Construction, performance and dismantling of the Mock-Up-CZ experiment

Jaroslav Pacovský, Jiří Svoboda, Radek Vašíček
Faculty of Civil Engineering, Czech Technical University in Prague, Czech Republic

Keywords: radioactive waste, engineered barrier, bentonite, physical model

ABSTRACT

The Mock-Up-CZ experiment, involving a large-scale physical model of the vertical placement of a vessel representing a radioactive waste container according to the Swedish KBS-3V system, commenced in May 2002 in the laboratory of the Centre of Experimental Geotechnics. The impact of the heat produced by the radioactive waste container was simulated by the use of a heater placed inside the model which was then surrounded by a sealing barrier (buffer). The barrier, consisting of highly compacted bentonite blocks, was gradually saturated with artificial granitic water. The model was fully instrumented so that continual measurements of changes in swelling pressure, temperature and the extent of saturation could be taken. Initially the barrier was heated for 6 months without water input. For the next 37 months it was heated and water was added. The final phase, cooling, lasted a further 2 weeks. The experiment ended in January 2006 whereupon dismantling and post mortem analysis commenced. The construction, operation and dismantling of this experiment provided the Mock-Up-CZ team with very valuable information which, it is hoped, will contribute towards future research into the safe isolation of highly radioactive waste.

1 INTRODUCTION

Scientists throughout the world are involved in research into the safe treatment of spent nuclear fuel from nuclear power plants. The safest option, based on current knowledge, appears to be the long-term isolation of nuclear waste in a multi-barrier deep underground repository. A multi-barrier system consists of two basic parts – natural and engineered. The natural barrier consists of the host rock whereas the engineered barrier consists of the container holding the radioactive waste and the geotechnical barrier of highly compacted bentonite blocks which surrounds it. This combined system must be able to prevent the migration of dangerous radionuclides into the biosphere over a period of roughly a hundred thousand years. The design of a safely functioning engineered structure of this type and involving a time period of such magnitude is an exceptional challenge for the scientific world and necessarily involves engineers from many related disciplines. The design of a deep geological repository is truly a multidisciplinary task requiring the use of all the experimental tools presently at our disposal. A physical model of the mock-up type (built at a scale of 1:1) is one such tool (Verstricht 1999).

2 MOCK-UP–CZ CONSTRUCTION

2.1 Basic description

Mock-Up-CZ was a vertical model of a bench-scale buffer mass test of Czech smectitic clay with a KBS-3V arrangement, constructed at the Centre of Experimental Geotechnics (CEG) of the Faculty of Civil Engineering, CTU in Prague from 2000 to 2002 (Pacovský 2003). It was designed as a long-term experiment the aim of which was to model the behaviour of a sealing barrier composed of highly compacted blocks.

The model was positioned in an underground test silo with dimensions 3000 x 3000 x 3000mm. The Mock-Up-CZ model itself consisted of a steel tank with a cylinder diameter of 800mm and a height of 2240mm. The system was designed to withstand internal pressure of up to 5MPa (see Figure 1). The vessel containing highly radioactive waste was simulated by using a heater placed in an experimental bin (see Figure 2).

Figure 1: Mock-Up-CZ Figure 2: Heater emplacement

The heater was fully automated and the temperature could be adjusted in the range 20°C to 300°C.

Based on a contemporary evaluation of Czech bentonite research, it was decided that the most appropriate buffer material would consist of a mixture of treated bentonite, silica sand and graphite. Sand was added in order to facilitate control of the buffer's swelling abilities and the plasticity of the bentonite mixture. Graphite was added to the mixture in order to increase thermal conductivity so that the heat produced by the container was more easily redistributed towards the natural barrier. The basic mixture consisted of 85% bentonite, 10% silica sand and 5% graphite. The lining of the container comprised individual blocks assembled into the form of an annulus whereas the space between the barrier blocks and the walls of the experimental bin was filled with a loose, hand-compacted mixture. The swelling pressure (swelling ability) of the highly compacted blocks was approximately 5MPa with a dry density of 1750kg/m^3.

The potential inflow of granitic water from the natural barrier (it is expected that the Czech underground repository will be constructed in granitic rock) was simulated by using a flooding system installed on the inner side of the bin. A hydration system allowing an increase in hydration pressure of up to 1MPa was placed outside the experimental silo. Synthetic granitic water was used for saturation; the amount of water and the saturation speed were continuously recorded (Pacovský 2003).

2.2 Model instrumentation

The Mock-Up physical model was equipped with 52 thermometers, 50 hydraulic pressure cells, 37 humidity sensors of varying construction and 20 resistive tensometers. Temperature, swelling pressure and hydration measurements were taken continuously from inside the bentonite barrier throughout the entire duration of the experiment. These checks were carried out at six measurement profiles located from the top to the bottom of the vertical model (see Figure 3). Measurements of energy consumption and the amount of saturation water used were also taken. Samples of several metals that may be used in future container construction were placed inside the barrier for corrosion research purposes.

The registration system and the evaluation and transfer of data required the use of 3 small portable AD-SYS data loggers connected to a CEG server and the data recorded was publicly available on the model's web site. The experiment was monitored using 4 web-cameras operating around the clock.

The model was constructed so that samples could be taken (at each stage of the experiment) from the bentonite barrier in a total of 22 locations using core drilling (see Figure 4).

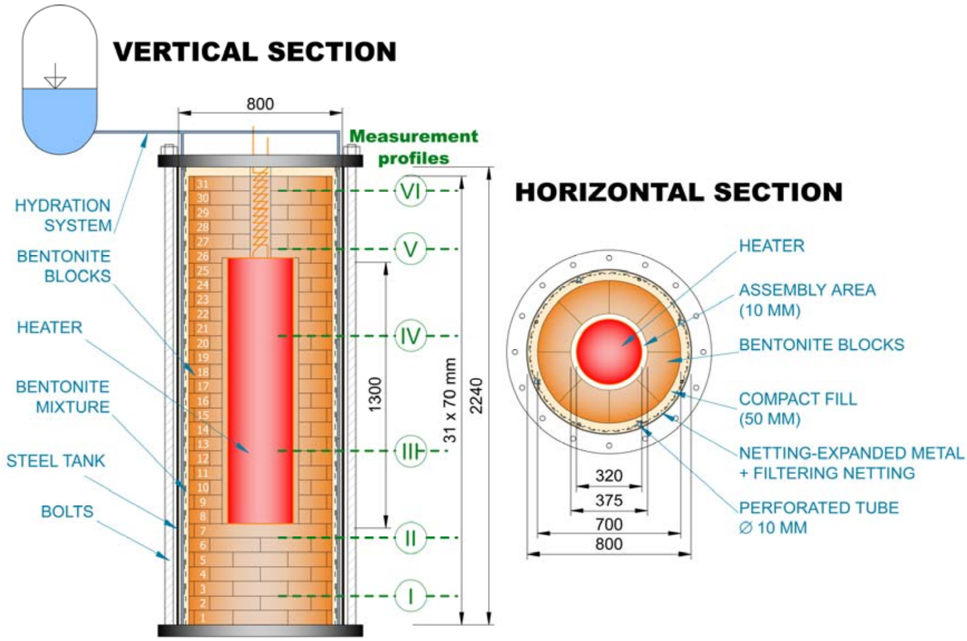

Figure 3: Plan of the experiment showing measurement profiles

Figure 4: Core drilling

3 PERFORMANCE OF THE EXPERIMENT

3.1 Experimental procedures

The experiment was divided into 3 phases.

Phase 1: The filter was kept dry and the heater was switched on to reach a maximum temperature in the bentonite of 90±5°C. Temperature, swelling pressure and hydration recordings were taken continuously for 6 months. Buffer evolution in Phase 1 consisted of the redistribution of initial pore water generated by the thermal gradient across the buffer and the homogenisation and subsequent consolidation of the filling mixture as a result of the swelling pressure exerted by the hydrating and expanding blocks.

Phase 2: The power to the heater was maintained at a constant level and synthetic granitic water was supplied to the vessel through the filter. Temperature, swelling pressure and hydration recordings were taken continuously as the buffer material was presumed to reach a state of full water saturation.

Core samples were taken at pre-set intervals throughout phase 2 in order to physically determine the saturation process and the effect of various processes at work on the permeability and swelling capacity of the bentonite mixture.

Phase 3: Saturation and temperature loading of the buffer by the heater were stopped during this phase. When the heater was switched off, the cooling phase, lasting nearly two weeks, commenced.

3.2 Data measurement

During phase 1 the experiment rapidly reached equilibrium thermal state; the impact of temperature resulted in a redistribution of the original water content. Water content increased to such an extent in those parts of the barrier farthest from the heater that swelling pressure was activated.

In phase 2 the barrier was gradually saturated (see Figure 5) and a rapid increase in swelling pressure occurred reaching a maximum value of 2.2MPa. The taking of samples allowed the accurate observation of the progress of saturation; full saturation was reached after 39 months at which time 400 litres of synthetic granitic water had been absorbed. Full saturation resulted in an increase in thermal conductivity which led to an overall decrease in barrier temperature.

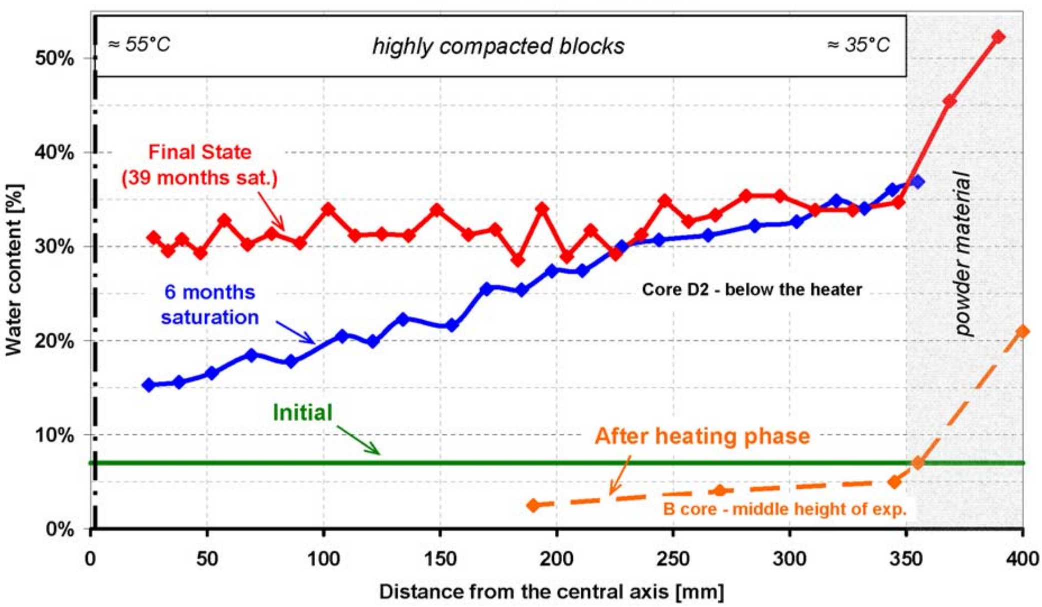

Figure 5: Evolution of water content distribution

4 DISMANTLING OF THE EXPERIMENT

Mock-Up-CZ was originally designed as a mono-disciplinary, geotechnical experiment the main aim of which was to gain experience in the construction and operation of large physical models for the research of the long-term behaviour of a sealing barrier made up of highly compacted blocks (Huertas 2000). It was not expected that the relatively low-cost instrumentation employed within the model would provide such interesting and useful information on the THM (thermo-hydro-mechanical) behaviour of the barrier. At the beginning of 2005, as a consequence of the outstanding success of the experiment, the Czech Technical University and the Radioactive Waste Repository Authority agreed that experts from various related scientific disciplines i.e. geochemical, mineralogical, corrosion and bacteriological research from 4 universities, The Czech Technical University (Prague), The Charles University (Prague), Masaryk University (Brno) and the Institute of Chemical Technology (Prague), would be invited to take part in the last phase of the experiment (dismantling and post mortem analysis)

4.1 Dismantling project

A detailed dismantling schedule in the form of a manual was drawn up so as to complete the process of removing the bentonite filling from the experimental vessel in as short a time as possible bearing in mind the various requirements of all the researchers involved.
The number of samples taken, their size and shape, their exact location within the vessel and the labelling system to be used were determined only after detailed consultation with all the partners. Moreover, the manual defined the ways in which particular samples should be protected (paraffin protection, light protective cover, vacuum protection in a PE cover). All the partners were connected to the CEG server, which, by means of 4 web cameras, provided on-line information on work in progress and the various samples being taken, even informing partners from other universities that their samples were ready for collection. Complete photographic documentation of the samples was made publicly available on the CEG server.

4.2 Course of dismantling

Dismantling commenced on 30th January 2006 when the heater was switched off and the saturation media disconnected. After the top bolts were unscrewed, the upper lid was removed. At this stage, measurement of the most important parameters (swelling pressure, moisture content) was still ongoing. The dismantling stage continued with the removal of the filling of the experiment (31 layers of highly compacted bentonite blocks) accompanied by the taking of both bentonite and corrosion samples, strictly according to the manual. Measurement gauges were dismantled in order that they could be recalibrated.
A total of 1372 samples were taken during the dismantling stage which ended on 17th March 2006 (see Figures 6, 7).

Figure 6: Opening of Mock-Up-CZ

Figure 7: Sampling

4.3 Selected results

The geotechnical, geochemical, mineralogical, micro-biological and corrosion research of samples taken from the experiment will be concluded in 2008. Results obtained to date have been discussed at specially organised workshops.
Geotechnical research is focused primarily on swelling ability, permeability, Atterberg limits and thermal conductivity. Maps of water content, temperature, density and swelling pressure distribution have been created based on test results (see Figure 8). Furthermore, it has been proven that 90% saturation was reached within the experimental vessel. In spite of the significant homogenisation of the barrier (dry density) equalisation of the pressure field did not occur (swelling pressure). The results of various geotechnical tests have still not proved the impact of thermal loading on changes in the behaviour and/or quality of the bentonite.
The results of geochemical and mineralogical research to date indicate a certain amount of degradation and irreversible changes to the bentonite.

Microbiological research has proved only the high quality of the heterotrophic organisms; no bacteria have been identified which are capable of oxidizing iron and sulphates.
The above results are provisional and multidisciplinary research continues.

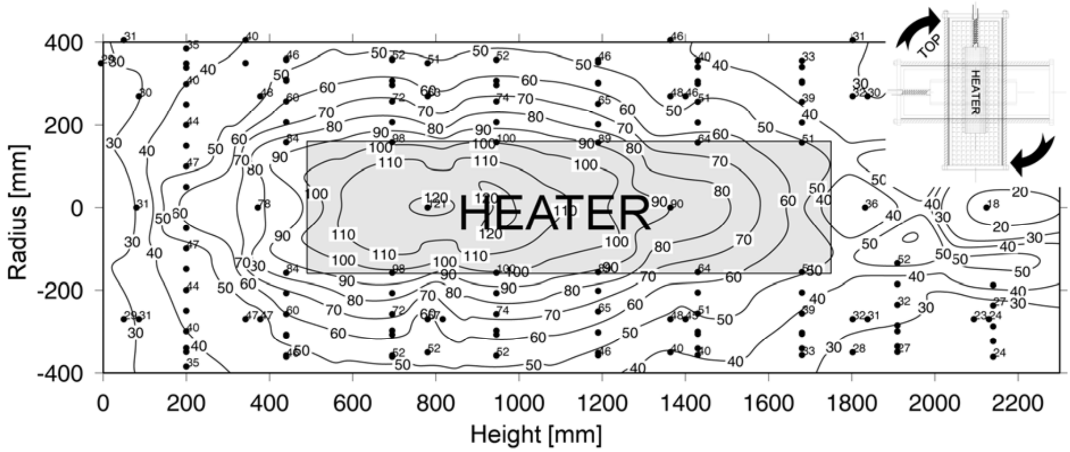

Figure 8: Temperature distribution

5 CONCLUSION

The Mock-Up-CZ experiment was the first experiment of its kind in Central Europe. In contrast to similar experiments abroad which are performed by specially established organisations devoted to the research of radioactive waste related issues, Mock-Up-CZ was operated solely by universities. The original aim was to gain experience in the use of physical models at a scale of 1:1, such models not being a traditional research tool employed by geotechnical engineers.
The study of the safe isolation of high level radioactive waste requires the training of young specialists and it is clear that universities have a valuable contribution to make in this area.
The construction, operation, dismantling and evaluation of the experiment have provided and will continue to provide important information on the potential use of Czech calcium – magnesium bentonites in the construction of deep repositories. The use of the world standard Wyoming sodium bentonite in such repositories is not feasible for most countries for economic reasons.
The Czech Republic intends to put a deep geological repository into operation before 2065 and we believe that Mock-Up-CZ has already made and will continue to make a valuable contribution to that project.

ACKNOWLEDGEMENTS

The experiment could not have taken place without the support of the CTU - Faculty of Civil Engineering, Prague – CIDEAS (project no. 1M6840770001) and RAWRA – Czech Radioactive Waste Repository Authority.

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