Seismic response of canister in buffer material under water invasion condition by centrifuge modeling

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Abstract

The high-level waste (HLW) disposal is isolated from Earth biosphere by multi-barrier systems including engineering and natural barriers at deep ground. The disposal holes are drilled and located in intact rock. Canister and buffer material were then set up in the hole. The canister should be very high stability and not easily affected by natural environment, humanity activities and tectonic movement. However, Taiwan locates at Pacific Rim of Fire and earthquake occurs frequently. As a result, the effect of earthquake-induced vibration on the canister, buffer and disposal system is impartment and needed to be investigated. This research assumes that the deposition is set up in granite deposit and the disposal hole has no deformation and cracks. Referring to KBS-3V concept and its geometry, the centrifuge model was designed with 1/10 size of prototype and tested in 10 g artificial acceleration field. Therefore, the in situ stress between canister and buffer material was simulated. Seismic events were then input by shaking table for pre-shaking and main shaking events. During shaking, acceleration, pore water pressure and total pressure histories were measured by sensors to realize the seismic interaction behavior between canister and buffer. Total 6 models were conducted with different initial water content conditions to simulate the buffer after construction, after underground water invading to disposal hole and after saturation of buffer material. After centrifuge modeling, container was disassembled to check the crack development on the surrounding buffer materials.

1. Introduction

According to IAEA statistical data by 2017, there are 451 nuclear reactors in operation and 60 reactors under construction. It will produce approximately 12000 tons high-level waste (HLW) for a year. Because byproducts of nuclear power generation and spent fuel are radiotoxic to the humanity and environment, the disposal of HLW is seriously considered. Several series of researched were conducted around the word for disposal systems. For HLW disposal, deep geological disposal, which is a multi-barrier system, a combination of natural barrier and engineering barrier, is a widely accepted design concept. Because of its robust defense against the external factor of geological activities.

According to the concept of Svensk Kärnbränslehantering AB (SKB) KBS-3 for final disposal, there are 4 points for basic concept. First, the spent nuclear fuel is encapsulated in tight, corrosion resistant and load bearing canisters. Second, the canisters are deposited in crystalline rock at a depth of 400–700 meters. Third, the canisters are surrounded by a buffer which prevents the water flow and protect them. Forth, the cavities in the rock that are required for the deposition of canisters have been backfilled and closed.

HLW will be stored in canister and then burry into disposal hole with buffer surrounded. Through the host rock and engineering barriers (canister and buffer) sealing, the system isolate the radioactive wastes and reduce the virulence to an acceptable range due to a long-term isolation and keep it safe from natural environment, humanity and tectonic activities. Even if, when HLW leaks out, the repository can seal leakage and dilute radio toxicity, thanks to the substantial expansion capacity of buffer and backfill material. Therefore, this design is considered as an adequate and appropriate solution.

The repository system need to have a concrete resistant against many hydrological and geological activities in a long period. Some of these are the extreme natural disaster such as earthquake, climate change, etc. Taiwan locates at Pacific Rim of Fire, a subduction area with earthquake frequently. Earthquake induced vibration have a certain effect to the safety of repository system. In addition, it is considered if the initial condition of disposal system changes under long-term storage, according to Jonny Rutqvist et al. (J. Rutqvist, 2013) the power of the radiation HLW may take more than 10000 years to fully dissipate. Therefore, a thoughtfully investigation about the effect of environment factors on the repository components.

There are several researches carried out on the physical and mechanical properties of bentonite based buffer material. For instance, the physical and mechanical properties reported in SKB reports (SKB, The Buffer and Backfill Hand book part II: Materials and techniques 2001), (SKB, The buffer and backfill handbook Part I: Definition, basis relationships and laboratory method 2001). These works provide the reference values for the properties of the buffer.

High level waste repository construction is a highly complex and cost consuming process, according to R. Pucsh (Pusch 1994) the cost for Swedish repository for radioactive waste is about 740 million SEK (about 89 million USD) in 1987. Therefore, the data of full scale testing of repository is very limited. Some large projects is developed by the international cooperation for a deeper understanding on this issue. DECOVALEX (Development of Coupled Models and their Validation against Experiments) start in 1992 is a considerable effort that sponsored and performed by an international organizations in Canada, Finland, France, Japan, Sweden, U.K. and USA. The main result of this project as also the numerical and theoretical approaches between 1992 and 1995 reported in various aspects by Ove Stephansson, Lanru Jing and Chin-Fu Fang (Stephansson, Jing and Tsang 1996). The current state of project updated on their official website (DECOVALEX 2017).

The seismic performance of canister and its surrounded buffer material is critical for a reliable design. As aforementioned, the full-scale experiments provide the reliable data for research with highly complex and enormously expensive that usually hold by an international research project. On the otherhand, the seismic load is very difficult to generate and control in a full-scale experiment.

Therefore, this study investigates the seismic response of the canister embedded in the bentonite-based buffer material via geotechnical centrifuge shaking table test, which is a more affordable approach to this problem.

2. Research equipment

2.1 Design of centrifuge model

Referring to final disposal concept of KBS-3V, a 1/10 model was designed. Geometry of disposal hole is show as Figure 1. Canister is installed at center of disposal hole surrounded by buffer, and a dead load is applied on top of buffer to simulate the loading by backfill of tunnel. The outer is aluminum alloy container to simulate the base rock. The aluminum alloy can apply sufficient strength with ductile behavior and lighten the total model weight as compared to the iron material. Before centrifuge modeling test, direct shear tests were conducted to know the friction coefficient of interface between bentonite with granite and bentonite with alumina alloy, respectively. Test result shows that the difference between two interfaces is only about one degree. As result, the alumina alloy container was then used without roughness treatment at the inside surface.

Accelerometers are installed to top and bottom of container and canister, labeled as BTA (Box-Top Acceleration), BBA (Box-Bottom Acceleration), CTA (Canister-Top Acceleration) and CBA (Canister -Bottom Acceleration), respectively. Around the surface of canister, the pore water pressure and total pressure transducers are arranged to measure the pore pressure and total pressure (including water pressure, earth pressure and impact pressure) during test.

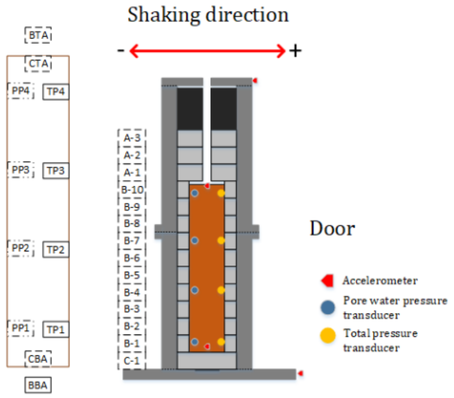
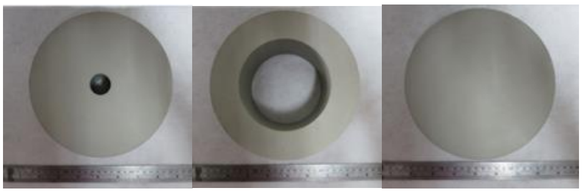


Figure 1: KBS-3V concept to centrifuge model

2.2 NCU geotechnical centrifuge

The geotechnical centrifuge of Centrifuge Modeling Laboratory of Experiment Center of Civil Engineering, National Central University (NCU) has a nominal radius of 3 m as shown in Figure 2. The capacity is 100 g-ton, meaning that the centrifuge can spin to 100 g with 1-ton model. A 1-D servo-hydraulically controlled shaking table is equipped on the platform. Therefore, one-dimensional horizontal base input shaking can be applied to the tested model during spinning of centrifuge. The shaking table has maximum shaking force of 53.4 kN with maximum table displacement of ±6.4 mm and raises up to 80g centrifugal acceleration. The nominal operating frequency range is 0-250 Hz. At 80 g artificial acceleration field, the maximum table payload is 400 kg (equivalent to a capacity of 32 g-ton).

Figure 2: NCU geotechnical Centrifuge



(a) (b) (c)

Figure 3: Different shape of buffer blocks

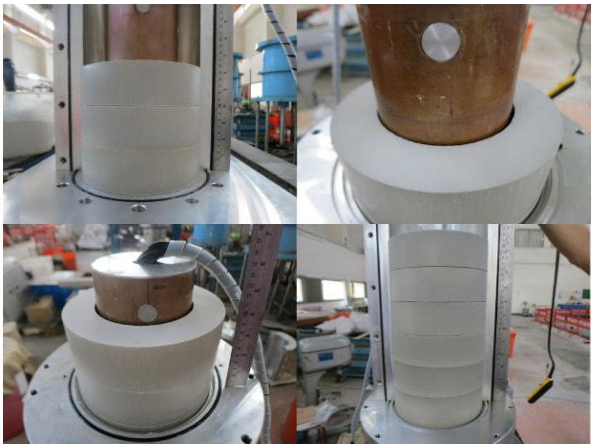


Figure 4: Assembling of 1/10 centrifuge model

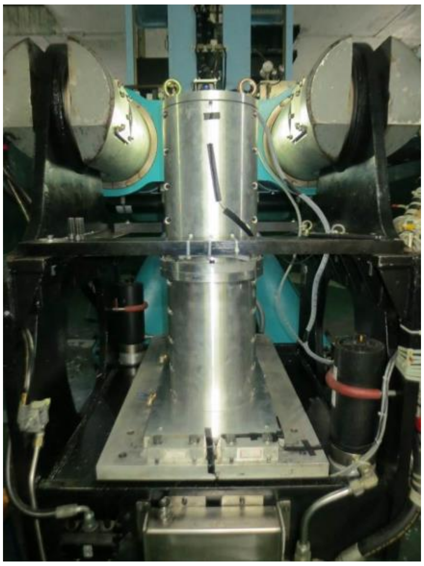


Figure 5: Setup of centrifuge model on platform

Table 1: Initial conditions of buffer materials for tested models

Test No.	Water content (%)	Bulk density (kg/m^3)	Remark
D-N	17	1885	No water
D-N-MX-80	17	1885	MX-80
D-W24	17	1885	24° water
D-W42	17	1885	42° water
W-W23	27	2008	23° water
W-W43	27	2008	43° water

2.3 Buffer material and model preparation

In this research, SPV 200 bentonite was used which is produced from Black hills in Wyoming U.S.A. It is sodium bentonite, which specific gravity is 2.67; PH is 8.5-10.5; liquid limit 495%; plastic limit 35.8% and plastic index 459.2%. According to USCS, it is classified as CH.

Large swelling ability and extremely low permeability make bentonite suitable for using as buffer material. Bentonite compacted with high pressure to form cylinder or ring shape blocks (Figure 3) that similar to the prototype disposal hole. The ring block with the small hole as Figure 3(a) is placed at the top of canister part (position A-1 and A-2 in Figure 1). The small hole is for lines of sensers. The ring block as Figure 3(b) locates aside the canister (position B-1 to B-10 in Figure 1). The solid cylinder block as Figure 3(c) is embed at the bottom of canister in diposal hole (position C-1 in Figure 1).

This research assumes that the deposition is set up in granite layer at certain depth. The disposal hole is regard as an entire intact space without deformation and cracks. Referring to KBS-3V concept and geometry, the test model was built with 1/10 scale of prototype (Figure 4 and Figure 5). Through the centrifuge modeling, 10 g artificial acceleration field was applied to simulate in situ stress between canister and buffer material. Seismic events were input by shaking table with 15-cycle sinusoidal waves. During shaking, acceleration, pore water pressure and total pressure histories were measured to realize the seismic behavior of canister and buffers in the disposal hole.

3. Test result and discussion

3.1 Test conditions

Total 6 tests were conducted as shown in Table 1 with different water content conditions. The notation D means water content of buffer (17 %) and W represent saturated water content (27 %). The alphabet after dash, N means no underground water invasion and W with number means water invading with respecting water temperature. Model D-N simulates the condition just after construction. Models D-W24 and D-W42 represent the condition that water just invades to disposal hole, where buffer is unsaturated and water invaded with different temperature. Models W-W23 and W-W43 simulate the condition after long-term disposal, where buffer is close to saturated and submerged in underground water.

According to SKB TR-10-10 report, final bulk density of saturated buffer ranging from 1950 to 2050 kg/m³ is recommend. At D-series tests, bulk density is 1885 kg/m³ with 17% water content. When water invades into disposal hole, buffer would gradually saturate and its density finally increases to 2008 kg/m³. As results, bulk density of blocks in W-series tests is 2008 kg/m^3 with water content 27% to simulate the saturated condition. During spinning, several seismic events including pre-shaking and main shaking events are input. A very small shaking was used for Pre-shaking event, and it can detect basic properties of system including nature frequency. Main shaking events are 15-cycle sinusoidal waves with different amplitude in 1 Hz, 2 Hz and 3 Hz.

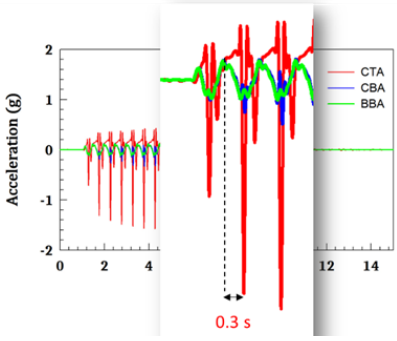


Figure 6: Acceleration time history (D-N test, 0.13 g-15cyc-2 Hz)

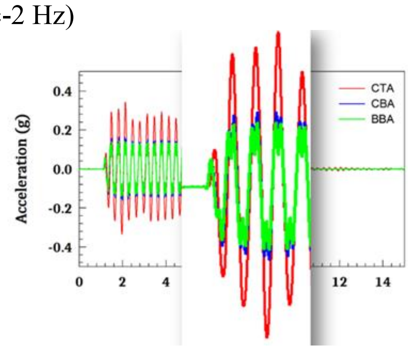


Figure 7: Acceleration time history (W-W23 test, 0.12 g-15cyc-3 Hz)

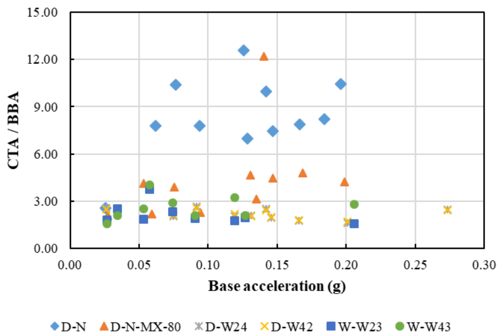


Figure 8: Acceleration amplification at top of canister

3.2 Acceleration response

From the tests without water invasion condition, such as Model D-N test as shown in Figure 6, it is observed that vibration response is not in synchronization. Acceleration at bottom of canister synchronize to base acceleration without phase change, however, acceleration at top of canister does not synchronize to base. For D-N test 0.13g-15cyc-2Hz event, the average peak to peak delay about 0.3 second. Because of the exist gap between buffer and canister, the rocking of canister during shaking would lead to impact loading and the spick of acceleration is observes. It should be noted that the container was fixed at the shaking table at bottom, and it is a kind of cantilever structure that is different from the real site environment at intact rock. Therefore, the acceleration amplitude at top container is about two times of that at bottom. In the future, the container will be reinforced to get higher rigidity for recreating the closer response of rock base.

In the tests with water invasion condition, such as Model W-W23 test as shown in Figure 7, acceleration histories for CTA, CBA and BBA are almost synchronization without significant time delay of shear wave propagation. It is inferring that bentonite blocks absorb water and then its swelling leads to the decrease of gap between canister and buffer, resulting to more confining effect to canister. The canister cyclic moves during shaking without rocking and addition impact loading. Also, the amplitudes of base input motion and at bottom of canister almost the same, indicating the shear wave entirely propagate from rock to canister through buffer without reduction even the buffer is saturated.

The amplification of acceleration response is defined as the ratio of acceleration at different elevation (CTA and CBA) to the maxima base input acceleration at Bottom of Box (BBA) shown in Figure 8, and the location of CTA and BBA are indicated in Figure 1. By normalization, it can be seen that the seismic response at top of canister is larger for the models without underground water invasion. Amplification are over four times at top of canister. Under water invasion condition, amplification is reduced to about two. Tests results show that the presence of water can reduce seismic motion because of the reducing of gap inside disposal hole.

3.3 Contact pressure during shaking

In this study, the pressure between canister and buffer caused by swelling of bentonite after absorbing water was not measured. In order to measure the contact pressure acting on canister and buffer, four total pressure transducers were installed on the surface of canister (TP1-TP4 in Figure 1). The following discussion is about the increment pressure caused by base shaking.

The maximum increment contact pressure for all tests subjected to different base shaking are showed in Figure 9. Model D-N for simulating the just finished construction condition is measured the highest contact pressure of 51 kPa, which is much smaller than the strength of canister under the base shaking of 0.20 g. The similar phenomenon as acceleration response, the increment contact pressure reduces after water invading to disposal hole because of well confining by swelled bentonite. After the test, the water content of buffer close to canister was detected. The water content is 29 % for Model D-W24, 42% for Model W-W23. With saturated water content and submerged into underground water, bentonite is a little soft resulting to high amplitude and increment contact pressure.

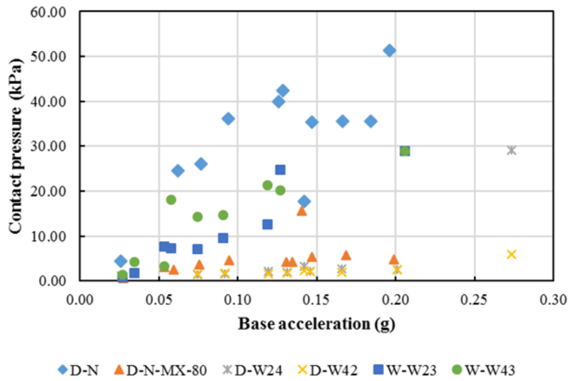


Figure 9: Maximum contact pressure at different base shaking events

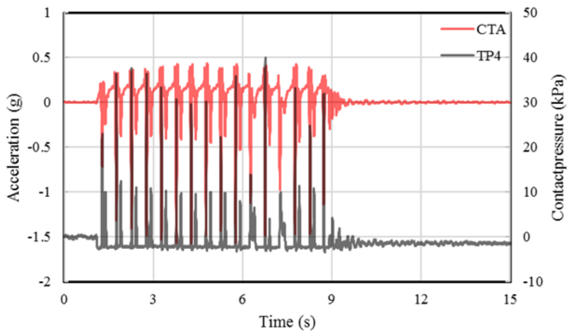


Figure 10: Acceleration and contact pressure time history (Model D-N, 0.13 g-15cyc-2 Hz)

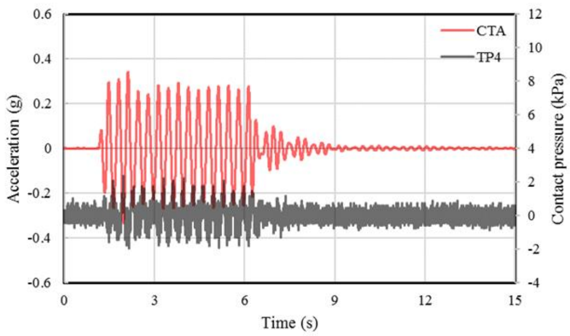


Figure 11: Acceleration and contact pressure time history (Model W-W23, 0.12 g-15cyc-3 Hz)

For seismic event of Model D-N test with base shaking of 0.13 g, 15 cycles, 2 Hz sinusoidal waves shown in Figure 10. From the arrangement of mode as shown in Figure 1, the right side is positive acceleration direction. Because the acceleration and inertial force are in opposite direction, it makes that when canister suffer negative acceleration, canister is moving to positive direction and causing contact pressure. In contrast, when canister suffer positive acceleration, contact would decrease.

Therefore, the negative acceleration leads to inertial force to positive direction of acceleration, and the canister moves right side and hits the buffer induces significant increment contact pressure. The canister quickly contact with buffer and the reaction force push it to collide with buffer inside the gap. Therefore, input base shaking is 2 Hz and the response of canister is higher around 4 Hz by not symmetric as shown in Figures 6.

For the model with saturated buffer and water invasion as Model W-W42, the seismic event with base shaking of 0.12 g, 15 cycles, 3 Hz sinusoidal waves shown in Figure 11. Because the well confining by swelled buffer, the responses of acceleration and increment contact pressure are synchronizing with base input motion. The positive total pressure was measured because the model was submerged in the water and the separate for buffer and canister would have suction pressure during shaking.

3.5 Cracking on bentonite blocks

Buffer is used to prevent radioactive wastes diffusing into underground water. Cracking on bentonite blocks would provide the path for conducting wastes and water to flow out or in, that would make buffer lose its function.

For the buffer with nature water content, Models D-N, D-W24 and D-W42, buffer blocks set around top potion of canister cracks after shaking as shown in Figures 12 and 13. Most of cracks are in vertical direction and just few are in horizontal direction. For advanced inspection, it is dry inside the most of the cracks. Therefore, the crakes may be caused by shaking, swelling of buffer close to canister or releasing confining pressure by disassembling of container. Advanced researches are needed to realize the crack development and its process. After water invading to disposal hole, the watermark appears at apart of outer interface between container and buffer, and inner interface between buffer and canister.

For the model with saturated buffer material, Models, Models W-W23 and W-W43, there is no crack and only watermark and swelled zone found on the surface of blocks as shown in Figure 14. As compared to 17% water content bentonite, the buffer material with saturated water content is lower strength but a little more ductile ability.

4. Conclusions

Total 6 dynamic centrifuge modeling tests were conducted in the artificial acceleration field of 10 g. The base shaking are applied to the model from shaking table. From the test results, it was observed that the gap between canister and buffer is filled with swelled bentonite leading to the better confining to canister after water invading. It would lead to the reduce of amplitude of canister and the contact pressure between canister and buffer during shaking.

Second, the maximum contact pressure is about 51 kPa which is much lower than the strength of canister during base shaking of 0.2 g, meaning that canister would not be damaged. However, the advanced studies is needed for larger base shaking.

Finally, before the buffer saturated by underground water, blocks would have possible cracks during base shaking. No matter the swelling of bentonite or artificial sealing during construction, the acceleration response and increment contact pressure could be reduced and the possible cracks could be avoided.

Figure 12: Cracks of buffer block (Model D-N)

Figure 13: Cracking blocks and watermark (Model D-W24)

Figure 14: Watermark (Model W-W23)

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