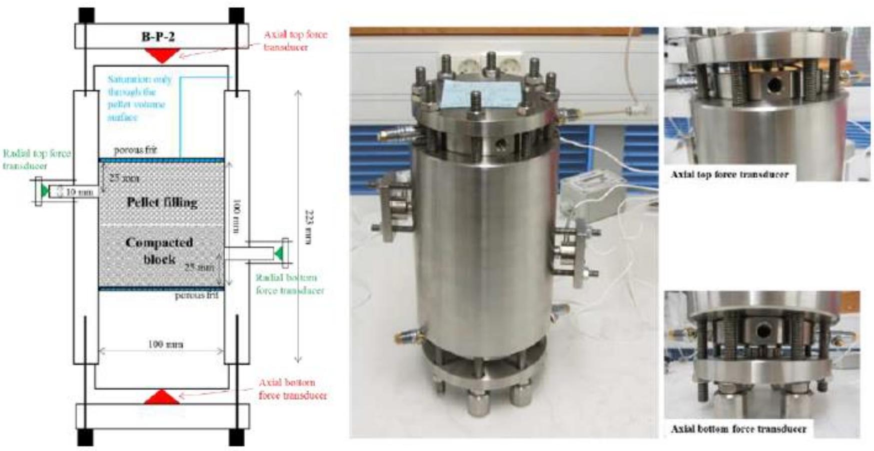
[10] https://www.beacon-h2020.eu/bentonite-experiments/

experiments. At the beginning of the project the work focussed on the smaller tests and then the modelling continued with the larger tests.

Firstly, the modelling groups in WP 3 modelled the three small laboratory tests that were:

a) “Swelling pressure tests for compacted plugs with free volume available” that was carried out by the Swedish company Clay Technology AB together with the Swedish implementer SKB
b) “Swelling pressure tests for pellets mixture” that was carried out by the French research organisation CEA together with the French implementer Andra
c) “Swelling pressure tests for block and pellets structure” that was carried out by the Finnish implementer Posiva

The modelling groups could compare their different ways of approaching the task and learn both from their own work and from other groups. The small laboratory tests are described in detail in the report “D5.1.1 Specifications for Beacon WP5: Testing, Verification and Validation of Models Step 1- Verification”, but all are based on the idea of enclosing clay in an experimental apparatus and then letting in water and observing with different sensors how the clay swells. An example of an apparatus is shown below, the one for the Posiva small laboratory test “Swelling pressure tests for pellets mixture” (test c).



The Posiva small laboratory test “Swelling pressure tests for block and pellets structure”

For the modellers of WP 3 the objective was to show that their models can reproduce the observations and measurements in the small laboratory tests. As the clay swells a pressure builds up and the change in swelling pressure is modelled.

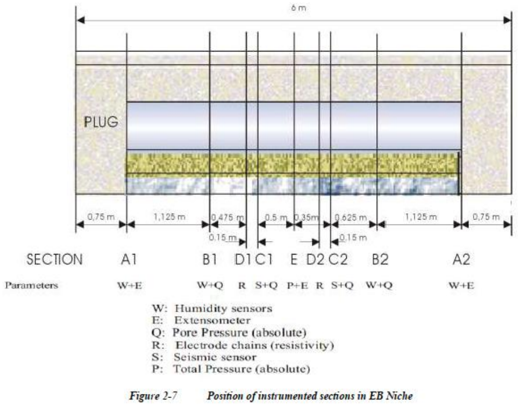
The second task for the modelling groups of WP 3 was to model the results of three large scale experiments. Three experiments were chosen:

a) The Engineered Barrier Emplacement Experiment EB carried out by the Spanish implementer ENRESA in cooperation with other European organizations
b) The Full-scale Engineered Barrier Experiment in Crystalline Host Rock (FEBEX) carried out by ENRESA in a first phase and by an international consortium afterwards
c) The Canister Retrieval Test (CRT) carried out by the Swedish implementor SKB.

The experiments are described in the report “D5.2.1 Specifications for Beacon WP5: Testing, Verification and Validation of Models Step 2- Large scale experiments” and are briefly described below.

Engineered Barrier Emplacement Experiment" (EB)

The Engineered Barrier Emplacement Experiment (EB experiment) at the Mont Terri underground research laboratory in Switzerland was dismantled in 2012 after almost eleven years of operation. It was operated by the Spanish implementer Enresa. In the experiment a dummy canister made from steel was placed in a tunnel in the bedrock and surrounded by clay. The canister was not heated. The experiment is shown below.

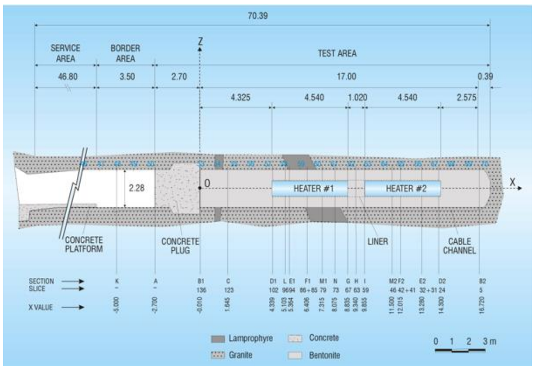


The EB experiment

Full-scale Engineered Barrier Experiment in Crystalline Host Rock (FEBEX)

The FEBEX experiment (Full-scale Engineered Barrier Experiment in Crystalline Host Rock) ran for 18 years at the Grimsel underground laboratory in Switzerland and was finally dismantled in 2015. It was operated by an international consortium of waste management organisations led by the Spanish implementor Enresa.

The general layout of the experiment is shown below. There are heated steel canisters surrounded by clay.



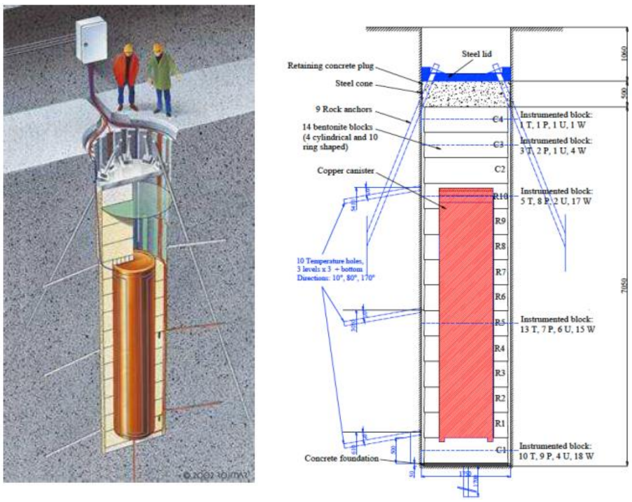
The FEBEX experiment

Canister Retrieval Test (CRT)

The Canister Retrieval Test (CRT) was a full-scale field experiment simulating a deposition hole with a copper canister and clay buffer according to the Swedish KBS-3 method. The experiment was carried out at the Äspö Hard Rock Laboratory in Sweden from 1999 to 2006 and was financed by the Swedish implementer SKB.

The Canister Retrieval Test was a full-scale field experiment simulating a deposition hole in a radioactive waste repository for spent nuclear fuel of the KBS-3 concept developed by SKB. It was designed to demonstrate the ability to retrieve a deposited canister after the clay had swollen completely.

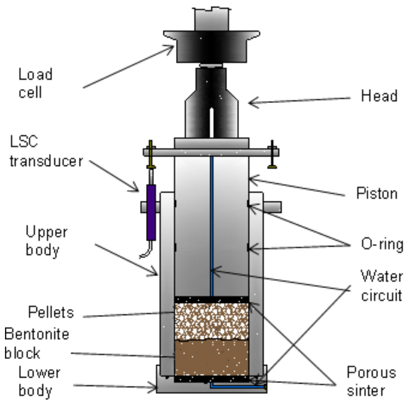
The CRT experiment is shown in the diagram below. There is a copper canister deposited in a hole in the tunnel floor and the canister is surrounded by a buffer made up of rings of clay. The space between the clay blocks and the surrounding rock is filled with clay pellets. The copper canister was heated, and water was artificially introduced in the experiment. It was dismantled after 5 years of operation.



The CRT experiment

For the modellers of WP 3 the objective was to show that their models can reproduce the observations and measurements in the large-scale experiments. Also here it was the swelling pressure in the clay in different directions that was the factor to model.

In the third modelling task experimental results from WP 4 were used. Three experiments carried out by the Beacon partner CIEMAT were chosen and they were of the same type as the small-scale tests type c described in section 4.5. An example of the apparatus used is shown below.



In two cases the modelling groups tried to model the results and in the third the modellers were asked to do a predictive modelling. The cases were described in the report “Specifications for Beacon WP5: Testing, Verification and Validation of Models Step 3 (deliverable D5.3.1)”.

In a final modelling task, the assessment cases chosen by WP 1 were modelled. These are described in section 2 and in more detailed in the report referenced in section 4.1.

At the end of the projects some of the modelling groups in WP 3 use their refined models to once again model the small laboratory tests that were a task at the beginning of the project to see if the results had improved.

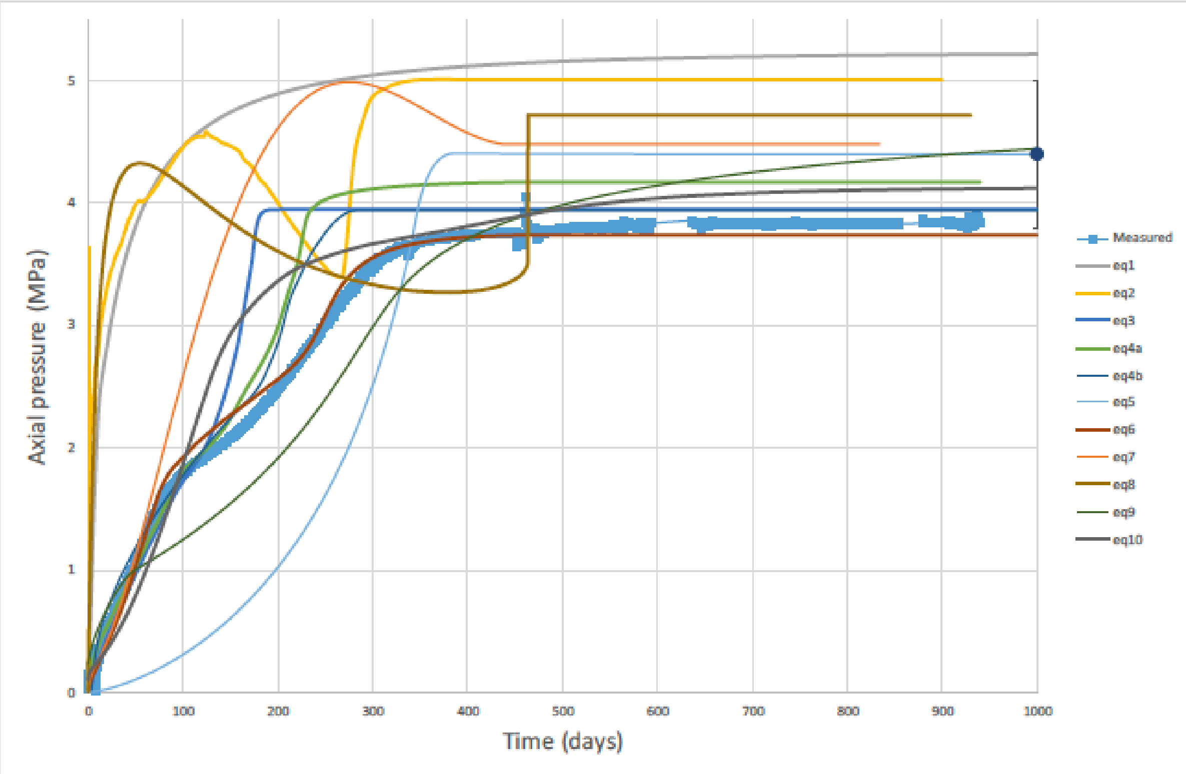
5 A short summary of the results of the Beacon project, with a focus on WP 5

The results of WP 1, WP 2, WP3 and WP 4 were summarised in the final reports of each work package as described in the previous section. In this section some of the results from WP 5 are shown and is what has been produced from the different modelling groups in WP 3 for the different cases described in section 4.5 above. There are very many results and only a few are chosen here for each of the modelling tasks.

5.1 The results of the modelling of the smaller laboratory tests

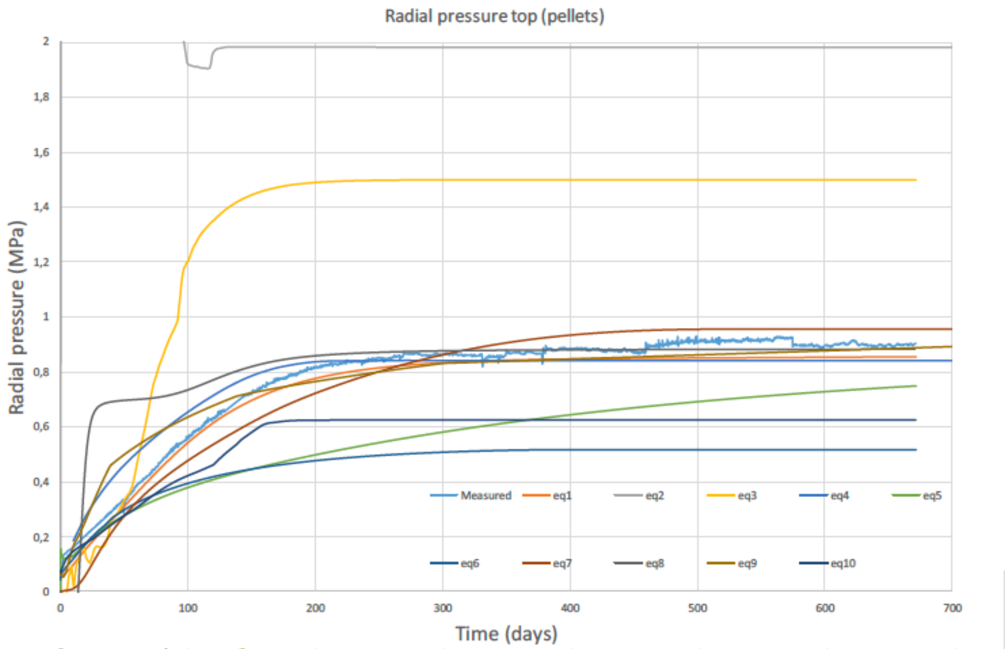
The results of the modelling of the smaller laboratory tests were reported in the report "Synthesis of results from task 5.1 (deliverable D5.1.2)"[11]. Below is an example from the "Swelling pressure tests for pellets mixtures" test that was shown in the section 4.5.

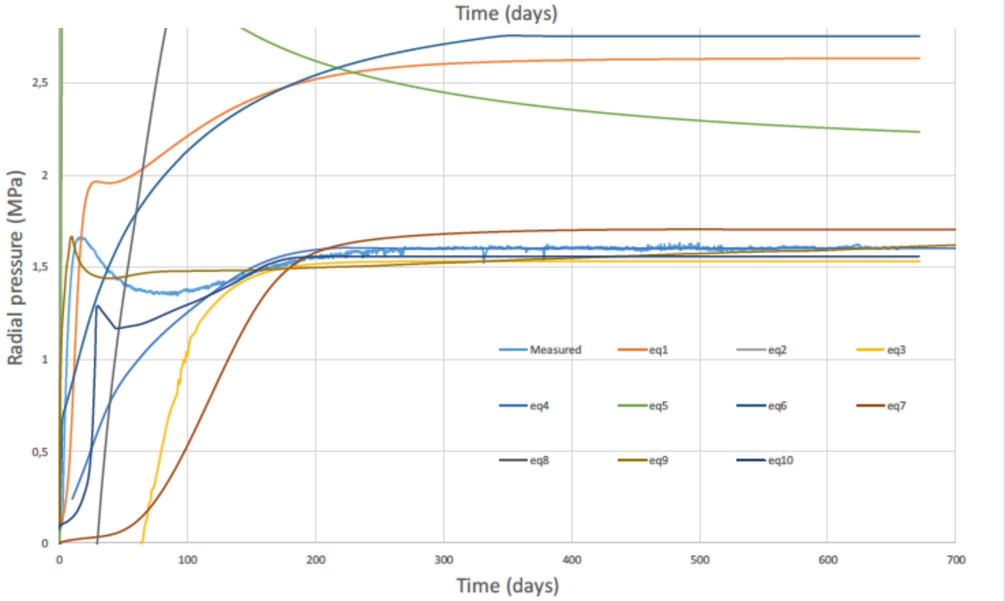
The thicker blue line shows the actual pressure that was measured over time as the swelling of the clay developed- The results of the modelling are the thinner lines and show a large spread in the beginning while all ending not too far from the final measured pressure. This was the second smaller laboratory test that was modelled. It is interesting that one group had quite a correct modelling result.



[11] There is also an effort to describe the results from the modelling of the smaller laboratory tests in the WP 6 report "CS perspectives with a focus on verification and validation of models, and comparing models with situations close to disposal conditions (task 5.1 and 5.2 of WP5) (deliverable D6.2)".

The results can be compared to similar curves for the third laboratory test “Swelling pressure tests for block and pellet structure”. It seems that the programming groups had already learned from one another as the results generally seem more accurate.

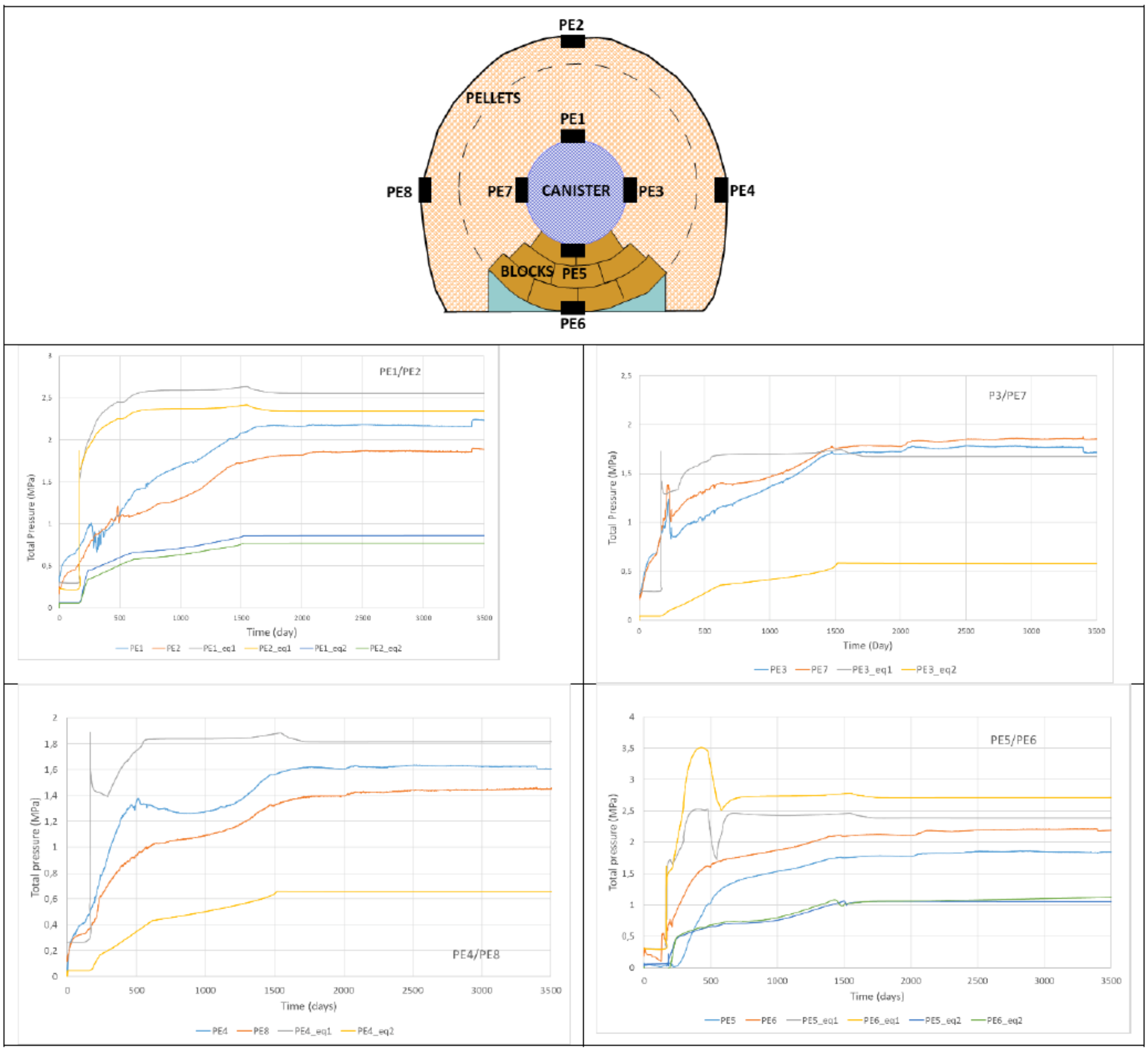




5.2 The results of the modelling of the large-scale experiments

After trying their skills on the small laboratory tests the modelling groups in WP 3 modelled the three large-scale experiments described in section 4.5. This task was much more difficult than the previous small laboratory experiments. There is a more complex geometry and there are uncertainties in the boundary and initial conditions. Sometimes the information given by the sensors in the experiments are difficult to interpret. In addition, for two of the experiments (CRT and Febex) it was necessary to take into account the heating of the experiment and how temperature affects the swelling behaviour of the clay. The results of the modelling of the large-scale experiments were reported in the report "Synthesis of results from task 5.2 (deliverable D5.2.2)"[12].

Below are some results from the modelling of the "Engineered Barrier Emplacement Experiment (EB)". It was only modelled by the groups UPC and ULG. The results obtained by both modelling groups are in good agreement with the measured values in the actual experiment. All the measurements could not be reproduced with the same accuracy – especially during the transient phase – but this was foreseen.



[12] There is also an effort to describe the results from the modelling of the smaller laboratory tests in the WP 6 report "CS perspectives with a focus on verification and validation of models, and comparing models with situations close to disposal conditions (task 5.1 and 5.2 of WP5) (deliverable D6.2)".

5.3 The results of the modelling of the experiments done by WP 4

The next step for the modelling groups in WP 3 was to try and model the results of the selected experiment from WP 4. The experimental results came from three experiments carried out by the Beacon project partner CIEMAT. These experiments were small laboratory tests of a similar kind as the small tests modelled at the beginning of the project. The results of the modelling were reported in the report "Synthesis of results from task 5.3 (deliverable D5.3.2)". Some results are also shown below where the thick black lines are measured results. It is clear that some modelling groups succeed quite well in capturing the results while others were less successful.

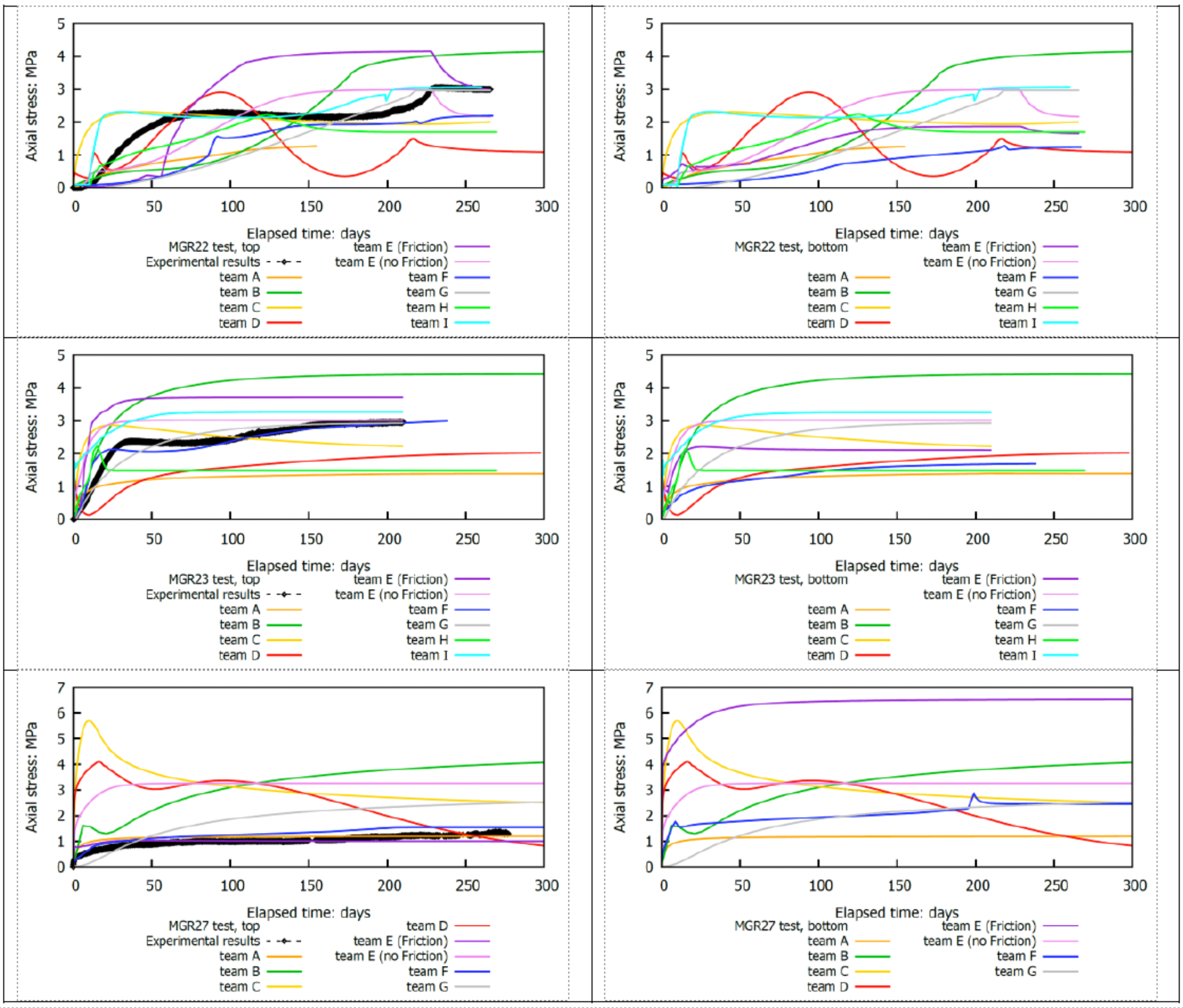
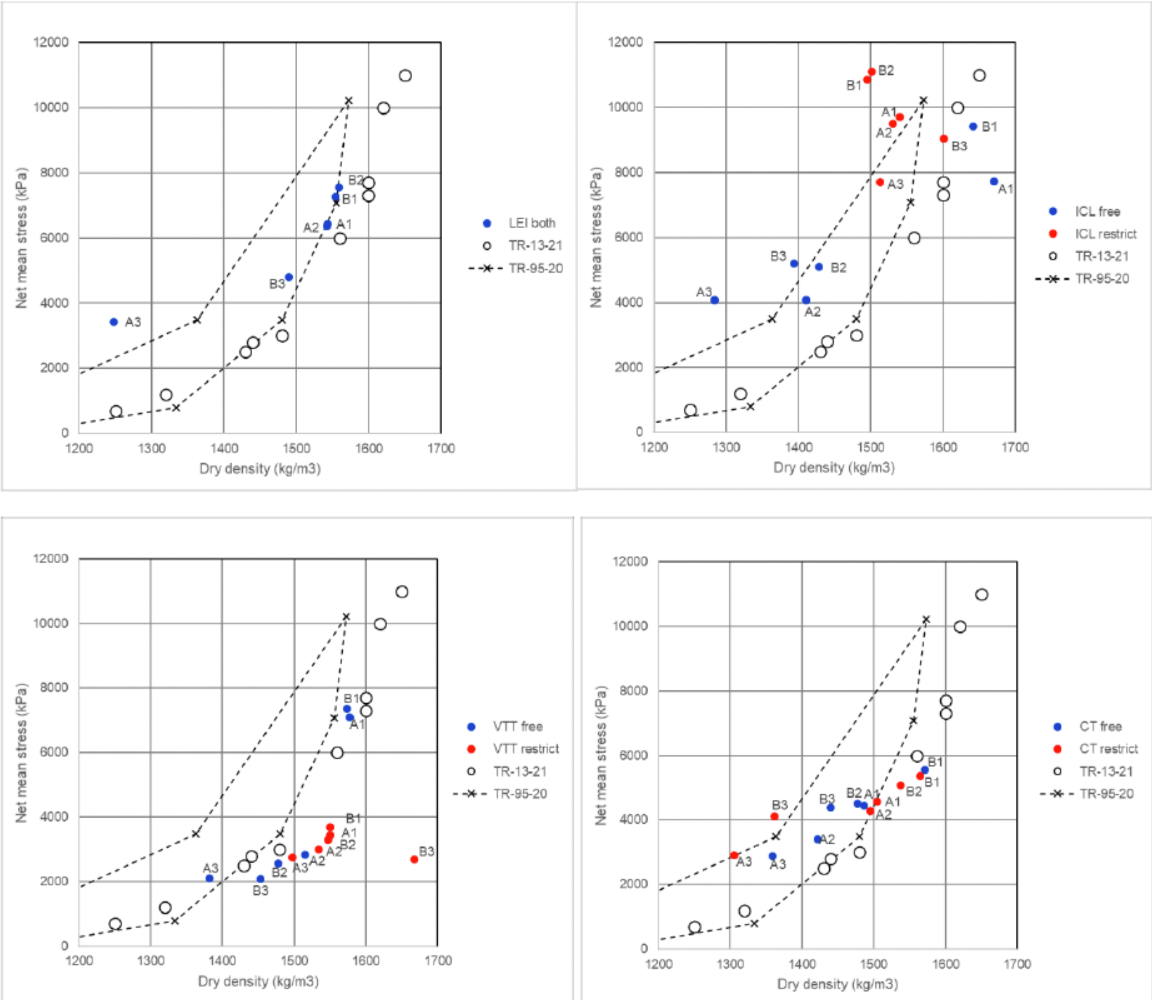


Figure 4-11 Axial stress, left top, right bottom, line 1 MGR22, line 2 MGR23, line 3 MGR27

5.4 The results of the modelling of the WP 1 assessment cases

The results of the modelling of the assessment cases are presented in the final report of WP 5 called Synthesis of the results obtained from all tasks in WP5: Final report for WP5 (deliverable D5.7)". Only a few modelling groups from WP 3 have done the modelling for the different assessment cases.

As an example, some results are shown below for the first assessment case, the “KBS-3 Tunnel backfill” case. It is the dry density of the clay in different positions that is presented and there is a difference between how the modelling groups were able to repeat the experimental results.



The results of the modelling of the assessment cases are also commented in the WP 1 final report “Final assessment report (deliverable D1.3)”. In the report it is stated:

“The assessment cases that have been modelled in Beacon was selected already in the proposal for the project. At that time, it was not clear how much work that would be needed to handle these cases. In hindsight, it is clear that the number and complexity of the modelling tasks in Beacon, including the benchmarks in WP5, have been over-ambitious. The modelling teams have been able to produce results for all tasks, but not enough time has been assigned to the evaluation and interpretation of the results. This is especially true for the assessment cases. The Covid-19 situation also made it impossible for the teams to meet in person to discuss the issues and the results from the assessment cases. Therefore, the results presented here should be seen as "very preliminary". If more time had been available, it is very likely that the results would have been more consistent.”

6 Final summary and conclusions

The final report of WP 5 is called "Synthesis of the results obtained from all tasks in WP5: Final report for WP5 (deliverable D5.7)" and can be seen as a summary of the results of the Beacon project. Apart from presenting the results from the modelling of the assessment cases (see section 5.4) some results from modelling groups repeating the modelling of the small laboratory tests from the beginning of the project are shown. All the modelling groups also present the progress in modelling throughout the project.

The project ended with a final workshop in London on 17-19 May 2022. At the meeting the leaders of the project, of WP 1-5 and a representative the EARB made presentations highlighting summarising the work and results of the project as well as providing observations and conclusions. Here are a few of the points made:

- Despite influences by the Covid-19 pandemi, the project has been smoothly initiated and successfully carried out.
- Outcomes from the project are highly relevant to the design and the safety analysis of different types of final disposal facilities that apply bentonite as an engineering barrier in relatively large dimensions.
- The project has identified main factors affecting the degree of homogenization and the general trend of the re-saturation and homogenization processes have been well captured by the different modelling approaches, despite relatively large scattering of input and fitted parametric data.
- Important and substantial advances have been made in the project and the models developed are able to reproduce what are the key features of behaviour underlying the homogenization processes.
- The smaller cases were easier to model. The modelling of the WP 1 assessment cases proved to be rather challenging with rather large differences in the predicted final dry density of the barriers.
- The project has resulted in a large expansion of bentonite modelling capabilities (in number and scope) across Europe.
- The project acknowledges that several questions remain open, and more efforts are required to achieve a more complete understanding of the phenomena and to assess the true predictive capability of the developed models.
- The observation was made that most of the tests selected for modelling were isothermal and did not consider explicitly the possible importance of chemistry for changes of clay behaviour. This needs further studies and connections should be made to the clay studies done in the EURAD project, especially the HITEC work package[13].

[13] https://igdtp.eu/activity/hitec-influence-of-temperature-on-clay-based-material-behaviour/