Experimental study of the effect on one-dimension erosion of compacted bentonite

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ABSTRACT

Bentonite swells after absorbing water and forms colloids that can release gel particles into solution causing the erosion of bentonite particle. The process of colloidal erosion can be described by the free expansion of bentonite. A new designed one-dimensional free swelling tests is performed to simulate one dimension erosion of compacted bentonite. Compacted specimens are made into two initial dry densities and water contents. De-ionized water and NaCl, Na₂SO₄, CaCl₂ solutions with concentrations of 0.1, 0.5, 1.0 and 2.0 mol/L were used to soak the specimens. The effects of initial dry density, initial water content and saline solution on the free swelling behavior of compacted commercial bentonite are analyzed. Results show that, the final total swelling deformation is almost independent of initial water content, but increases with the initial dry density and decreases with the increase in osmotic suction of the infiltration solution.

Keywords: Compacted bentonite; Free swelling; One dimension erosion; Saline solution

1 INTRODUCTION

Bentonite is filled between the waste tank and the surrounding rock mass as a cushion material for the nuclear waste repository due to its high expansion and low permeability (Yong et al., 1985). After absorbing the fissure water, the bentonite swells into the surrounding rock fissure and forms colloids. The colloidal particles migrate with the seepage, which reduces the bentonite content of the cushion and endangers the safety of the repository (Missana et al., 2004). Studying the erosion process of bentonite in rock mass fissures is of great significance for evaluating the safety of the repository. Bentonite intrusion into a fracture is a complex process, where several mechanisms are active simultaneously Tanai and Matsumoto (2008) and Moreno et al. (2011) believe that the basic mechanism of erosion of bentonite in cracks is the free expansion of bentonite. Liu et al. (2009) established a one dimensional colloidal erosion model based on the dynamic force balance during the expansion of smectite into the fracture.

Moreover, certain chemical compositions such as Na⁺, Cl⁻ and SO₄²⁻ exist in solution from surrounding rock fractures in disposal (Zhang et al., 2012). The physicochemical effects can strongly influence mechanical behavior of the bentonite when salt-concentrated pore fluids are introduced to clays (Rao and Thyagaraj, 2007). Investigation the erosion process for bentonite in saline solution is important to ensure the security of the nuclear waste repository. The chemical effects on the swelling behaviour of clays have been widely investigated through a number of experiments (Ye et al., 2014). The experimental results show that different kinds of salt solutions have different degrees of inhibition on the swelling of bentonite, and for the same salt solution, the swelling ability of bentonite decreases with the increase of the concentration of salt solution (Mesir and Olson, 1971).

In this paper, a new designed 1-D free swelling tests were performed on compacted bentonite to simulate 1-D erosion of bentonite in cracks. The final total swelling deformation of specimen with different initial water contents and dry densities were compared to study the influence of initial water contents and dry densities on swelling deformation. Besides, three types of soaking solution with four concentrations of solutions, 0.1, 0.5, 1.0 and 2.0 mol/L, were considered. Based on the test results, the effects of saline solution on the swelling characteristics of compacted bentonite were analyzed.

2 MATERIALS AND METHODS

For the traditional free swelling test, the oedometer is used with no additional vertical load applying on the soil specimen. While, the swelling deformation of soil specimen is impeded by the gravity of the top cap, the frictional force of the dial gauge probe and the friction among the soil specimen, the porous stone and the wall of specimen-ring. Besides, the saline soaking solution can rust the oedometer. In order to simulate the 1-D...
erosion process, a new designed free expansion test in this paper is carried out in smooth glass tubes, and the height change of the specimen is measured by ruler. Thus the effect of friction on the expansion of the soil is reduced to negligible and the erosion of salt solutions to the instrument is on relief.

Specimens were prepared by mixing the dry powdered bentonite with distilled water and the initial water content of 20% and 30% for the specimen preparation were adopted. The wet soil was placed in a sealed bag for at least 24 hours to ensure uniform moisture of the soil. Specimens with 37 mm diameter and 10 mm thickness were statically compacted at a velocity of about 0.2 mm/min to two target dry densities of about 1.0 g/cm$^3$ and 1.2 g/cm$^3$. Figure 2a shows the compacted specimens. Three sets of specimens with initial dry density $\rho_d=1.2$ g/cm$^3$, initial water content $w=30\%$; $\rho_d=1.0$ g/cm$^3$, $w=30\%$ and $\rho_d=1.2$ g/cm$^3$, $w=20\%$ were made.

### 2.2 Test procedures

To ensure that the expansion occurred only in one dimension, the soil sample was placed in a glass tube of exactly same diameter (Fig. 2b). The tests were carried out on compacted specimens immersed in distilled water and three salt solutions (NaCl, Na$_2$SO$_4$ and CaCl$_2$) at different concentrations of 0.1, 0.5, 1.0 and 2.0 mol/L. In each test case, three sets of parallel tests were performed. Considering that water in the glass tubes can evaporate during the swelling process, a blank control group was set to replenish water in time. The vertical swelling strain experienced by the specimens, changed rapidly at the initial stage of swelling, and was recorded at intervals of 10 minutes. The measurement interval extended as the height change slowing down. When the height of the specimen stayed within 48 h, the swelling process was considered complete. The swelling strain $\varepsilon$ was defined as:

$$\varepsilon = \frac{H - H_0}{H_0} \times 100\%$$  \hspace{1cm} (1)

where $H$ is the measured height of the specimen, $H_0$ is the initial height of the specimen. The final state of the specimens with $\rho_d=1.2$ g/cm$^3$ and $w=30\%$ immersed in different concentrations of NaCl solutions are shown in Fig. 3.

### 3 RESULTS AND DISCUSSIONS

The evolutions of total swelling strains for the
specimen with an initial dry density of 1.2 g/cm³ and an initial water content of 20% in NaCl solutions are presented in Fig. 4. The trends of the soil swelling strains of specimens with conditions along with time are similar to that shown in Fig. 4, and therefore are omitted here.

It can be observed from Fig. 4 that, for all types of solutes, although the swelling speed of the same specimen increases as the concentration of the soaking solution increased, the duration of the tests and the total vertical swelling strains was reduced by an increase in salt concentration. Specimens swelled with a swelling rate slowing down leading to the strain-time curves in S-shaped in double logarithmic coordinates. The influences of initial dry density, initial water content and soaking solution on final total swelling strain are analyzed in following parts.

3.1 Impact of initial water content
The soil specimens with two different initial water contents but same initial dry density, were separately immersed in NaCl, Na₂SO₄ and CaCl₂ solutions of four concentrations. Fig. 5 shows the relationship of the final total swelling strain of specimens at w=30% versus that at w=20%. It can be seen that the 12 test points satisfy the \( y=x \) relationship within the error tolerance, namely the specimens with different initial water content have same total swelling strains. The swelling mechanism of compacted bentonite is considered on the basis of the swelling behavior of swelling clay particles such as montmorillonite. Thus, with all else held equal, the initial water content has no effect on the final total swelling strain of the bentonite specimens.

3.2 Impact of initial dry density
The results for specimens with same initial water content but different dry density are also compared. Figure 6 shows the final total swelling strains for compacted bentonite specimens with different initial dry densities and same initial water content being 30%. It can be seen from the bar graphs in Fig. 6(a)-(c), that in the same soaking solution, the final swelling strain of the specimen with a dry density of 1.2 g/cm³ is larger than that of the specimen with a dry density of 1.0 g/cm³. The specimens with a greater initial dry density possess more montmorillonite, which is the swelling clay particle controlling the swelling behavior of bentonite. Thus, under the same solution concentration, the final total swelling strain of bentonite specimen increases with increasing initial dry density.

![Fig. 5. Final total strains at different water contents.](image)

![Fig. 6. Final total swelling strain under different concentrations.](image)

3.3 Impact of solution
The curves in Fig. 6 indicates that for all solution types, the final total swelling strain of soil specimen decreases as the concentration increases. The higher concentration has stronger restricting effect on the swelling of bentonite. According to the DLVO theory, an increase in the concentration of the pore solution
reduces the electrical repulsions between the particles, resulting in a decrease in the swelling force and the swelling strain.

In order to facilitate the analysis of the influence of the solution type on the expansion deformation, the experimental results of the specimen with an initial dry density of 1.2 g/cm³ and an initial water content of 20% were taken as an example. Its final total swelling strain under different solution is shown in Fig. 7. It is worth to notice that for all concentrations, the final total strains of specimens in CaCl₂ solutions are smaller than that in same concentration of NaCl and Na₂SO₄ solutions.

Table 1. Osmotic suctions of different solutes (kPa).

| c (mol/L) | NaCl     | CaCl₂    | Na₂SO₄  |
|----------|----------|----------|---------|
| 0.1      | 461.79704| 635.470854| 589.575975 |
| 0.5      | 2281.8468| 3398.78154| 2566.75656  |
| 1        | 4636.238 | 7780.67175| 4763.06938  |
| 2        | 9751.9676| 20580.2393| 9281.33922  |

The influences of the type and concentration of salt solution can be reflected by the osmotic suction. In order to embody the effect of the osmotic suction, an osmotic stress component is added to the effective stress. The effective stress is proposed to represent the total net vertical stress experienced by compacted bentonite and has the following form (Xu et al., 2014):

\[ p^* = p + \beta \pi \]

where \( p^* \) is the modified effective stress and \( p \) the vertical overload. \( \beta \pi \) is the osmotic stress, equaling to \( \beta \pi \) with the parameter \( \beta \) ranging from 0 to 1. Thus, the effective stress suffered by bentonite increases as the osmotic suction increases. The osmotic suctions for three solutions under 4 different concentrations at 298 K are calculated by Debye-Hückel equation (Pitzer and Mayorga, 1973) and the results are listed in table 1. The osmotic suctions of CaCl₂ solutions are larger than that of NaCl and Na₂SO₄ solutions under the same concentration. According to Eq. (2), the specimens suffer more stress in CaCl₂ solutions, and have smaller swelling strains than that in NaCl and Na₂SO₄ solutions.

4 CONCLUSIONS

1-D free swelling tests were performed on compacted bentonite to simulate 1-D erosion of bentonite in cracks. The conclusions were obtained as follows:

1. The swelling mechanism of compacted bentonite depends on the swelling behavior of swelling clay particles such as montmorillonite. Thus, the final total swelling deformation is independent of initial water content, but increases with the initial dry density.

2. The final swelling strain of bentonite decreases with increasing concentration. The effect of salt solution on the mechanical properties of bentonite is reflected by osmotic suction, which acts like the vertical pressure applied on the soil and restrains the expansion. The saline solution with high osmotic suction can repress the soil erosion.

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REFERENCES

1) Liu, L., Moreno, L. and Neretnieks, I. (2009): A dynamic force balance model for colloidal erosion and its DLVO-based application, Langmuir, 25(2), 679-687.
2) Mesir, G. and Olson, R.E. (1971). Consolidation characteristics of montmorillonite, Géotechnique, 21(4), 341-352.
3) Missana, T., Alonso, U., Albarran, N., et al. (2011): Analysis of colloids erosion from the bentonite barrier of a high level radioactive waste repository and implications in safety assessment, Physics and Chemistry of the Earth, 36(17-18), 1607-1615.
4) Moreno, L., Liu, L., Neretnieks, I. (2011): Erosion of sodium bentonite by flow and soil erosion, Physics and Chemistry of the Earth Parts A/B/C, 36(17), 1600-1606.
5) Pitzer, K.S. and Mayorga, G. (1973): Thermodynamics of electrolytes. II. Activity and osmotic coefficients for strong electrolytes with one or both ions univalent, J. Phy. Chem., 77(19), 2300-2308.
6) Rao, S.M. and Thyagaraj, T. (2007), Swell-compression behavior of compacted clays under chemical gradients, Canad. Geotech. J., 44(5), 520-532. DOI: 10.1139/T07002
7) Tanai, K. and Matsumoto, K. (2008): A study of extrusion behavior of buffer material into fractures, Science and Technology Series, 334, 57-64.
8) Xu, Y.F., Xiang, G.S., Jiang, H., Chen, T., Chu, F. (2014): Role of osmotic suction in volume change of clays in salt solution, App. Clay Sci., 101, 354-361.
9) Ye, W.M., Zhang, F., Chen, B., et al. (2014): Effects of salt solutions on the hydro-mechanical behavior of compacted GMZ01 bentonite, Environ. Earth Sci., 72(7), 2621-2630.
10) Yong, R.N., Boomsinsuk, P., Yiotis, D. (1985): Creep behaviour of a buffer material for nuclear fuel waste vault, Canad. Geotech. J., 22(4), 541-550.
11) Zhang, H.Y., Cui, S.L., Zhang, M., Jia, L.Y. (2012): Swelling behaviors of GMZ bentonite-sand mixtures inundated in NaCl-Na₂SO₄ solutions. Nuclear Engineering and Design, 242, 115-123.