Creep and swelling of bentonite for the safety of disposal pit in high-level radioactive waste repository

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Abstract. Displacement of the canisters with high-level radioactive waste (HLW) could be induced by creep and swelling of buffer material bentonite in the disposal pit of HLW geological repository. The displacement of the canisters could lead to the safety of HLW repository decrease. Several large scale experiments with bentonite and heater which was only regarded as components that would simulate the reference canister with respect to dimensions, weight and thermal emission were conducted in situ and laboratory respectively. The evolution of displacement of the heater, RH and stress in the bentonite indicate that the displacements of the heater are controlled by consolidation and volumetric/deviatoric creep of the bentonite under the heater induced by weight of heater, thermal expansion of heater and bentonite with heating, as well as swelling process of bentonite with the hydration. The canisters could move upward slightly in disposal pit during the early phase of HLW disposal. With the saturation of bentonite and stress redistribution in bentonite, the canisters could remain steady and minor fluctuation. After the bentonite in the disposal pit saturated fully, the canisters might move downward due to the weight of canisters. The thickness of buffer material around HLW canister and long-term stability of HLW canister should be considered in the design of the HLW repository. The parameters and evaluation of THM processes taking place in the compacted bentonite-buffer during the early phase of HLW disposal can provide a reliable database for numerical modeling and further investigations of EBS, and the design of HLW repository.

1. Introduction
An improved design with a copper canister surrounded by a bentonite buffer in a vertical deposition hole placed in crystalline rock at a depth of approximately 500 m, and with carefully backfilled deposition tunnels – the KBS-3 method (SKBF/KBS 1983) – was in 1983 approved by the Swedish Government to fulfill the then applicable Swedish law as “a method for final disposal of spent nuclear fuel, which can be accepted with respect to safety and radiation protection” [1].
The development work following the Governmental approval continued with laboratory research, underground research laboratory (URL) tests and system analyses having the objective of decreasing uncertainties in prediction of long-term evolution and performance, as well as of establishing robust engineering practice for manufacturing and deposition technologies. The Canister Retrieval Test (CRT, from 1999 to 2006) and the Prototype Repository (since 2001) were full scale field experiments simulating a deposition hole in a HLW repository of KBS-3V at Åspö Hard Rock Laboratory (Åspö HRL) [2, 3].
The main purpose of CRT was to demonstrate that retrieving a canister is technically feasible after full water saturation of the bentonite buffer encapsulating the canister has been achieved [4]. The representative total vertical plug displacement measured by transducer with 13 mm additional free swelling before installation of the rock anchors was 36 mm in 5 years operation in CRT [5]. The Prototype Repository was located to the very end of the Åspö HRL ramp, at 450 m depth below ground surface. It was designed as a replica of a part of a KBS-3V repository and represented an upscauling of the Stripa Mine Buffer Mass Test. The Prototype Repository included studies of individual engineered barriers (EB) as well as their combined engineered barrier system (EBS) and their interaction with groundwater and surrounding rock. Displacement of the canisters was tracked in Prototype Repository [6, 7]. 23 mm and 15 mm upward of the canisters were measured in hole No 6 and hole No 5 separately.

Börgesson et al. [8] studied the processes of consolidation/swelling, volumetric creep and deviatoric creep caused by the canister weight, as well as stress caused by buffer/backfill material swelling for canister displacement in KBS-3V concept. Liu et al. [9] simulated the evolution of a conceptual HLW repository in China and indicated the safety for nuclide transport would be reduced because the overpack may creep to the floor of disposal pit in hydro-mechanical swelling (HMS, coupled hydro-mechanical and swelling pressure of buffer and backfill) case. The preliminary concept of high-level radioactive waste (HLW) repository in China will be a shaft-tunnel model with a multi-barrier system, located in saturated zones in granite [10]. Engineered barrier system (EBS) with buffer material that surrounds the canisters containing the waste is main part of multi-barrier system. The Gaomiaozi (GMZ) bentonite is considered as the potential EBS buffer material and Beishan site as the most potential site for HLW disposal project in China [11]. A large scale thermal-hydro-mechanical-chemical (THMC) China-Mock-Up test was designed as a vertical cylindrical tank (inner diameter 900mm and height 2200mm) filled with compacted GMZ-bentonite to simulate the evolution of canister of HLW repository in China. It was built in 2010 and operated continually until now. The relationship between displacement of the heater and the temperature of heater, as well as the evolution of the bentonite are analyzed in this paper.

2. Experimental Infrastructure and Test Procedure

2.1. Structure of China-Mock-Up Test

The China-Mock-Up test were constructed as 8 main components (Fig. 1): a steel tank; a central electrical heater with a temperature control system; a hydration system; the engineered barrier; sensors; gas measurement and collection system; and a Data Acquisition System (DAS). The steel tank was to simulate the vertical disposal pit in dimensions of inner diameter 900mm and height 2200mm. The heater in the China-Mock-Up was manufactured of 1 ton carbon steel in dimensions of diameter 300mm and height 1600mm. The pressure due to the weight of heater is 1.24 MPa. It was only simulated the thermal emission, dimensions, and weight of the reference canister. The temperature of the heater was controlled by temperature monitoring system automatically.

The hydration system was to simulate the water penetration from the host rock. The main chemical compositions of water used in hydration system are \( \text{SO}_4^{2-}(718\text{mg/L}), \text{Cl}^- (771\text{mg/L}), \text{Na}^+(798\text{mg/L}), \text{Ca}^{2+}(177\text{mg/L}) \) from borehole BS05 of Beishan site.

The engineered barrier composed of the compacted GMZ bentonite blocks and pellets surrounding the heater. The GMZ bentonite powders were compacted to bentonite blocks with dry density of 1710 kg/m³. The averaged dry density of bentonite pellets was 1300 kg/m³. The installation space between heater and bentonite blocks, or steel tank were filled with bentonite pellets and powders. About 2058 kg bentonites were filled in the tank. Its average dry density was 1600 kg/m³.

More than 160 sensors including the temperature, relative humidity (RH), stress and displacement were installed inside and outside the facility to monitor the evolution of bentonite and heater etc. The inside sensors were distributed in bentonite blocks and pellets at 7 sections (I–VII) vertically.
2.2. Displacement Sensor

The selected displacement sensor, Linear Variable Differential Transformer (LVDT) sensors HTGGA-20 from KING SENSOR (China) shown in Fig. 2, were fairly small for to disturbing the whole system as less as possible. The measured principal is Magnetic transfer. The lengths of LVDT sensors at the bottom and top of the heater are 250mm and 300mm, respectively. The measuring range of displacement sensor is ±20mm and the accuracy is more than 0.1%. The diameter of the main part of the LVDT sensor is 22mm. LVDT sensors were specifically constructed in steel 316L with rubber sleeve at the top assuring corrosion resistance and water tightness.

The LVDT sensors were placed vertically into holes drilled in the bentonite blocks in the direction as Fig. 2. The top of LVDT1 to LVDT3 was screwed on a steel plate which connected to the bottom of the heater. The bottom of LVDT1 to LVDT3 was screwed on the inner bottom surface of the steel tank. The top of LVDT6 to LVDT8 were screwed on a steel plate which connected to the steel tank lid. The bottom of LVDT6 to LVDT8 was screwed on the top of the heater.

2.3. Relative Humidity Sensor

The selected RH sensors were HC2-C04 which measured principal was capacitance from Rotronic (Switzerland). 24 RH sensors were placed into holes drilled into the bentonite blocks at seven sections
(I–VII) vertically. RH sensors H2 & H4 located in the bentonite blocks at section I and II under the heater respectively. RH sensor H20 located in the bentonite block at section VI above the heater. Because the permeability of bentonite is very low and measurement data of RH sensors could be influenced by recessed hollows, moisture content of the bentonite might be deduced by measurement results initially.

2.4. Stress Sensor
The selected stress sensors were CYG-1712 which measured principal was Wheatstone bridge from SQSENSOR (China). 37 stress sensors were distributed in bentonite blocks at 7 sections. Stress sensor S15 was placed under the heater at section II. Stress sensor S36 was placed above the heater at section VI. Stress sensor S32 was placed around the heater in hoop at section V.

2.5. Test Procedure
The China-Mock-Up experiment was assembled completely on 10th September 2010. The data acquisition and monitoring system has recorded real-time all the measurement data from January 1, 2011, and the data identified as ‘day 0’ on the time scale after pre-operation. The heater was switched on to reach temperature 30°C and kept constant from January 19, 2011. Then the temperature raised to 90°C gradually at speed 1°C/d from day 188 to day 400. Finally, the constant temperature control model by the computer automatically to maintain 90°C was switched on. It was commenced on real THMC experiment with the water injection started from July 8, 2011 (day 188). Water injection rate increased from about 400g/day to 1500 g/day gradually was controlled artificially to avoid potential damage to the sensors by a rapid saturation process in the first stage. Then a constant pressure increase from 0.2MPa to 1MPa gradually was controlled since August 25, 2013 (day 967). To be mentioned here, there were no water supplies artificially sometimes which were due to the holiday and some maintenance.

3. Test Evolution and Discussion

3.1. Displacement Evolution of Heater
The vertical displacements measured by 6 LVDT sensors are given in Fig. 3. The positive value recorded by the LVDT6 to LVDT8 indicates the sensor compressed and the heater moved upward. The negative value recorded by the LVDT1 to LVDT3 indicates the sensor tensile and the heater moved upward. Maybe because the electric part of the LVDT6 to LVDT8 sensor connected with the heater directly and the THMC harsh environment, LVDT6 to LVDT8 failed one after another after the temperature of the heater reached 90°C and hydration. As for the movement evolution of the heater, 4 phases could be observed: a) the heater moved downward and upward slowly with a maximum downward displacement 0.06mm and upward displacement 0.29mm in 188 days; b) the heater moved upward 2.6mm quickly when the THMC experiment was commenced on with the water injection started and the heater temperature increased to 90°C in 346 days; c) the heater moved upward continuously, but the movement rate gradually decreased to a stable displacement 5.6mm with some fluctuations when temperature was kept on 90°C and water injection continually in 730 days; d) the heater moved upward slowly again with water injection. A maximum upward displacement 8.64mm of the heater was recorded by LVDT3 at day 1590. The six LVDT sensors have similar data in different direction at phase I to phases III. The reason for the difference between LVDT6 and LVDT7 maybe is bentonite penetrated into the gap between the steel plate which screwed the LVDT6 to LVDT8 and the top lid of the steel tank. The reason for the difference among LVDT1, LVDT2 and LVDT3 maybe is bentonite penetrated into the gap between the steel plate which screwed the LVDT1 to LVDT3 and the bottom of the heater. The penetration point of bentonite is likely near the LVDT6, LVDT1 and LVDT2 respectively.
Figure 3. Evolution of the heater displacement (positive value means the LVDT was compressed, negative value means the LVDT was tensile.)

The heater was supported by the compacted bentonite completely in China-Mock-Up. Therefore, the movement evolution of heater could be influenced by mechanical performance of compacted bentonite. With the weight 1 ton of the heater and 1.24 MPa pressure under the heater, the compacted bentonite under the heater could be consolidated and had volumetric/deviatoric creep. With the heating, the thermal expansion of the heater and bentonite could occur. Swelling of the bentonite with hydration could be the main reason for the upward movement of the heater.

3.2. Effect of Temperature and RH on the Heater Displacement
The temperature of heater and the evolution of compacted bentonite recorded by different sensors indicate that the displacement have directly relationship with the evolution of temperature and the RH in bentonite (Fig. 4).

For the phase I, heater moved upward a little and kept stable with some fluctuations because of the thermal expansion on heater and bentonite as the temperature increased to 30°C and kept constant.

For phase II, heater moved upward quickly because of the continuous thermal expansion of heater and bentonite which induced by the temperature increased to 90°C gradually. The increase of RH could be observed by RH sensor H2 slowly. That meant the bentonite under heater wet and the swelling of the bentonite occurred a little. The decrease of RH could be observed by RH sensor H20. That meant heat transferred from the heater led to the drying effect at the bentonite above the heater and the volume of the bentonite might decrease.

For phase III, temperature was kept constantly on 90°C. The increase of RH could be observed by RH sensor H2 & H4 quickly. That meant the bentonite under heater wet and swelling quickly. The curves of displacement have the same trend with the curve of RH of H2. With the bentonite under the heater saturated, the heater gradually stop moved upward. The decrease of RH can be observed by RH sensor H20. That meant the bentonite above the heater dried continually. The movement upwards of the heater at phase III was mainly caused by swelling of bentonite under the heater.

For phase IV, the increase of RH can be observed by RH sensor H20 quickly after 700 days. That meant the bentonite above the heater wet and swelling quickly. Because the total mass of bentonite in the test tank had not change and the volume of the bentonite above the heater swelled, the bentonite above the heater pushed the bentonite around the heater to the bottom of the heater and induced the heater moved upward again.
3.3. Effect of Stress in Bentonite on the Heater Displacement

Evolution of displacement and stress in bentonite are shown in Fig. 5. The stress might be induced by the gravity of heater, thermal expansion on heater and bentonite due to rising temperature, and bentonite swelling due to water penetration.

For the phase I, a maximum downward displacement 0.06 mm of the heater was recorded at day 46. That can be deduced the bentonite under heater might be consolidated and had volumetric/deviatoric creep at 1.24 MPa induced by the weight 1 ton of the heater.

For the phase II, the stress recorded by S15 which located in section II under the heater and the stress recorded by S36 which located in section VI above the heater indicated that the stress in the bentonite under the heater increased slightly with fluctuation. That meant the bentonite under heater wet and the swelling of the bentonite occurred. The movement upwards of the heater at phase II was partly caused by the swelling bentonite.

Figure 4. Evolution of displacement with temperature and RH in the bentonite

Figure 5. Evolutions of displacement and stress in the bentonite blocks

For the phase III and IV, the stress recorded by S15 indicated stress in bentonite under the heater increased quickly from 700 days to 1060 days. Then the stress kept on 2 MPa with a fluctuation. The
stress recorded by S32 which located in section V around the heater increases from 646 days to 1426 days quickly because it is near the water tube than S15 and S36. Based on the stress and RH, the bentonite under the heater was saturated after 1060 days could be deduced. The stress under the heater adjusts with the stress increase around the heater and the weight of heater. The heater moved up slowly again with the saturation of bentonite under the heater and around the heater after 700 days. The fluctuation of LVD T1 and LVD T2 has the same trend with the stress sensor S15 and S32. The stress recorded by S36 increased during phase III, then kept fluctuation, and increased quickly after 1200 days. That indicated the heater moved up and induced the pressure in the bentonite above heater increased. The stress kept fluctuation with the heater kept fluctuation. The stress above the heater exceeds the stress under the heater after 1296 days. Then the stress above the heater push the heater moved down. With the heater moved down, the stress above the heater decreased. As the water penetrated to bentonite and the bentonite swelling continuously, the stress in the bentonite increased again. The bentonite above the heater pushed the bentonite around the heater to the bottom of the heater and induced the heater moved upward again. The fluctuation of LVD T3 has the same trend with the stress sensor S36 after 1296 days. A maximum upward displacement 8.64mm of the heater was recorded at 1590 days. With the saturation of bentonite and stress redistribution in bentonite, the heater remains steady and minor fluctuation. Therefore, the movement upwards and fluctuation of the heater at phase IV was mainly caused by swelling of bentonite, as well as stress redistribution.

After the bentonite in the disposal pit saturated fully, the canisters might move downward due to the weight of canisters as the phase I. But with the in situ stress, the canisters might remain steady and minor fluctuation. More tests about the movement of canisters in the disposal pit should be done in the future.

4. Summary
A large scale THMC China-Mock-Up test was built and operated specially to simulate the movement evolution of canister based on a preliminary concept of HLW repository in China. A series of valuable data about the evolution of heater displacement, temperature, RH and stress in bentonite have been obtained. The movement evolution of heater showed four phases: a) downward and upward displacement slowly in 188 days; b) upward displacement quickly when the THMC experiment was commenced on with the water injection started and the heater temperature increased to 90°C in 346 days; c) upward displacement continuously with movement rate gradually decreased to a stable in 730 days; d) upward displacement slowly with fluctuation. A maximum downward displacement 0.06mm and upward displacement 8.64mm of the heater were recorded at day 46 and 1590 separately. Heater displacement could be strongly influenced by thermal expansion of heater and mechanical performance of bentonite. The movement downward of the heater was controlled by consolidation and volumetric/deviatoric creep at 1.24 MPa induced by the weight 1 ton of the heater. The movement upwards of the heater was controlled by the thermal expansion of heater and bentonite, swelling of bentonite under the heater, around the heater, and above the heater in turn. With the saturation of bentonite and stress redistribution in bentonite, the heater remains steady and minor fluctuation. The thickness of buffer material around canister and the long-term safety of canister should be considered in the design of the HLW repository. The parameters obtained by China-Mock-Up test can provide a reliable database for numerical modeling and long term prediction of the THMC coupled behavior of EBS in HLW repository.

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