BEACON

# Bentonite Mechanical Evolution

The sealing ability is essential for all engineered clay (bentonite) barriers in geological repository concepts. The overall objective of the Beacon project has been to develop and test the tools necessary for the assessment of the mechanical evolution of an installed bentonite barrier and the resulting sealing ability of the barrier.

The Beacon project has consisted of:

- Modelling of homogenisation of the bentonite barriers
- Experimental work on the mechanical properties of bentonite
- Development of THM models

# Beacon objectives

The sealing ability is a principle safety function for all bentonite-based barriers in geological repository concepts. Sealing is achieved by the combination of a high swelling potential and a low hydraulic conductivity. The swelling potential will ensure self-sealing, but may mechanically impact the other barriers in the repository as well. The low hydraulic conductivity ensures that transport of dissolved species by advection will be very limited. Swelling pressure and hydraulic conductivity can normally be expressed as a function of dry densities of the bentonite materials. The required quantitative values thereof strongly depend on the repository concept and the environment.

The bentonite is installed as blocks, pellets, and/ or granules depending on the overall repository concept and the required density. Despite the precautions taken when installing these materials, technological voids may occur and dry density variations may be observed in the structure. Therefore, the bentonite barrier needs to be conceptualized such that these technical voids can be compensated for by the swelling of the bentonite and that density variations after hydration are minimized or in the range of the expectations.

Despite the high swelling potential of bentonite, full homogenization between the installed components is never expected to be reached. The key question is: "is the homogenization sufficient to reach the targets for the safety functions after the barrier is saturated with water?" If the answer is yes, then the barrier can be assumed to have its assigned properties in the safety case. If the answer is no, then the effect of a heterogenous barrier needs to be considered (e.g. advection in the barrier) and/or the design and installation of the barrier components need to be improved.

This makes it necessary to have predictive models that can describe the evolution of the properties of the bentonite barriers from "the installed state" to a "saturated state". The input to the models should be the design specification, including uncertainties, and the site properties, also including uncertainties. In this aspect uncertainties include variability and tolerances. The output should be the final state of the barrier, preferably expressed in distribution of dry density and evolution of stresses. The results from the models can then be compared with the indicators/targets for the safety functions to check whether they are fulfilled. The key parameter to check is the dry density, which has a direct relation to the swelling pressure and the hydraulic conductivity.

The overall objective of the Beacon project has been to develop, test and improve models that are able to predict the mechanical evolution of installed bentonite components. The application of the models is both to support the handling of the barriers in the safety case and to give feedback to the design and the engineering of the barrier components.

The Beacon group at Milos 2018

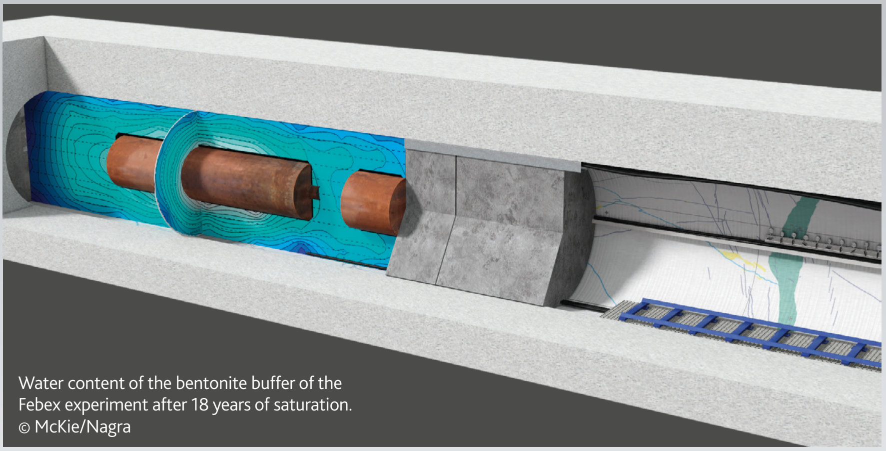
A full scale model of the Swiss High-Level Waste (HLW) disposal concept with the waste inside a steel canister on top of blocks of bentonite and surrounded by bentonite pellets © Comet Photoshopping GmbH, Dieter Enz

# Accurate barrier modelling for nuclear waste management

**Patrik Sellin** of the BEACON project explains why modelling the performance of bentonite's mechanical behaviour, will mean predictive models will benefit engineers and satisfy regulators by understanding how it can be used as an effective sealant, in nuclear waste repositories.

**Bentonite is an** absorbent clay substance, possessing qualities which make it useful for very specific applications. Made up of natural materials, it is used in many sectors, for everything from cosmetics to cat litter. Crucial, for those tasked with disposing of nuclear waste safely, it will be used for creating a natural seal for engineered barriers in geological repository concepts, as it expands into voids when you add water to the mix.

In this respect, the Beacon project has been studying bentonite's mechanical properties in the context of being a barrier for repositories containing radioactive waste, where it is critical to ensure effective seals are in place indefinitely. Engineered Barrier Systems (EBS) are repositories designed to hold radioactive waste for hundreds of thousands of years. They vary in design around the world, all with the purpose of creating a leak-proof, sealed containment system within the ground. Implicitly understanding the sealing abilities to these systems is key to having confidence that they are meeting their requirements.



Water content of the bentonite buffer of the Febex experiment after 18 years of saturation. © McKie/Nagra

## Barrier science for Radioactive Waste Management

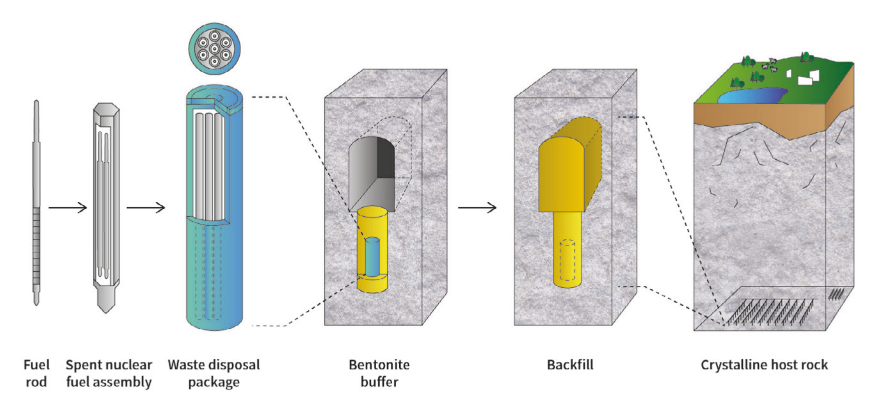
"Bentonite is used as a seal, and a buffer. Bentonites have been stable for millions of years in nature, so it's something that we can rely on for long term stability," begins Patrik Sellin, co-coordinator of the Beacon project, whose experience derives from working in an expert capacity for SKB, Swedish Nuclear Fuel and Waste Management Co. "It acts like a sponge and it keeps the water intact, in the system, which means that all water transport through this engineered barrier will be very, very limited. This is the basis of this project, how to show that we have put in something that is engineered into a rock cavity and then after water saturation it gets to have the properties that we want it to have, low water permeability is the main factor here. You don't want the ground water to go through the barrier and since this is a mixture of bentonite blocks and pellets and also voids, for Beacon, it is to see after the water uptake, what the final properties of this barrier will be. What we want to show is that it is sufficiently homogeneous."

For high level radioactive waste systems, all the relevant programmes are still in the planning stage. Beacon relied on a banquet of data available from previous practical experiments around repositories, using that data as a means to test and create accurate, predictive mathematical modelling. It proved cost efficient and highly effective to use abundant existing data rather than to produce new data. This was in fact the first time this data was used in mathematical modelling in this way.

## Predicting performance

"There are quite a few experiments available from the past, field experiments in underground laboratories, that looked at bentonite swelling but the experiments have not been evaluated in a way that people can predict them, and what we need, if we want to license a repository, is to have models that can predict the performance of an installed barrier, because you cannot test the barrier or material, or buffer after the repository has been backfilled or sealed. The Beacon project is about the more subtle performance of the bentonite barriers," said Sellin.

The work's aim has been to intricately understand the soil mechanics involved and the design performance of these barriers, so engineered systems are futureproof for regulators wanting confidence in designs of EBS's that remained sealed over time. Regulators may need provable assurances in




KBS3 koncept – three engineered barriers: the canister, the bentonite buffer (and backfill) and the rock. © SURAO

barrier effectiveness, so testable modelling is a way to truly understand the intricacies of how bentonite reacts, expands, and fills void dimensions.

"Regulators will probably ask us at some point, 'how homogenous will it actually be?'" predicts Sellin. "We have seen in certain instances the homogeneity has been not so good and in other tests it's been very good, so this means that it's not an issue you can drop, you have to understand your system to be able to design your barriers and to show and demonstrate that they fulfil their requirements.

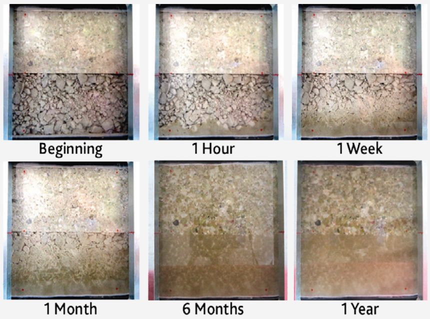
"Our work is to demonstrate that we understand the homogeneity of the barriers. What we need is to understand the properties of our barriers in the repository and that we are able to predict them. We need to do this as we will not be able to control it after the closure of the repositories. We need to understand this water uptake saturation process, which may take hundreds of thousands of years. It's definitely not possible to change the state of the barrier after full saturation so that is why we need tools that are predictive for these types of questions."

## Filling in the gaps

The Beacon consortium involves over 30 collaborating organisations and partners, large and small, from across Europe, which initially had varying levels of understanding about the mechanics of bentonite. This group or organisations includes an effective mix of radioactive waste management programmes, national research centres, innovative SMEs and civil society non-governmental organisations. It became apparent from the very first test case, in work package five, that to replicate accurate mechanical modelling would be far more challenging than anyone initially anticipated, making the project's relevance all the more apparent.

**Bentonite** is used as a **seal**, and a **buffer.** Bentonites have been **stable for millions of years** in nature, so it's something that we can rely on for **long term stability.**

Bentonite quarry




Bentonite pellets (bottom) and bentonite compacted block (top) hydrated from the bottom: evolution of appearance. Photos by Rubén J. Iglesias © CIEMAT

Bentonite components need careful and humidity regulated conditions before and under installation. Cracked bentonite buffer block. © SKB

Experimental set up with a bentonite block and extruded bentonite pellets around it. © SKB

In the test, different research teams were given the same task. Researchers attempted to detect a very simple swelling of bentonite in a cylinder 50mm high. The bentonite sample was 40mm high and they added water and it was supposed to expand into the remaining 10mm. Despite the basic nature of this small experiment, what occurred drove a deeper understanding of not what was known, but what was not known.

"Incredibly, all the teams came up with totally different results!" exclaimed Sellin. "No one could predict it and we thought that this was very simple, but it wasn't, and this stage of mechanical modelling and the deviation in this project wasn't expected. The further we progressed into the project, however, the modelling cases people came up with had much better results because it's a learning curve around conceptual ideas and mathematical solutions. So, this very first test case in work package five was extremely challenging – much more than we thought. Some overpredicted and some underpredicted but the results were not consistent as everyone was off in different ways."

The power of collaborating and coordination between researchers became a driver for significant improvement for everyone involved, levelling the comprehension between groups and improving the accuracy of predictions.

"We ensured people could talk to each other and help each other toward better solutions to these problems. If you do this all by yourself, you may hit a dead-end because your thinking is limited by one person or group, but if you have many groups talking to each other, they can help each other in different areas. One idea around this project is to help less developed programmes, in this respect. We have since seen that groups at their beginning of this, are now at the level of the more experienced programmes."

All participating waste management organisations agreed that developing accurate modelling tools, understanding material properties, the water saturation processes that lead to homogenisation and the scale effects, would prove very useful for design and engineering purposes in radioactive waste management.

As Sellin concluded, "We need something that can be trusted both now and in the future."



## BEACON

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### Project Objectives

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### Project Funding

**This project receives funding from the Euratom research and training programme 2014-2018 under grant agreement No 745942**

### Project Partners

• SKB, Sweden • RAWRA/SURAO, Czech Republic • POSIVA, Finland • ANDRA, France • NAGRA, Switzerland • ENRESA, Spain • RWM/NDA, United Kingdom • MKG, Sweden • UPC, Spain • GRS, Germany • CTU, Czech Republic • CUNI, Czech Republic • CEA, France • VTT, Finland • ULG, Belgium • BGR, Germany • KIT, Germany • LEI, Lithuania • CIEMAT, Spain • CLAY, Sweden • EPFL, Switzerland • ICL, United Kingdom • QUINTESSA, United Kingdom • NERC/BGS, United Kingdom • JYU, Finland / Expert Advisory and Review Board: IRSN • FANC • TU Clausthal • PSI • SSM

### Contact Details

Mary Westermark, Project Manager
SVENSK KÄRNBRÄNSLEHANTERING AB
Evenemangsgatan 13, Box 3091, SE-169 03 Solna, Sweden
**T:** +46 8 459 84 20
**E:** beacon@skb.se
**W:** https://www.beacon-h2020.eu

Mary Westermark | Patrik Sellin

**Mary Westermark** is the Primary Coordinator Contact and administrative coordinator for the Beacon project. She is certified PMI PMP and has a long experience in managing and coordinating projects, and employed at the Swedish Nuclear Fuel and Waste Management Co (SKB). At the moment she is also managing e g a project in regarding development of bentonite clay backfill installation equipment at SKB, she was WP leader and Primary coordinator contact of BELBaR, is main participant contact for DOPAS and has been involved in the management of LUCOEx, all earlier EU-projects.

**Patrik Sellin** is the scientific and technical coordinator of Beacon. He is a civil engineer, specialized on clay materials and has worked at Swedish Nuclear Fuel and Waste Management Co (SKB) since 1988. He is manager of the R&D programme for buffer and backfill long-term performance. He has been scientific coordinator and WP leader of the 7th framework BELBaR and WP leader of e.g. PEBS and Forge, all earlier EU-projects on bentonite clay.

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# Final workshop presentations

Beacon introduction (WP-leaders Antonio Gens, Olivier Leupin, Simon Norris, Patrik Sellin, Johan Swahn, Jean Talandier, Klaus Wieczorek)

Geomechanical coupled models involving unsaturated clays (Invited speaker Sebastià Olivella)

Experimental insights into pellet-based and granular bentonite buffer materials
(Invited speaker Enrique Romero-Morales, UPC)

Microstructural evolution of binary barriers during saturation (Maria Victoria Villar, Ciemat)

Bentonite homogenization and microstructure evolution modelled using a double structure constitutive law
(Antonio Gens, UPC)

How does wall friction drive bentonite heterogeneity?
(Robert Charlier, ULiege)

Swelling into a void as function of sample/void ratio, temperature and salinity (Caroline Graham, BGS)

Microstructure evolution in pellet based bentonite hydration: focus on pore size distribution characteristics
(Liliana Gramegna, ULiege)

Prediction of bentonite behaviour using hydro-mechanical model developed in COMSOL Multiphysics
(Darius Justinavicius, LEI)

Simultaneous determination of deformation and liquid content in swelling clay using X-ray radiography
(Joni Tanttu, JYU)

Large-scale testing of a Sandwich shaft seal
(Klaus Wieczorek, GRS)

Long-term aspects of bentonite self-healing and self-sealing via the IBL-project (Heini Reijonen, GTK)

Hydration survey of a large scale sealing experiment
(Bure, France)(Matías Alonso, Andra)

Study of coupled gas migration phenomena through clay barrier systems intended for the isolation of high-level nuclear waste (Marcelo Sánchez, Texas A&M University)

Hydro-chemo-mechanical modelling of bentonite sealing components (Marcelo Laviña, Amphos21)

Analysis of the mechanical behaviour of a heterogeneous bentonite backfill upon non-isothermal saturation
(Jose A. Bosch, EPFL)

Applications of a thermo-hydro-mechanical internal limit model to bentonite experiments
(Rebecca Newson, Quintessa)

Double porosity model for bentonite in thermo-hydro-mechanical processes (Steffen Beese, BGR)

Investigation of BCV bentonite (Jiri Svoboda, CTU/CU)

Modelling of the SKB assessment case using the HBM model (Daniel Malmberg, Clay Tech)

Sensitivity analysis of bentonite block-pellet tunnel backfill mechanical evolution during saturation
(Heidar Gharbieh, DSA ex. VTT)

Hydro-mechanical properties of compacted bentonites GMZ and MX80 (Chun-Liang Zhang, GRS/Bruig)

Estimation of the buffer homogenisation in the prototype repository (Mattias Åkesson, SKB)

Implementation of an advanced constitutive model for bentonite using MFront for safety and performance assessments of HLW-repositories in the numerical code OpenGeoSys (Eric Simo, CU)

Description of the hysteresis based material model
(Ola Kristensson, Clay)

Modeling of initially heterogen systems using the hysteresis based material model (Alex Spets, Clay)

Hypoplastic modelling of bentonite homogenisation
(David Mašín, CU)

Numerical modelling of an inhomogeneous bentonite barrier for radioactive waste disposal applications
(Giuseppe Pedrone (Lidija Zdravkovic), ICL)

Downscaled tests for studying the influence of the temperature in the homogenization process
(Xavier Pintado, Mitta Engineering)

EARB: Input towards submitted deliverables, the workshop contents and the project as a whole

Summarizing Beacon (Gens, Talandier, Wieczorek)

Impact on the treatment of the mechanical evolution of bentonite barriers in future assessments
(Olivier Leupin/Patrik Sellin)

### The objective of the final workshop

is to present, discuss, document and disseminate the findings and recent results of the Beacon project, and other projects and scientific studies concerning bentonite mechanical evolution, as well as the related modelling.

### Background and outcome

The workshop has been organized to discuss the final results from the Beacon project in relation to the current expectations of engineers, regulators, scientists, concerned stakeholders and the interested public. The workshop presents scientific-technical achievements and will highlight the current state of the art. It will include results from international scientific projects. It will also provide a forum for communicating and discussing the scientific-technical progress within the EURATOM disposal programme and other international studies. Participants will get access to all presentations.

The key audience for the workshop is the scientific and engineering community involved with studies of the mechanical evolution of bentonite barriers. Other important audiences are those generally interested in the project which could be civil society representatives, regulators, WMOs, those involved in final repository EURATOM programmes etc.

# Beacon conclusions

The Beacon project has made a significant contribution by improving knowledge on bentonite behaviour and the simulation of bentonite-based components for underground radioactive waste repositories. While much of the project was devoted to modelling and model development, the implementation of experimental tests using novel techniques such as imaging provided important data to calibrate and feed the models specially to describe the coupling between micro and macro scales.

The development of a database integrating a description of experimental tests from the bibliography identified at the beginning of the project to establish the state of the art and information on the THM models used to represent the behaviour of bentonites has constituted one of the first tasks. The database is now available and updated with the results obtained during the project.

The modelling teams participating in Beacon have significantly improved the capabilities of their models through the test cases proposed and simulated along the project. As a result of these developments and improvements, 10 teams are now equipped with coupled THM models that reasonably represent the behavior of bentonite-based components in the context of an underground radioactive waste repository. Thanks to this, they were able to model test cases representative of the engineered barrier and sealing concepts proposed by SKB, Nagra and Andra in the final modelling stage. The teams are generally able to reproduce and predict the mechanical evolution of bentonite in small-scale and large in-situ experiments, particularly the final swelling pressures, dry densities and degrees of saturation of the bentonite. These are key safety indicators for bentonite used as a buffer or seal in geological disposal facilities for radioactive waste.

The progress made throughout the project are illustrated by the improved agreement between models and experiments. This is a consequence of model updates with the inclusion of friction, improved formulations of water retention curves, inclusion of thermal effects, and the development of numerical solvers. At the beginning of Beacon, there was very little experience on this type of issues, but thanks to the joint effort, there are now at least 10 teams in the European Community that can deal with the mechanical evolution of bentonite barriers.

**Publications so far in Beacon**

**Beacon deliverables and database available at www.beacon-h2020.eu**


Bosch, J. A., Ferrari, A., & Laloui, L., 2020a. A numerical study on the coupled hydro-mechanical behaviour of compacted bentonite. E3S Web of Conferences.

Bosch, J. A., Ferrari, A., & Laloui, L., 2021. Coupled hydro-mechanical analysis of compacted bentonite behaviour during hydration. Computers and Geotechnics, Pergamon Press, Ltd.

Bosch, J. A., Ferrari, A., & Laloui, L., 2020b. A coupled hydro–mechanical approach for modelling the volume change behaviour of compacted bentonite. E3S Web of Conferences.

Daniels, K.A., Harrington, J.F., Sellin, P. , Norris, S., 2021a. Closing repository void spaces using bentonite: does heat make a difference? Applied Clay Science, Elsevier BV.

Daniels, K.A., Harrington, J.F., Milodowski, A.E., Kemp, S.J., Mounteney, I., Sellin, P., 2021b. Gel Formation at the Front of Expanding Calcium Bentonites. Minerals, MDPI.

Ferrari, A., Bosch, J. A., Baryla, P., & Rosone, M., 2022. Volume change response and fabric evolution of granular MX80 bentonite along different hydro-mechanical stress paths. Acta Geotechnica, 1-12.

Gens, A., Pomaro, B., Sánchez, M., Villar, M.V., 2010. On the hydration of unsaturated barriers for high-level nuclear waste disposal. Unsaturated soils. The 7th International Conference on Unsaturated Soils 2018 (UNSAT2018). University of Science and Technology, Hong Kong., Ng, C.W.W., Leung, A.K., Chiu, A.C.F., Zhou, C. (Eds)

Harrington, J.F., Daniels, K.A., Wiseall, A.C., Sellin, P., 2020. Bentonite homogenisation during the closure of void spaces. International Journal of Rock Mechanics & Mining Sciences, Pergamon Press Ltd.

Narkuniene, A., Poskas, P., Justinavicius, D., 2021. The Modeling of Laboratory Experiments with COMSOL Multiphysics Using Simplified Hydromechanical Model. Minerals.

Narkuniene, A.; Justinavicius, D; Poskas, P.; Grigaliuniene, D.; Ragaisis, V., 2022. The Modeling of Laboratory Experiments on Granular MX-80 Bentonite with COMSOL Multiphysics. Minerals, 2022; 12(3), 277.

Navarro, V., Asensio, L., De la Morena, G., Gharbieh, H., Alonso, J., Pulkkanen, V-M., 2020. From double to triple porosity modelling of bentonite pellet mixtures. Engineering Geology, Elsevier.

Iglesias, R.J., Gutiérrez, C., Carbonell, B., Villar M.V., 2018. Evolución de una barrera de bentonita inicialmente inhomogénea durante su hidratación. Avances en minerales de la arcilla. Libro de Resúmenes de la XXV Reunión de la Sociedad Española de Arcilla. XXV Reunión de la Sociedad Española de Arcilla. Suárez, M. & Morales, J.M. (eds.)

Sellin, P., Westermark, M., Leupin, O., Norris, S., Gens, A., Wieczorek, K., Talandier, J., Swahn, J., 2020. Beacon: bentonite mechanical evolution. EPJ Nuclear Sciences & Technologies.

Sun, H, Mašín, D., Najser, J., Neděla, V., Navrátilová, E., 2018. Bentonite microstructure and saturation evolution in wetting–drying cycles evaluated using ESEM, MIP and WRC measurements. Géotechnique.

Villar, M.V., Iglesias, R.J., García-Siñeriz, J.L., 2018. State of the in situ Febex test (GTS, Switzerland) after 18 years: a heterogeneous bentonite barrier. Environmental Geotechnics.

Villar, M.V., Iglesias, R.J., Carbonell, B., Gutiérrez-Álvarez, C., Martín, P.L., 2019. Evolution of a bentonite barrier initially inhomogeneous upon hydration. Euroclay 2019 Book of Abstracts.

Villar, M.V., Iglesias, R.J., García-Siñeriz, J.L., Lloret, A., Huertas, F., 2020. Physical evolution of a bentonite buffer during 18 years of heating and hydration. Engineering Geology.

Villar, M.V., Iglesias, R.J., Gutiérrez-Álvarez, C., Carbonell, B. 2021. Pellets/block bentonite barriers: laboratory study of their evolution upon hydration. Engineering Geology 292: 106272.

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