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DEFORMATION ON EMBANKMENTS DUE TO SLAKING PHENOMENON AND ITS COUNTERMEASURE

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ABSTRACT

Geotechnical issues have increased in the last two decades since sedimentary rocks material such as mudstone or shale has been widely used as embankment material. They, however, tend to be weathered once they are immersed in the water. This phenomenon is a kind of weathering processes known as slaking and may cause a reduction of stiffness and peak strength. This paper, in order to evaluate the slaking induced deformation, a number of one-dimensional compression slaking tests and scanning electron microscopy (SEM) tests to observe the physical morphology of mudstone were performed. These data confirm that slaking in crushed mudstone is accompanied by a variation in the particle size distribution during wetting and drying cycles, and a variation in grading results in an irreversible change in mechanical characteristics, such as the reference packing density. Since the particle size distribution was transformed under confined stress constant occurs without a change in the maximum particle size, it can be described by existing indexes of grading such as breakage parameter *Br*. Furthermore, to eliminate the deformation behavior of sedimentary rocks, changing the particle size distribution in the beginning by applying loading/unloading history before slaking cycle has exhibited the significant result. The compressibility during wetting and drying cycle decreases to 50% of conventional compression by applying this countermeasure method. In earth construction works, the process of roller compaction is necessary in order to encourage the particle crushing. Proper compaction can control the occurrence of slaking under wetting and drying cycle so that volumetric compression does not occur easily.

Keywords: mudstone, slaking, particle size distribution, one-dimensional compression, deformation

INTRODUCTION

Soft sedimentary soft rock such as mudstone or shale are highly susceptible to weathering. They have a tendency to slake and soften when immersed into the water and as a result their strength diminishes gradually with time. Due to this natural behavior, mudstone material has been mostly disposed as waste material. However, while dealing with economic considerations and environmental concerns, several earth constructions projects propose to utilize the crushed mudstones or shales as embankment materials. Since large embankment made of these materials was considered, long term stability problem may possibly occur to slaking [1] - [3]. One of these embankments located on the Tomei expressway in Makinohara district in Japan failed during the earthquake in 2009, with subsequent field investigation and analysis identifying the primary cause to be slaking of the mudstone [4]. The cross section of Tomei expressway after and before collapse is shown in Fig. 1. The slaking behavior of mudstone has been studied experimentally [5] - [7] through slake-durability tests and other similar tests, in which a number of wetting and drying cycles are applied to evaluate the weathering resistance of weak rocks such as shales, mudstones and siltstones. This has demonstrated that slaking cycles significantly affect the degradation process and evolution of particle size distribution in such rocks [8] – [10]. Particle size distribution characteristics such as the gradation of weak rock tend to transform in response to slaking induced by wetting and drying, and this will ultimately affect the mechanical behavior as the material after slaking is quite different from the original material [11], [12]. Weak rocks may lose their strength or stiffness through slaking, as this usually results in a gradation with small particle sizes.

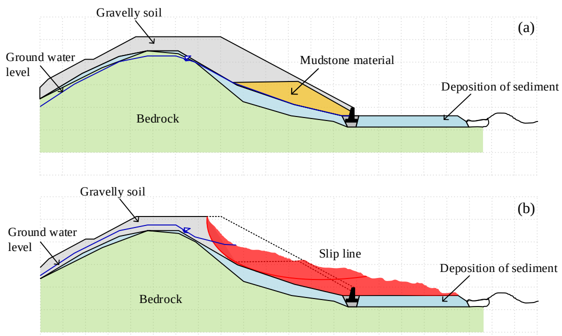

Fig. 1 Cross section of Tomei expressway fault after and before the earthquake in 2009

Such variation in mechanical characteristics during slaking can directly affect the deformation and failure behavior of the ground, but so far, most studies have only looked at the role of slaking in the evolution of the particle size distribution or the change in behavior of weak rocks. As there has been little discussion of the deformation behavior that is directly induced by slaking, this paper attempts to address the slaking-induced deformation based on the one-dimensional compression slaking tests and to propose a rational way to eliminate the issues of the granulated weak rocks in earth construction projects.

MATERIALS AND METHODS

Weak rock materials

The tested materials presented in this paper has originated from several embankments which caused deformation issues due to slaking phenomena. Kakegawa mudstone was derived from the embankment on Tomei expressway in Japan. Hattian Bala mudstone was obtained from a natural dam which was generated by Kashmir earthquake 2005 that locates at 3.5 km of Karli River in Pakistan. In addition, to investigate the rational countermeasures to the issues related with the weak rocks in embankments, loading histories (loading/unloading) were applied before the wetting and drying cycles. The test was carried out on Nou mudstone since the deformation issues in the field has occurred due to slaking. The particle size distribution of mudstone specimens at the initial state of the one-dimensional compression slaking test was a unit grading having a diameter of 0.85-2.00 mm (passed by sieve no. 10 and restrained by sieve no. 20 ASTM [14]). The physical surface morphology and general properties of the material are summarized in Fig. 2 and Table 1.

Several mechanisms of the slaking of weak rocks were attributed to the compression of air entrapped in the intra-granular pores of the particles [5]. Moreover, the size and the roughness of the pore boundaries have dominant effects on the resistance of particles against slaking. Therefore, it is necessary to explore the surface characteristics of the granulated weak rocks through SEM (Scanning Electron Microscopy) analysis using the same particle size distribution for one-dimensional compression slaking test.

Table 1 General properties of weak rocks materials

Properties	Kakegawa	Hattian Bala	Nou
Particle density (gr/cm^3)	2.65	2.75	2.69
Max. Void ratio (e_{max})	1.83	1.09	1.97
Min. Void ratio (e_{min})	1.29	0.79	1.40

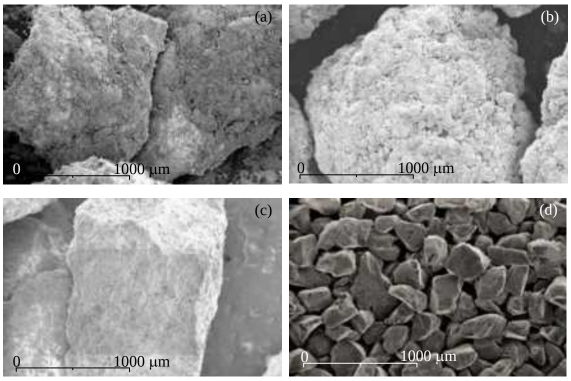

Fig. 2 Physical surface appearance of granulated mudstone magnified to 50 x: (a) Kakegawa; (b) Nou; (c) Hattian Bala and (d) Toyoura sand

Slaking under Confined Condition: One-Dimensional Compression Slaking Tests

In order to evaluate the slaking induced deformation on mudstone, a one-dimensional compression test that incorporates wetting and drying cycles [11] was modified. The schematic setup of testing apparatus is shown in Fig. 3, and consisted of: a measuring system (left), loading system (centre), and wetting and drying paths (right). The specimen container was a rigid steel cylinder with dimension of 60 mm in diameter and 40 mm high, with porous stones installed on the top and bottom loading plates, respectively. For testing, dried specimens were first installed in the steel cylinder, after which the load cell and contact-type displacement gauge were installed and initialized. The initial height of the specimen was measured to determine the initial void ratio, and then a vertical stress was applied in stages (9.8, 19.6, 39.2, 78.5, 157, 314, 628, 1256 kPa) by a pneumatic cylinder by way of a loading rod. The time for each loading was set to 30 min, as compression of the specimen immediately occurred and the volumetric behavior did not appear time dependent during the compression stage. After reaching a prescribed vertical stress, a wetting and drying cycle was carried out while keeping the vertical stress constant.

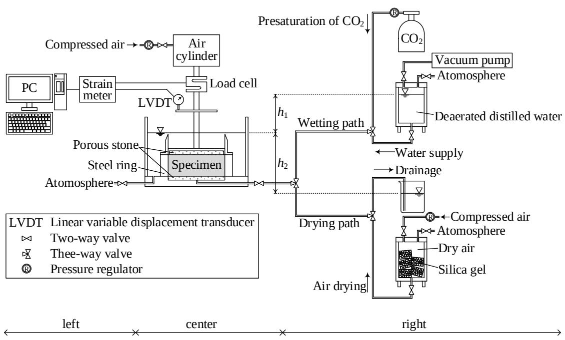

Fig. 3 The schematic of one dimensional compression slaking test

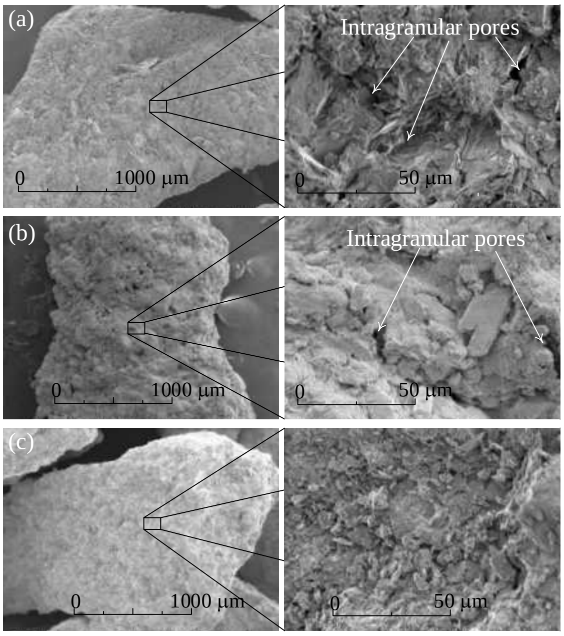

Fig. 4 SEM images of the weak rocks: (a) Kakegawa mudstone; (b) Nou mudstone and (c) Hattian Bala mudstone.

The wetting process started by permeating carbon dioxide slowly through the specimen without changing the void pressure for 30 min to remove any air, after which distilled water was permeated through the specimen by a slight difference in water level between the water tank and specimen container (h1) until the specimen was fully submerged. After leaving the specimen submerged for 6 h, the drying process was commenced by draining the void water from the specimen for 30 min through light difference (h2) in water level. Silica gel packs were then set around the steel cylinder of the specimen container, and dried air was slowly permeated through the specimen for 48 h to ensure it was completely dry. This cycle of wetting and drying was repeated three times, during which time the volumetric behavior was observed. Following the final drying process, the specimen was oven-dried and then sieved using only horizontal circular movements without any tapping impulse being added.

RESULTS AND DISCUSSIONS

Intra-granular pores

Several different mechanisms of the slaking of weak rocks have been pointed out in past studies. One of the slaking mechanisms is attributed to the compression of air entrapped in the intra-granular pores of the particles. The effect of the geometry of the intra-granular pores and revealed that the size of the pores and the roughness of the pore boundaries have dominant effects on the resistance of particles against slaking [5], [13]. The surface characteristics of the granulated mudstones were explored through SEM. The low-magnification images of each specimen on the left side in Fig. 4 clearly expose that clay-sized particles that produce a rough surface texture. It is note that the particles of the Kakegawa and Nou mudstone there is a particularly pronounced accumulation of tiny particles, with apparent intra-granular pores appearing to form within each bulk particle (the right side in Fig. 4.). In comparison, the surface texture of the Hattian Bala mudstone looks relatively smoother, but is still rougher than that of the Toyoura sand presented in Fig. 2.

Deformation on Weak rocks due to Slaking

The test result of one dimensional compression slaking for the crushed Kakegawa and Nou mudstones under a vertical effective stress σ_v' of 314 and 1256 kPa are shown in Figs. 9 and 10, respectively, whereas the results for the crushed Hattian Bala mudstone under a vertical effective stress σ_v' of 314 kPa are provided in Fig. 11. It is evident from this that the particle size distributions of the crushed Kakegawa was transformed after compression, and that mudstone types experience particle breakage during one-dimensional compression. It is also clear that there is a slightly greater change in particle size distribution at 1256 kPa, and so the evolution of grading due to particle breakage is related to an increase in the stress level. The effect that changes in grading due to slaking have on the mechanical characteristics were investigated by monitoring the maximum and minimum void ratios of the Kakegawa mudstones, Nou mudstone and Hattian Bala mudstone after each cycle of wetting and drying. As seen in Fig. 5 to Fig. 7, the maximum and minimum void ratios decrease by almost the same amount until the third cycle. For the Hattian bala mudstone, these ratios remain almost constant, while in the Kakegawa and Nou mudstone they slightly decrease. The crushed Hattian Bala mudstone, however, retains its original void ratios, and does not seem to exhibit any particle breakage under a stress of less than 314 kPa (Fig. 7).

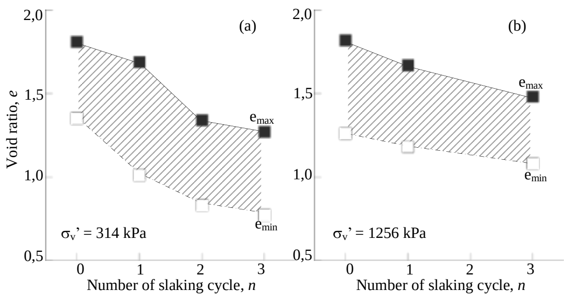

Fig. 5 Changes in void ratio (e) during slaking cycles (n) of Kakegawa mudstone

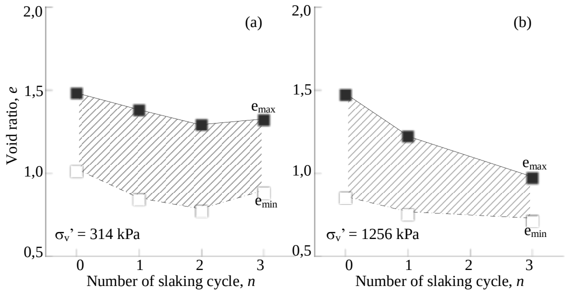

Fig. 6 Changes in void ratio (e) during slaking cycles (n) of Nou mudstone

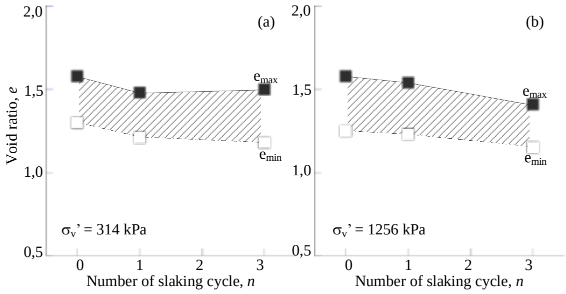

Fig. 7 Changes in void ratio (e) during slaking cycles (n) of Hattian Bala mudstone

Furthermore, the Hattian Bala mudstone particles did not contain any intra-granular pores (Fig. 4(c)), which would explain why there is so little change in particle size distribution during wetting and drying cycles shown by the breakage parameter (B_r) value. Figures 9, 10 and 11 exhibit the relationships between the vertical effective stress σ_v', number of wetting and drying cycles n, void ratio e and breakage parameter B_r for the all crushed mudstone, respectively. The upper figures ((a) and (b)) illustrate the behavior in compression, whereas the lower figures ((c) and (d)) show the variation in grading based on the B_r value. From the behavior of the Kakegawa mudstone shown in Fig. 9, it is clear that the value of B_r (Fig. 9(c)) increases to 0.12 at 314 kPa and to 0.19 at 1256 kPa, which is consistent with particle crushing theory. The compression line in the semi-logarithmic plot of e and log σ_v' also becomes steeper, which further confirms that particle crushing occurred [8]. After wetting and drying, the B_r value increased to 0.44 (Fig. 9(d)) and the specimen experienced significant compression, to the extent that the decrease in void ratio was greater than 0.6. For the crushed Nou mudstone, the results for which is summarized in Fig. 10, the B_r value increases from 0.21 to 0.25 at 314 kPa but decreases from 0.35 to 0.29 at 1256 kPa during wetting and drying. It was confirmed that particle breakage increases the proportion of fine particles to fill the void space between larger particles without considerably changing the maximum particle size.

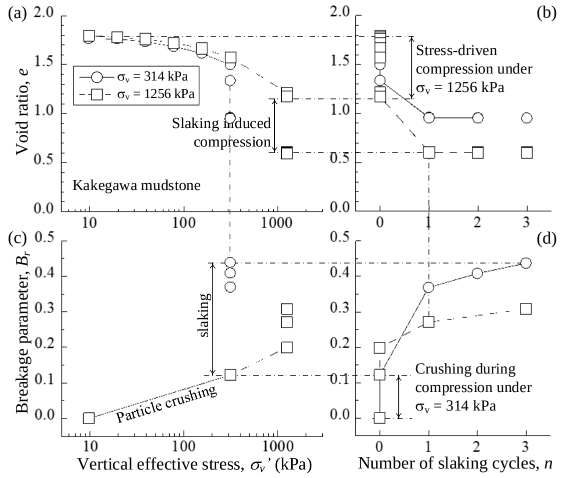

Fig. 8 Changes in the compressive properties and particle size of the Kakegawa mudstone

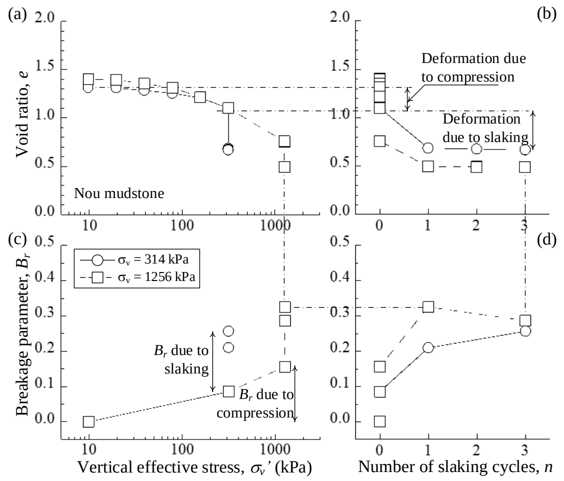

Fig. 9 Changes in the compressive properties and particle size of the Nou mudstone

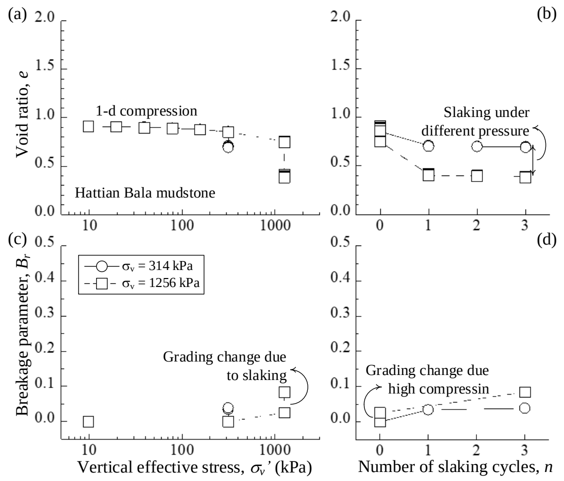

Fig. 10 Changes in the compressive properties and particle size of the Hattian Bala mudstone

The decrease in void ratio e (volumetric compression) were not significant, comparing to the Kakegawa mudstone. In contrast, the increase in Br of the crushed Hattian Bala mudstone (Fig.11) was almost zero during the compression stage at 314 kPa and slightly increase due to high compression at 1256 kPa. The compression line in the e-ln σ_v' plane was comparatively flat. This indicates that the variation in Br during wetting and drying is small. It can be inferred that slaking induced by wetting and drying cycle under a constant vertical effective stress causes substantial compression of geo-materials derived from mudstone.

An Effort to Eliminate the Deformation on Weak Rocks

A rational countermeasure technique is needed for reducing the deformation due to slaking on the earth construction project. A number of one-dimensional compression slaking test has been performed on Nou mudstone to get a better understanding related to these circumstances. The effect of loading/unloading compression history before wetting and drying cycle applied is one technique to consider. The procedure for the loading stage was similar with the previous one-dimensional compression slaking test already explained. Except for the effect of loading/unloading, after the high compression of 1256 kPa is applied for 30 min, then followed with the unloading process to 314 kPa for 30 min. Further, the wetting and drying cycles were applied as one cycle. The combination loading patterns in this section are summarized in Table 2. The particle size distribution (PSDs) changes of each case patterns of the test are shown in Fig. 12. It is significant that the PSD curve after loading history (case 7 and case 8) almost similar, despite the initial void ratios are different. It is inferred that the void ratio did not significantly affect to the grading changes. In spite of the high compression applied on the specimen, the final grading change (case 7 and case 8) almost similar with the test result of one-dimensional compression slaking under constant vertical effective stress at 314 kPa (case 3).

The total volume compression between case 3 and case 7 (Fig. 13(a)) also exhibit similar behavior, even though in case 7 the high compression stress has been applied in the beginning. It is pointed out that during the earth construction utilizing the geomaterial which has slaking properties, paying attention to roller compaction throughout the embanking work enhances the crushing of particles, controlling the occurrence of slaking under cyclic wetting and drying so that volumetric compression does not occur easily.

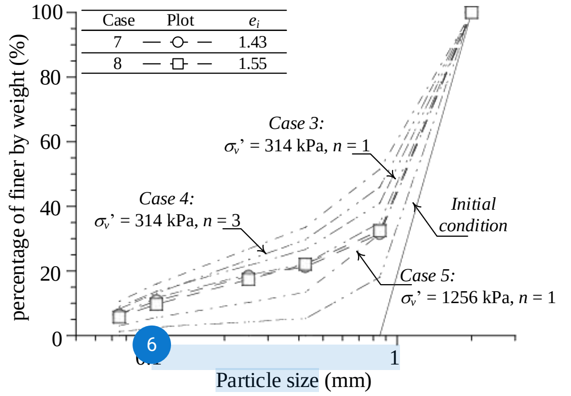

Fig. 11 The particle size distribution changes during stress history applied

Table 2 The one dimensional compression slaking testing series of Nou mudstone

case	1	2	3	4	5	6	7	8
e_i	1.3	1.5	1.3	1.3	1.4	1.4	1.4	1.6
σ_v'	314				1256		1256 - 314	
n	0	1	1	3	1	3	1	1

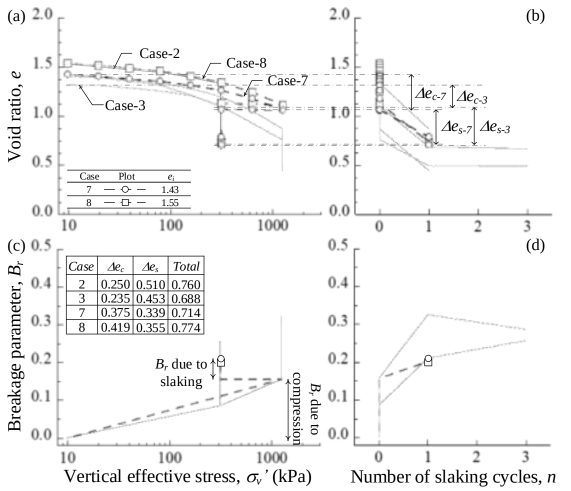

Fig. 12 Change in compressive properties during the stress history (loading/unloading) of Nou mudstone

CONCLUSIONS

In order to investigate the deformation due to slaking behavior, a number of one-dimensional compression slaking tests has performed in this paper. The surface morphology of mudstone based on SEM result indicated the different slaking and deformation behavior caused by the intra-granular pores within particle. The transformation of particle size distribution due to slaking is influenced by the existences of intra-granular pores. As a result, it causes an irreversible change in the mechanical properties of weak rocks attributable to variation in the density compaction. Moreover, the changes in particle size distribution as an evolution grading during compression can increase the compressibility of weak rocks, with wetting and drying cycles causing significant compression even if the effective stress remains constant. Since the evolution of particle size distribution under confined stress constant occurs without a change in the maximum particle size, it can be described by existing indexes of grading such as breakage parameter B_r. A countermeasures technique of the deformation behavior of weak rocks was performed in this study. Changing the particle size distribution in the beginning by applying loading/unloading history before wetting and drying cycle has exhibited the significant result. The compressibility during wetting and drying cycle decreases to 50% of conventional compression by applying this countermeasure method. In earth construction works, the process of roller compaction is necessary in order to encourage the crushing of particle. A proper compaction can control the occurrence of slaking under wetting and drying cycle so that volumetric compression does not occur easily.

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