Estimation of one-dimensional swelling deformation using surface fractal dimension

Nagoya Institute of Technology CSCE Member ○Yongfu Xu
Nagoya Institute of Technology JSCE Member De'an Sun & Hajime Matsuoka

1. INTRODUCTION

Solving the numerous problems connected with the safe disposal of nuclear waste is a challenge. In all the conceptual designs for nuclear waste, engineered barriers supplement the natural (host rock) barriers to ensure the long-term isolation potential of the disposal system. Since the major mechanism through which the radioactive materials can be released to the biota is by dissolution in and transport through groundwater, repository-design studies focus on mechanism that limit the access of water to the waste form, which itself is generally designed to be lowly soluble. Bentonite, with a low hydraulic conductivity, has abilities to expand and completely fill up openings and to create a tight contact with confining rock in the repository. Prediction of swelling deformation is very important to examine the validity of bentonite barrier in the disposal system. The water volume absorbed by bentonite in swelling process is related to the surface texture of bentonite (Xu et al., 2002). Fractal approach seems to be a potentially useful tool to study the soil surface texture formation (Mandelbrot, 1982). In the present paper, the maximum swelling strain is calculated using the surface fractal dimension of Tsukinuno bentonite. The surface fractal dimension is measured in the swelling pressure and swelling deformation tests.

2. SURFACE FRACTAL DIMENSION

Avnir & Jaroniec (1989) proposed a convenient method to determine the surface fractal dimension from a single adsorption isotherm. Similarly with the adsorption isotherm equation, the normalized water volume by the volume of montmorillonite is related to the vapour pressure, i.e.

$$\frac{V_w}{V_m} = k\left[\ln\left(\frac{P_0}{P}\right)\right]^{D_s-3} \qquad (1)$$

where V_w is the water volume absorbed by montmorillonite, V_m is the volume of montmorillonite, P is the partial water vapour pressure in equilibrium with bentonite, P_0 is the equilibrium water vapour pressure of pure water. The water volume absorbed by montmorillonite can be calculated from the following equation,

$$V_w = V_{v2}S_{r2} - \left(V_{v1} - \frac{V_{v1}}{A}\right)(S_{r2} - S_{r1}) \qquad (2)$$

where V_{v1} and V_{v2} are the void volumes before and after swelling, respectively, $V_{v2} = V_{v1} + V_{sw}$, S_{r1} and S_{r2} are the degrees of saturation before and after swelling, respectively, $A = V_m / V_{solid}$, $V_{solid} = V_m + V_{nm} + V_{sd}$, V_{solid}, V_m, V_{nm} and V_{sd} are the volume of solid, montmorillonite, nonswelling clay and sand, respectively. The adsorption isotherm also allows the calculation of swelling pressure of bentonite and its mixtures (Kahr et al., 1990).

$$p_s = -\frac{RT}{M_w \overline{v_w}}\ln\left(\frac{P}{P_0}\right) \qquad (3)$$

where p_s is the swelling pressure, R is the molar gas constant, T is the Kelvin temperature, M_w is the water molecular mass,

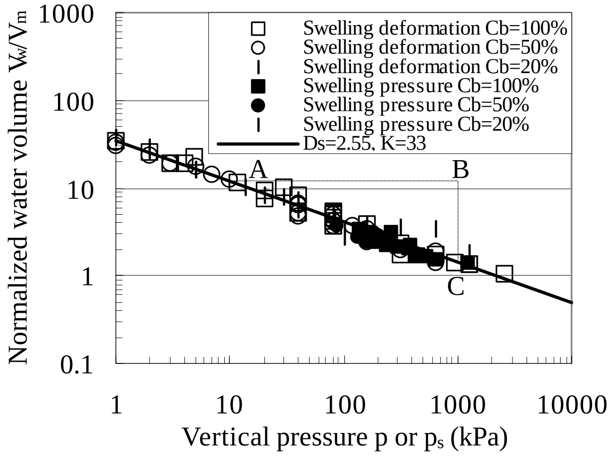


Fig. 1. Surface fractal dimension obtained from swelling deformation test and swelling pressure test

$\overline{v_w}$ is the partial specific volume of water. According to Eq. (1) and Eq. (3), the relationship of the normalized water volume to swelling pressure is written as

$$\frac{V_w}{V_m} = Kp_s^{\,D_s-3} \qquad (4)$$

where K is a constant. The correlation of the normalized water volume to swelling pressure is shown in Fig. 1. C_b is the bentonite content. A linear function exists between the normalized water volume and swelling pressure in log-log plot in Fig. 1. D_s equals 2.55 and K is 33 in Fig. 1. The value of the surface fractal dimension obtained from the swelling pressure test is in the range of 2.0-3.0, which agrees with the physical implication of the surface fractality.

If the original sample height does not keep constant when swelling pressure is measured in Fig. 1. Let the specimen, such as point A in Fig. 1 with the swelling strain of e_s. In order to compress specimen A to the original height, an increment of pressure Δp is necessary to apply, see point B in Fig. 1. Under the increment of pressure Δp, the change in the normalized water volume $\Delta(V_w/V_m)$ is given by Eq. (4),

$$\Delta\left(\frac{V_w}{V_m}\right) = K(\Delta p_s)^{D_s-3} \qquad (5)$$

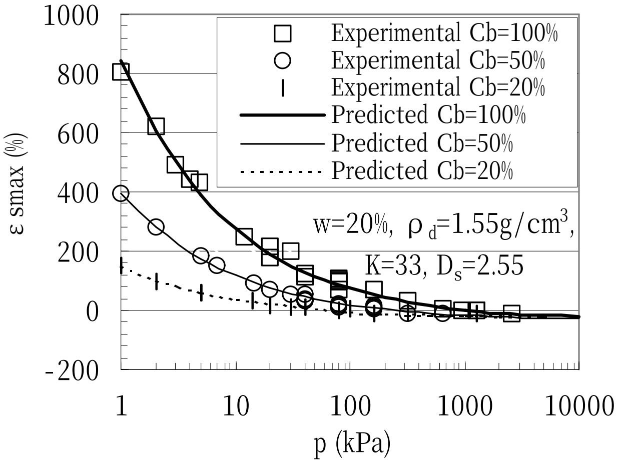
Thus, point B would be changed to point C in Fig. 1. It is seen that point C is lay in the solid line in Fig. 1 from Eq. (4). Therefore, the solid line in Fig. 1 represents the relationship between the normalized water volume and vertical overburden pressure, not only swelling pressure. The experimental data of swelling deformation are also drawn in Fig. 1. The experimental data of swelling deformation are in good accord with Eq. (4).

3. MAXIMUM SWELLING STRAIN

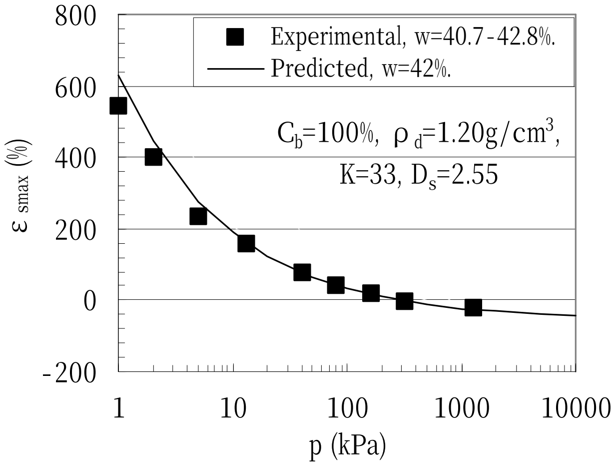
For one-dimensional condition, swelling strain is given by

$$e_s = \frac{\Delta H}{H_0} \times 100 \quad (\%) \qquad (6)$$

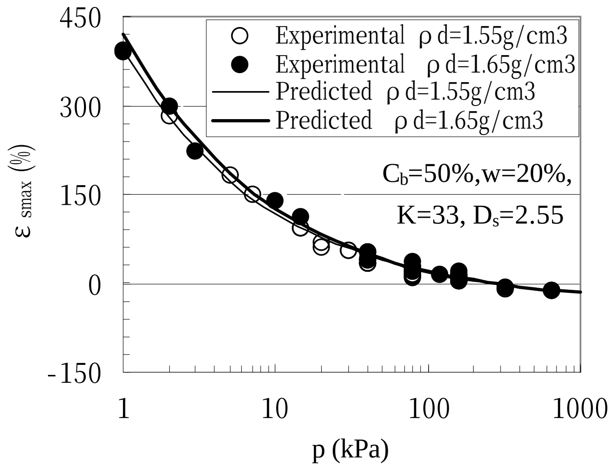
where e_s is the swelling strain, ΔH is the increment of the specimen height, H_0 is the initial height of specimen. The



(a) Effect of bentonite content on swelling strain



(b) Effect of water content on swelling strain



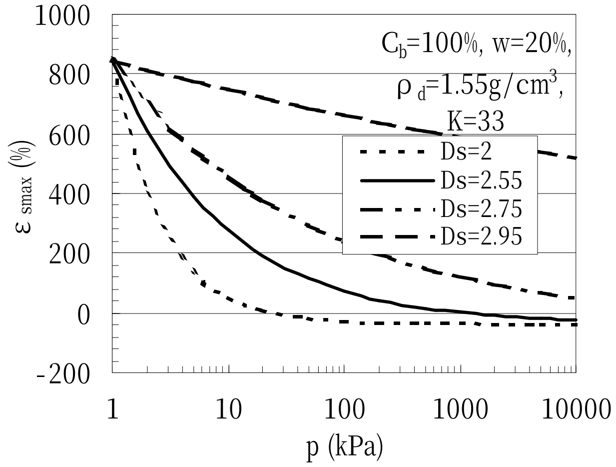
(c) Effect of dry density on swelling strain

Fig. 2. Comparisons between predictions and experimental data of the maximum swelling strain

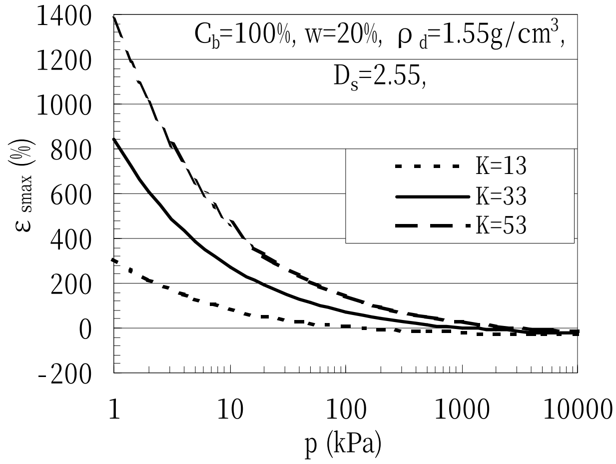
maximum swelling strain can be obtained from Eqs. (4), (6),

$$\varepsilon_{s\max} = \frac{\rho_d\left[Kp^{D_s-3}+(A-1)\left(\frac{G_s}{\rho_d}-1\right)\left(1-\frac{G_s\rho_d w_1}{100(G_s-\rho_d)}\right)\right]-A(G_s-\rho_d)}{AG_s}\times 100 \quad (\%) \tag{7}$$

where ρ_d and w_1 are the initial dry density and water content, $A = 1+(100/C_m-1)(\rho_m/\rho_{nm})+(100/C_b-1)(100/C_m)(\rho_m/\rho_{sd})$, G_s is the specific gravity, C_m is the content of montmorillonite in bentonite, ρ_m, ρ_{nm} and ρ_{sd} are the density of montmorillonite, non-swelling clay and sand, respectively. Comparisons between the estimations and experimental results of the maximum swelling strain are shown in Fig. 2. The estimation of the maximum swelling strain is obtained from Eq. (7) using the parameters K and D_s, which are obtained in Fig. 1. The estimations are in good accord with the experimental data. The maximum swelling strain for bentonite with different surface fractal dimension and different value of K are also estimated in Fig. 3. The maximum swelling strain is strongly related to the parameters K and D_s in Fig. 3, and increases with K and D_s.



(a) For different surface fractal dimension



(b) For different parameter K

Fig. 3. Estimation of the maximum swelling strain

ACKNOWLEDGEMENT

The first author would like to express his sincere gratitude to the Japanese Society for Promotion of Science (JSPS) for its financial support.

REFERENCES

Avnir, D. and Jaroniec, M., Langmuir, 1989, 5, 1431-1433.
Kahr, G., F. et al., Clay Miner., 1990, 25, 499-506.
Mandelbrot, B.B., Freeman W. H., San Francisco, 1982.
Xu, Y.F., Sun, D.A. and Matsuoka, H., Proc. 37th Japan National Conf. on Geotech. Eng., 2002(in press).