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Mechanical properties of mudstone aggregate subjected to cyclic drying-immersion under constant vertical load, and seismic response analysis of mudstone embankments

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ABSTRACT

The definition of slaking is a soft rock/mudstone changing into a slurry soil and crushed fine-grained soil due to the action of water. This study consists of three parts. Firstly, one-dimensional compression behavior of dense compacted crushed mudstone aggregates of the degree of compression Dc of 95% was examined with drying-wetting cycles under one-dimensional compressive stress. Then, the shear behavior of the aggregates was examined using a triaxial compression test. Secondly, the triaxial test results were reproduced using SYS Cam-clay model. Finally, based on the simulation result, a seismic response analysis on typical road embankments made of mudstone was carried out using GEOASIA. The new findings are as follows:(1) The dense compacted crushed mudstone aggregates of Dc of 95% compressed by three drying-wetting cycles under one-dimensional compressive stress, and the final vertical strain was 8% under 3 drying-wetting cycles. (2) As for the triaxial compression test, the maximum deviator stress q_{max} of the mudstone aggregates in Test-1, which was subjected to 3 drying-wetting cycles, was larger than q_{max} for Test-2, which underwent no drying-wetting cycles, because the dry density of Test-1 was increased by the drying-wetting cycles. (3) In the simulation of triaxial compression tests, the degree of structure decreased as the number of drying-wetting cycles increased. As for the seismic response analysis, the embankment made of mudstone that was subjected to 3 drying-wetting cycles was more deformed than the embankment that was not subjected to drying-wetting cycles.

Keywords: mudstone, slaking, seismic response analysis

1 INTRODUCTION

When a mudstone road embankment is first built, the mudstone grains are hard, so the embankment has high stability. However, as the embankment have been submerged over a long period of time, some kinds of mudstone grains become fragile, and the embankment was gradually deformed. Shima et al. (1980) suggested that settlement due to slaking in road embankments should be prevented by compacting the material so that air content is no higher than 15%, and this suggestion is currently put into practice in the design and construction of mudstone embankments on expressways in Japan. However, as a result of an earthquake that occurred offshore of Suruga Bay in August 2009, a mudstone road embankment located near Makinohara Service Area collapsed. One reason for the collapse was that mudstone in the lower portion of the embankment had undergone considerable slaking. This accident led us to suspect that in preventing slaking, what needs to be taken into consideration is not just compression settlement but also shear deformation.

The authors have for some time approximated the long-term progression of slaking in mudstone through experiments that promote slaking by subjecting mudstone grains, whose size has been, to repeated cycles of drying and immersion (hereafter "cyclic drying-immersion"), then compacting the mudstone grains and investigating the compression and shear behavior of the resulting mudstone aggregates.

The aforementioned research by Shima et al. involved subjecting the material to cycles of drying and immersion while it was under one-dimensional loading, and Kato et al (2009). and Kikumoto et al. (2016) also focused on slaking caused by drying-immersion experience when the material was under one-dimensional compressive stress.

In this study, we took mudstone aggregate compacted with a degree of compaction (Dc) of 95% (to approximate an actual road embankment) and subjected it to cyclic drying-immersion while it was under one-dimensional loading so as to simulate the progression of slaking and investigate the mudstone's consolidation and shear behavior. Particularly, the effect of the grain size of mudstone on the shear behavior will be studied. In addition, we investigated the earthquake resistance of embankments with advanced slaking both by using an elasto-plastic constitutive model, the SYS Cam-clay model (Asaoka et al, 2000) to attempt to reproduce the shear behavior, and by using a soil-water coupled finite deformation analysis code, GEOASIA (Noda et al, 2008), to analyze seismic response.

2 MECHANICAL BEHAVIOR OF THE MUDSTONE AGGREGATE DURING AND AFTER CYCLIC DRYING-IMMERSION UNDER CONSTANT VERTICAL LOAD

The mudstone used in this study came from road work in Kobe (hereafter "Kobe mudstone"). This mudstone has a slaking ratio of 82%, meaning that it is easy to slaking. An initial grain size of Kobe mudstone was modified to 26.5–37.5 mm, and was statically compacted in a mold measuring 10 cm in diameter and 20 cm in height, placed in the drying-immersion compression apparatus shown in Fig. 1. It was subjected to vertical stress of 300 kPa. The test cases are shown in Table 1. In Test-1, the mudstone sample was first immersed in water for 3 days, and then subjected to 3 drying-immersion cycles, each consisting of 13 days of drying followed by 3 days of water immersion for a total of 16 days per cycle. In Test-2 and Test-3, the sample was only subjected to 3 days of immersion in water. In the experimental apparatus, the drying process consists of filling the interior of the container with a hot wind (having a temperature of 110°C), and the immersion process consists of conducting water to the specimen via holes in the base plate and the loading plate of the mold. The number of days for the drying and immersion processes were determined through preliminary experiments, where the length of the drying process is the number of days necessary for the degree of saturation to reach 0%, and the length of the immersion process is the number of days necessary for the degree of saturation to stop increasing and become constant.

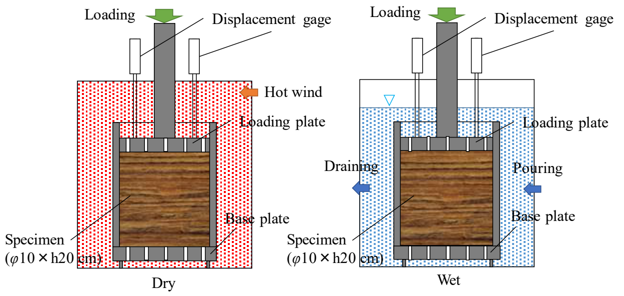

Fig. 1. Schematic diagram of drying-immersion compression apparatus.

After subjecting the sample to the aforesaid drying-immersion cycles, the specimen was saturated sufficiently using the double-suction method in the triaxial compression apparatus, and then consolidated for 24 hours at an isotropic pressure of 300 kPa, and an undrained triaxial compression test was carried out. As shown in Table 1, the specimens for Test-1 and Test-2 were prepared in such a way that their initial density would be identical and their degree of compaction would be 95%, while the specimen for Test-3 was prepared in such a way that its initial density would be the same as the density of the specimen for Test-1 after isotropic consolidation.

Table 1. Test cases.

Test	Dry – Wet Cycle	Initial Dry density (g/cm^3)	Dry density under shear (g/cm^3)
1	3	1.41	1.54
2	0	1.41	1.46
3	0	1.53	1.55

Fig. 2 shows the relationship between compression strain and time during the drying-immersion compression cycles. In Test-1, the specimen underwent compression in the drying process and expanded during the immersion process, and the compression increased with cyclic drying-immersion. After 1 drying-immersion cycle, the vertical strain was roughly 6%, but after 3 drying-immersion cycles it had increased to almost 8%. In Test-2 and Test-3, however, compression increased hardly at all.

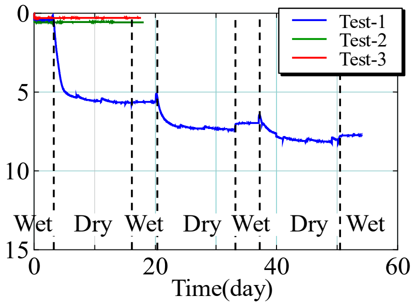

Fig. 2. Relationship between compression strain and time for Tests 1–3 across the drying-immersion compression cycles.

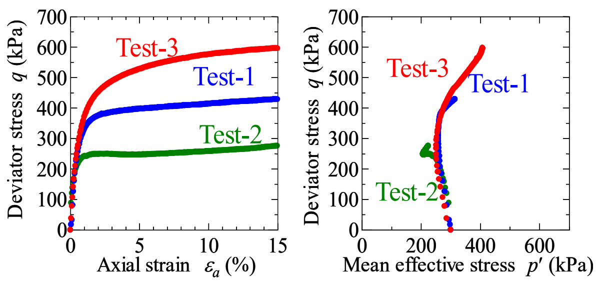

Fig. 3. Results of undrained triaxial compression test.

Fig. 3 shows the shear behavior in Test-1, which underwent 3 drying-immersion cycles, while in Test-2 and Test-3, in which drying and immersion were not carried out. The maximum deviator stress of Test-1 exceeded that of Test-2. One reason for this is that the cyclic drying-immersion under constant vertical load prior to shearing process compressed the specimen and increased its density. In comparison between Test-1 and Test-3, even though they had the same density. Test-3 had a higher maximum deviator stress than Test-1.

Fig. 4 shows grain size distribution after the triaxial compression test. Because we prepared the grains of mudstone cut from bedrock so that their grain size would fall within the range 26.5–37.5 mm, the original grain sizes at the time of cutting are unknown. In Test-1, the grain sizes changed as a result of cyclic drying-immersion compression and/or shear. Compared with Test-2, no more than 10% of the grains in the size range 2–20 mm underwent granulation in Test-1. In the case of Test-1 and Test-3, however, there was almost no change in grain size. When the specimen for Test-3 was prepared by compaction, a heavy compaction load needed to increase the density, so we believe that some of the grains were crushed during compaction.

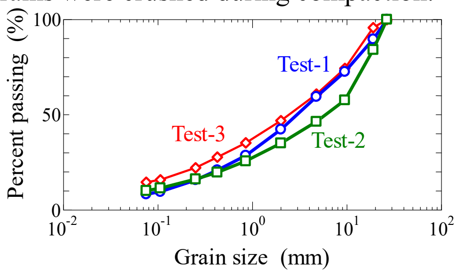

Fig. 4. Grain size distribution of specimens after shearing.

3 REPRODUCTION OF SHEAR BEHAVIOR, AND SEISMIC RESPONSE ANALYSIS OF MUDSTONE EMBANKMENTS

Using the SYS Cam-clay model, an elasto-plastic constitutive model that incorporates the soil skeleton structure concept, we performed numerical simulation of that shear behavior after cyclic drying-immersion under constant vertical loading. Because Test-1, Test-2, and Test-3 all used the same mudstone sample, their material constants are assumed to be identical, as shown in Table 2. The results of the simulation regarding the shear behavior of the mudstone aggregate are given in Fig. 5. As shown in Table 3, a comparison of Test-1 and Test-2 reveals that as the number of drying-immersion cycles increases, the degree of structure decreases. Although Test-3 was subjected to 0 drying-immersion cycles, overconsolidation ratio is high because its dry density roughly equal to that of Test-1 by compaction.

The seismic response analysis of Test-1, Test-2, and Test-3 are carried out before and after the progression of slaking in hypothetical road embankments. Fig. 6 is a full cross-section view of the embankment and the ground used in the analysis. The ground was assumed to be hard, with poor permeability. The embankment was taken to be a high, 3-level embankment that was 18 m in height and had a slope inclination of 1:1.8. The width of the crown was taken to be 25 m.

Fig. 7 shows the seismic motion that was input. The input seismic motion was a level-2 seismic motion based on the hypothesis of an inland, near-field earthquake.

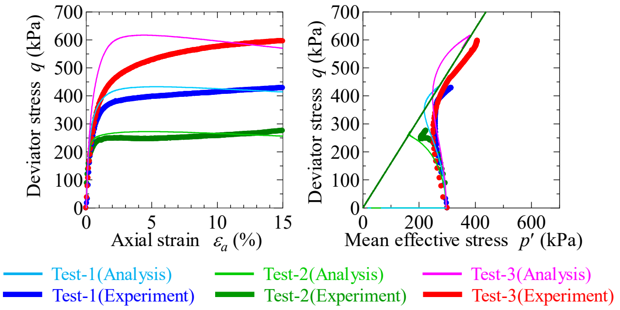

Fig. 5. Simulation of undrained shear tests.

Table 2. Material constants.

Elasto-plastic parameters		
Compression index	$\tilde{\lambda}$	0.085
Swelling index	$\tilde{\kappa}$	0.012
Critical state constant	M	1.600
NCL intersection	N	1.730
Poisson's ratio	ν	0.100
Evolution rule parameters		
Normal consolidated soil index	m	4.000
Structural decay index (b=c=1)	a	0.400
Plastic index	c_s	0.100
Rotational hardening index	b_r	1.000
Rotational hardening limit constant	m_b	0.200

Table 3. Initial condisions.

Test	Dry density (g/cm^3)	Degree of structure	Overconsolidation ratio
1	1.53	2.5	44.9
2	1.41	6.5	14.8
3	1.51	5.5	71.4

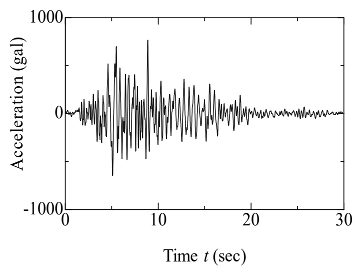

Fig. 7. Input seismic motion.

Fig. 8 shows the distribution of shear strain 20 years after the earthquake, including the amount of settlement in the center of the crown. In the embankment of Test-2, shear strain of about 30% occurred near the toe of the slope. The amount of crown settlement immediately after the earthquake was roughly 0.55 m, and 20 years after the earthquake, when consolidation was complete, the settlement was roughly 0.64 m. The embankment of Test-1 underwent less deformation than that of Test-2, and its maximum shear strain was roughly 10%; the amount of crown settlement was roughly 0.27 m 20 years after the earthquake. The embankment of Test-1,

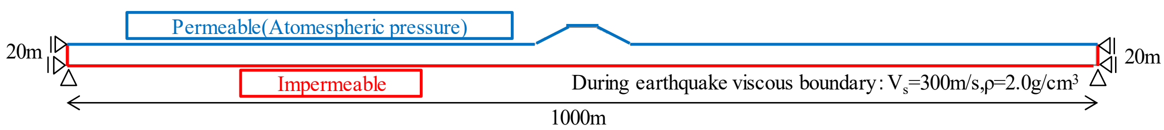

Fig. 6. Full cross section used in analysis.

which was subjected to 3 cyclic drying-immersions, displayed less deformation and greater earthquake resistance than the embankment of Test-2, which was not subjected to drying-immersion. One reason for this is identical to the reason that the maximum deviator stress for Test-1 in the triaxial compression test was high, i.e., that the cyclic drying-immersion under constant vertical load compressed the mudstone specimen and increased its density. Next, compared the embankment of Test-3 with the embankment of Test-1, it turns out that the embankment of Test-3 had about 40% less deformation, and higher earthquake resistance, than that of Test-1. This indicates that as drying and immersion increase the slaking, the earthquake resistance for a given density declines.

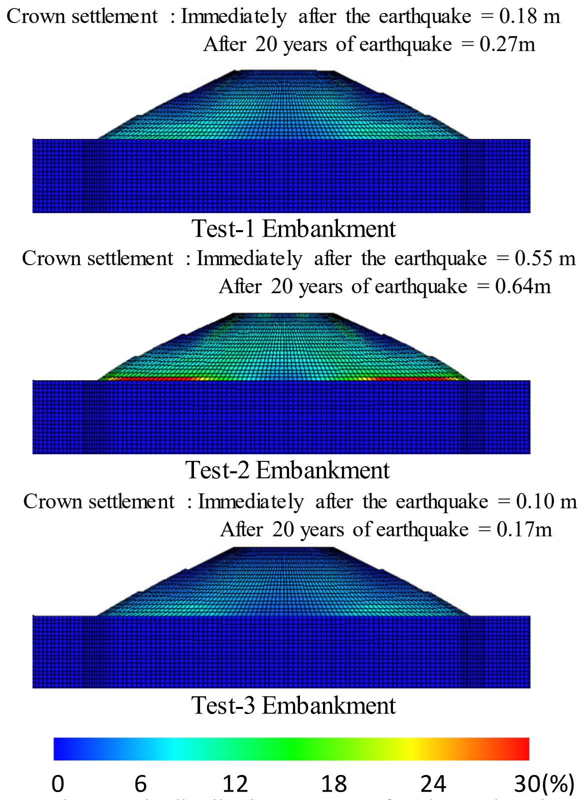

Fig. 8. Shear strain distribution 20 years after the earthquake.

4 CONCLUSIONS

The conclusions are as indicated below.

1) As regards the one-dimensional compression behavior of mudstone aggregate compacted to Dc of 95% and subjected to cyclic drying-immersion under a constant vertical load of 300 kPa, the mudstone underwent compression in the drying process and expanded during the immersion process, with compression increasing with cyclic drying-immersion. The final vertical strain was 8% when the mudstone was subjected to 3 cycles.

2) As regards the shear behavior of mudstone after cyclic drying-immersion under constant vertical load, because the dry density of the mudstone aggregate that was subjected to 3 drying-immersion cycles (Test-1) increased, its maximum deviator stress became greater than that of the mudstone aggregate that was not subjected to drying and immersion (Test-2). The grain size distribution after shearing changed somewhat due to the drying and immersion, and there was an increase in granulation.

3) The shear behavior in a mudstone aggregate was simulated using the SYS Cam-clay model with the material constants being equalized and given the same degree of compaction. When the number of drying-immersion cycles increased, the dry density increased due to settlement and the initial degree of structure decreased.

4) In a seismic response analysis of mudstone embankments, the embankment of Test-1, of which density is increased due to 3 drying-immersion cycles, exhibited the amount of crown settlement 20 years after the earthquake was roughly 0.27 m, compared to crown settlement of roughly 0.64 m in the case of the embankment of Test-2, which was not subjected to drying and immersion, so increase of the density due to the drying and immersion reduced subsequent crown settlement and increased earthquake resistance. However, compared to the embankment of Test-3, which had the same density as the embankment of Test-1 but was not subjected to drying and immersion, the embankment of Test-1 had lower earthquake resistance than that of Test-3, so it is evident that as drying and immersion increase the slaking, the earthquake resistance declines for the same density.

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