TRIAXIAL TESTS ON UNDISTURBED SAMPLES RETRIEVED FROM FAILED SLOPES DUE TO 2004 NIIGATA-KEN CHUETSU EARTHQUAKE

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ABSTRACT: Triaxial compression tests were performed on undisturbed specimens to reveal the mechanism of slope failure in the 2004 Niigata-ken Chuetsu Earthquake. The specimens were retrieved from two failed slopes which were located at Yokowatashi and Higashi-Takezawa, respectively. Drained monotonic loading test results showed that the mobilized friction angle is significantly larger than the inclination angle of slope in both cases. Undrained cyclic loading test results showed that full liquefaction did not occur. For the specimens retrieved from Yokowatashi site, the characteristics of shear band showed several different patterns which are likely to be relevant to material type, degree of weathering and existence of cavities in the sandy layer.

Key Words: Triaxial compression test, thin weak layer, slope failure, earthquake

INTRODUCTION

The Niigata-ken Chuetsu Earthquake, with a main shock of Mj=6.8, triggered extensive slope failures in Mid Niigata Prefecture, Japan on October 23 in 2004. After the mainshock, many large aftershocks repeatedly struck this area within about two months. According to aerial photo interpretation (MLIT, 2005), 3,791 slopes failed with total breakdown volume of about 100×10^6 m^3 over an area of about 1,310 km^2.

Besides the main shock and large aftershocks, the rainfall before the earthquake is likely to affect the extensive slope failure as well. This area had been subjected to a continuous heavy rainfall, more than 100 mm/day, leading up to 20th October, so the soil was well saturated and the ground water level was raised from the normal level. With saturated soil and higher ground water level, slope failure is more likely to occur than under normal conditions.

This study intends to investigate the mechanism of slope failure triggered in the Chuetsu Earthquake by performing triaxial compression (TC) tests. Two cases of failed slope in the earthquake were investigated: one is located at Yokowatashi, Ojiya City near Shinano River, and the other is at Higashi-Takezawa at Yamakoshi Village (currently Nagaoka City). In Yokowatashi case, the failed slope is 40 m wide and 70 m long with a dip angle of about 22 degrees, and its conditions before failure required more detailed investigation. A feature of this failure is that, on the planar sliding

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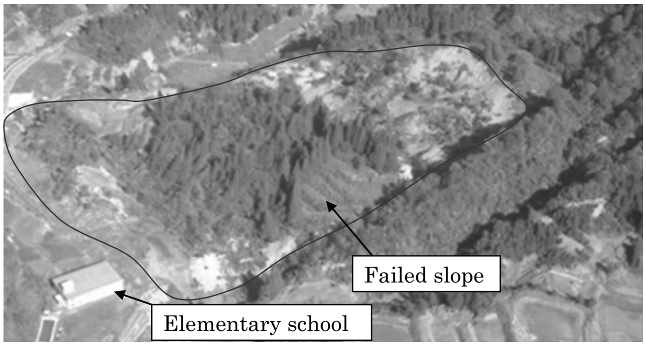
surface, there was a sandy soil layer with a thickness of 1 to 3 cm which is sandwiched by silt softrocks. This sandy layer is the emphasis of this study, but may be easily overlooked at the time of geotechnical survey. In Higashi-Takezawa case, the failed slope is 295 m wide, 350 m long with a dip angle of 18° at top region and 20° at toe region of the slope. Regarding its morphological characteristics, Chigira *et al.* (2006) argued that the earthquake reactivated a pre-existing failure plane which then formed most of the present sliding plane.

This paper focuses on the triaxial compression test results on undisturbed cylindrical specimens from Yokowatashi site and prismatic specimens from Higashi-Takezawa site. Comparison will be made between the present test results and the results of plane strain compression (PSC) tests and TC tests on prismatic specimens from Yokowatashi site in Deng *et al.* (2007). The conclusion in this paper can be used to analyze the stability of the two slopes before failure, which will be reported elsewhere.

a)



b) (photo by Kokusai Kogyo, 2004)

Figure 1. Investigated failed slopes **a)** at Yokowatashi and **b)** at Higashi-Takezawa

APPARATUS, SPECIMENS AND TEST PROCEDURES

Apparatus

Although direct shear tests and ring shear tests are usually conducted in studies on slope failure, triaxial compression tests were performed in this research due to the existence of the weak layer. Some of the specimens used in this research had a weak layer as described later in this paper, and a shear band formed within the weak layer. However, the exact location of the shear band could not be predicted accurately before shear. This inaccuracy may induce large scatter in the measured strengths. Direct shear tests and ring shear tests have disadvantages in investigating the strength of such specimens, because a clear sliding surface should be determined before shear in these tests. On the contrary, in triaxial compression tests, shear band can form without any artificial interference.

The apparatus used in this study was a modified version of PSC test apparatus (Salas Monge *et al.*, 2002, and Deng *et al.*, 2007). Without employing the lateral confining plates, this apparatus can be used to perform TC test on prismatic specimens and cylindrical specimens by changing the top cap and pedestal.

An external displacement transducer was used to measure the global axial strain, and Local Deformation Transducers (LDTs) were used to measure the deformation near the weak layer and the deformation of softrock. The volume change was measured by a Low Capacity Differential Pressure Transducer (LCDPT), and the minor principal stress was measured by a High Capacity Differential Pressure Transducer (HCDPT).

A 0.3-mm-thick membrane was used, and dots were imprinted on the membrane at a spacing of 5 mm. For prismatic specimens, a digital camera with a resolution of 8 mega pixels was used to take photos of these dots for image analysis.

Specimens and Test procedures

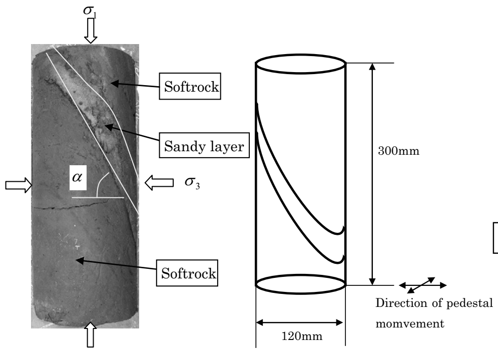
In total, seven types of specimens retrieved from two failed slopes were used in the current study for various purposes as listed in **Table 1**.

Table 1. Summary of test conditions

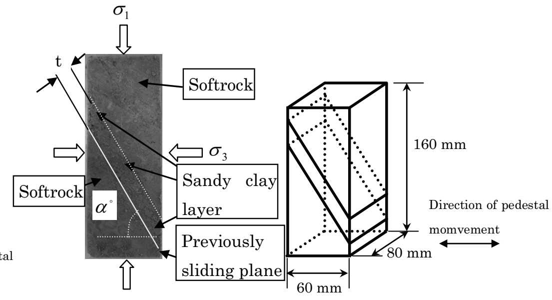
test No.	test type[1]	saturation condition[2]	test condition for shear[3]	B-value (%)	effective confining pressure σ'_{3i} (kPa)	q_0[4] (kPa)	α[5] (°)	t[6] (mm)
R-1[7]	PSC	DVS	D	67.5	50	-	-	-
R-2[7]	PSC	DVS	UD	94.2	54	-	-	-
PSC-1[7]	PSC	DVS	UD	97.4	49	39	61.7	-
TC-1[7]	TC	DVS	UD	86.7	48	45	54.4	-
TC-2[7]	TC	DVS	UD	98.9	51	45	54.8	-
TC-3[7]	TC	DVS	D	98.2	90	-	56.3	-
TC-4[7]	TC	DVS	D	97.6	20	-	60.1	-
TC-5[7]	TC	US	D	-	45	-	47.5	-
TC-6[7]	TC	US	D	-	90	-	51.9	-
TC-7[7]	TC	US	D	-	20	-	62.2	-
TC-8[7]	TC	DVS	UD	98.5	52	44	53.1	-
TC-9[7]	TC	DVS	UD	98.8	45	45	51.3	-
R-P-1	UcC	Air-dried	-	-	0	-	-	-
R-P-2	UcC	Air-dried	-	-	0	-	-	-
TC-PU-1	TC	DV	UD	99.0	43	37	60.4	-
TC-PU-2	TC	DV	UD	98.3	44	20	64.0	-
TC-PU-3	TC	DV	UD	99.2	20	45	62.6	-
TC-PB-1	TC	DV	UD	99.2	45	45	66.7	-
TC-PB-2	TC	DV	UD	98.7	46	45	67.4	-
TC-PB-3	TC	DV	UD	99.1	45	-	60.1	-
H-1	TC	DV	UD	99.1	46	28	67.9	3
H-2	TC	DV	D	99.1	44	-	66.4	3-24
H-3	TC	DV	D	98.3	20	-	65.4	7-32
H-4	TC	DV	D	98.8	90	-	62.5	3
H-5	TC	DV	D	98.8	90	-	54.9	12-22
H-6	TC	DV	D	99.2	89	-	55.9	3-18
H-7	TC	DV	UD	98.8	45		60.0	3
H-8	TC	DV	UD	99.2	45	45	56.0	3

[1] UcC: Unconfined Compression test; TC: Triaxial Compression test.
[2] DV: Saturated by double vacuuming method
[3] D: Drained; UD: Undrained.
[4] deviator stress during creep, q_0 (kPa)
[5] orientation of sandy or clay layer, α (°)
[6] clay layer thickness, t (mm)
[7] reported in detail by Deng *et al*. (2007)

Undisturbed cylindrical specimens (ϕ120×300 mm, typically as shown in **Figure 2 a)**) including R-P-group, TC-PU-group and TC-PB-group were retrieved by a rotary sampler using a planet gear (Sugawara *et al*., 1996) from the Yokowatashi site. **Figure 3** is a sketch showing the sampling location, where the sketched cross-section corresponds to the direction of the arrow shown in **Figure 1**. Although only one boring hole is shown in **Figure 3**, the other holes were also drilled in parallel to this hole at a horizontal distance of 2~8m from the sketched surface. As shown in **Figure 3**, R-P-group specimens were softrock which did not contain the thin sandy layer; TC-PU-group contained a slightly weathered sandy layer which was located about 2m higher than the sliding plane; TC-PB-group contained a sandy layer on which the sliding took place. The sandy layer in TC-PB-group was weathered, while the weathered soil did not flow away with water except one small cavity that was found in the sandy layer in specimen TC-PB-2. All the specimens were trimmed in laboratory to avoid contact between the sandy layer and top cap or pedestal, with the exception of TC-PB-3, where a small part of sandy layer was in contact with the pedestal which is discussed later in the paper.



a). Cylindrical specimen (TC-PB-1)



b). Prismatic specimen (H-2)

Figure 2. Sandwiched specimen

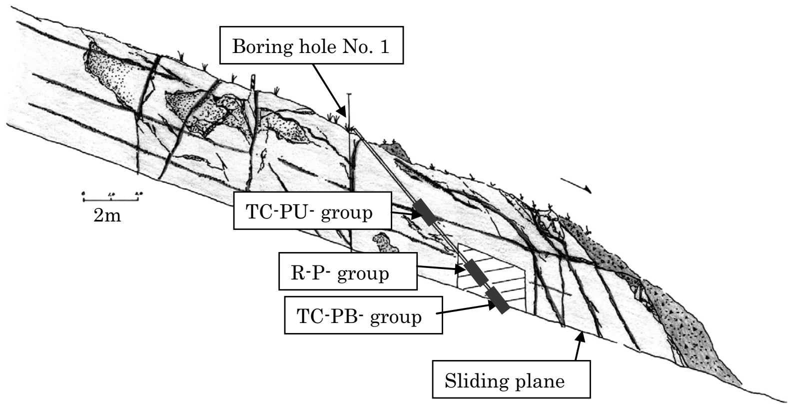


Figure 3. Sampling location at Yokowatashi site

R-group prismatic specimens (Deng *et al.*, 2007) were retrieved by the block sampling corresponding to the R-P-group (**Figure 3)**. TC-group and PSC-group prismatic specimens (Deng *et al.*, 2007) which contained a sandy layer were also retrieved by block sampling near the sketched surface which is marked as a shadowed area in **Figure 3.**

H-group specimens (width×length×height=60×80×160 mm, typically as shown in **Figure 2 b)**) were retrieved from the Higashi-Takezawa siteby block sampling method at the location where the previous sliding plane passed through (**Figure 4**). According to Kameya *et al.* (2007), some small cavities were found in the sandy clay layer.

Except for the specimens R-P-1 and R-P-2, all the other specimens in Table 1 were saturated, and filter paper was used at the side of the specimen to ensure saturation and possible drainage. With an effective confining stress σ_3' of 20~30 kPa, the specimens were firstly saturated by using the double vacuuming method which consists of vacuuming, flushing with de-aired water and back pressurization

(Ampadu and Tatsuoka, 1993). For undrained shearing tests, TC-PB-1, TC-PB-2, H-1 and H-7, after isotropic consolidation, drained loading was performed until the deviator stress q_1 ($=\sigma_1 - \sigma_3$) reached the prescribed value (q_0) to reproduce the in-situ drained state before earthquake. After a 50-minute drained creep loading with the deviator stress $q_1=q_0$, undrained creep loading was applied for 10 minutes to reproduce the in-situ stress condition just before the earthquake. Finally, undrained monotonic/cyclic shearing was applied until the end of test. For the other undrained shearing tests, undrained shearing was started from the isotropic stress state.

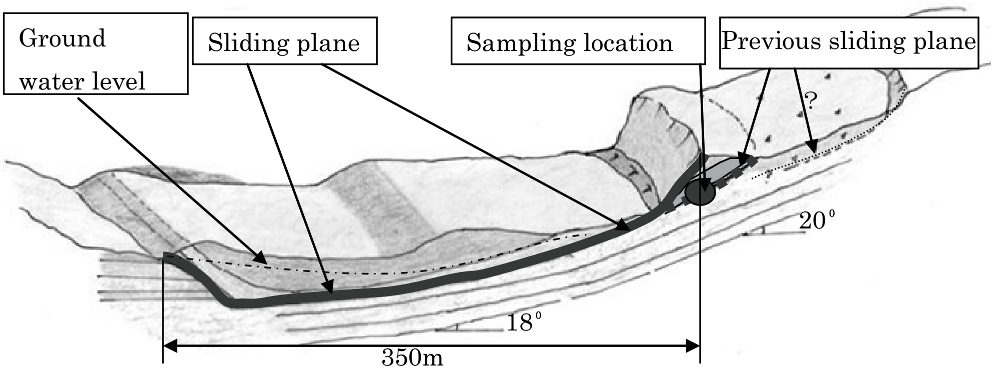


Figure 4. Sampling location at Higashi-Takezawa site
(sketch by SABO Technical Center et al. (2005))

In the cyclic loading tests, undrained cyclic loadings with a double amplitude deviator stress, q_d, of 30, 60, 90, 120 and 150 kPa were applied step by step. At each loading step, ten cycles were applied. Finally, undrained monotonic loading was applied to the specimen.

For saturated drained test, the specimens were consolidated isotropically. The B value was measured after saturation. Finally, drained monotonic loading was applied under a constant confining stress. For unsaturated tests, specimens were sheared directly after consolidation under a constant confining stress, while maintaining the initial water content.

For all the H-group tests, lubrication was applied at the interfaces between the specimen and the top cap and pedestal. The pedestal used in this group tests could move horizontally in one direction (**Figure 2 b)**). For the other groups of specimens, the pedestal could move in any arbitrary direction in the horizontal plane (**Figure 2 a)**), making lubrication at the interfaces between the specimen and the top cap and pedestal unnecessary.

For all the tests, during monotonic loading and cyclic loading, the axial strain rate was 0.2%/min.

TEST RESULTS AND DISCUSSION

Test results on R-P-group specimens

Figure 4 shows that softrock specimens (R-P-group) had a peak strength of about 3000 kPa and their corresponding secant Young's modulus E_{sec}, measured with the external displacement transducer, was about 130~230 MPa. As compared to the previous test results on R-group in Deng *et al.* (2007), the strength of R-P-group was similar to that of the R-group, while its secant Young's modulus E_{sec} was significantly smaller than that of R-group. Similarly, a smaller secant Young's modulus was also confirmed by LDT measurement as shown in **Figure 5**. The softer behavior of R-P-group specimens was likely to be relevant to the cross-sectional cracks, possibly induced during the sampling process, while the strength of softrock seemed to be unaffected by the cracks.

Test results on TC-PU-group specimens

Figure 6 shows the undrained test results of TC-PU-group specimens with different effective confining stresses. In **Figure 6 a)**, the specimen TC-PU-3 had a peak strength of over 500 kPa with an initial effective confining stress of 20 kPa. It can be seen in **Figure 6 b)** that though the specimens

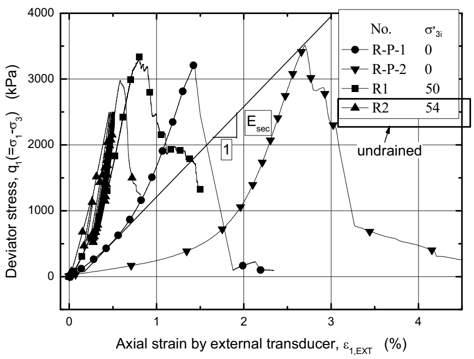


Figure 4. Stress-strain relationships measured by external transducer in R-P-group specimens

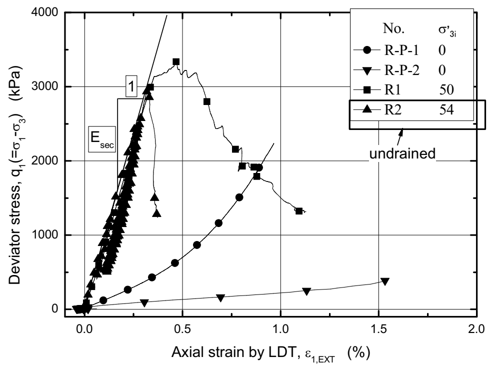
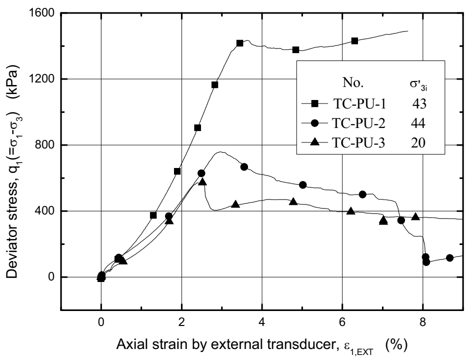
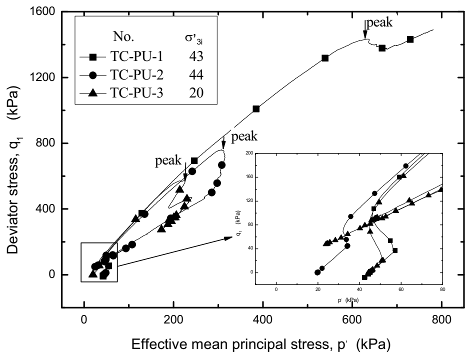


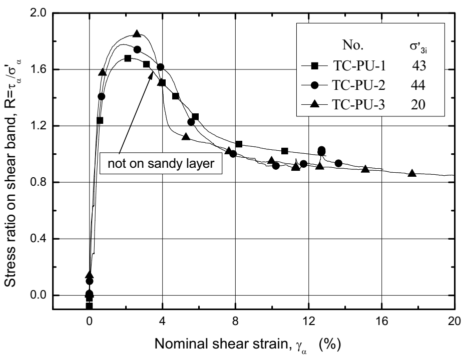
Figure 5. Stress-strain relationships measured by LDT in R-P-group specimens



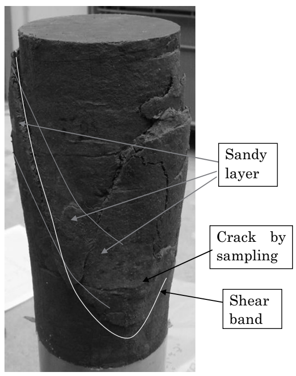
a) Stress-strain relationships



b) p'-q_1 relationships



c) R-γ_α relationships

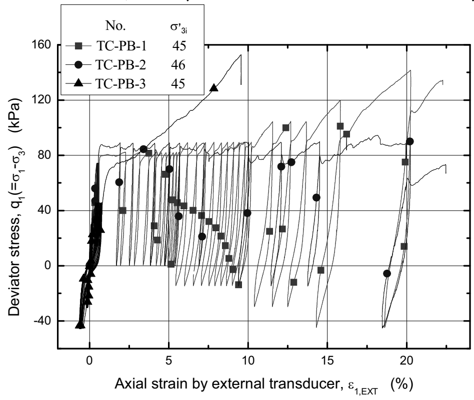


d) Failure in TC-PU-1

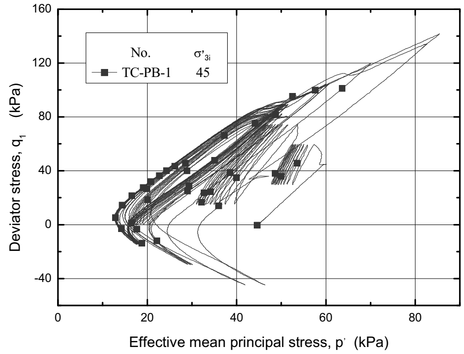
Figure 6. Tests on TC-PU-group

were contractive at the beginning of shearing, the dilative behavior was mobilized at the peak state. The contractive behavior of this group at the start of undrained shear may be affected partly by horizontal cracks which were possibly induced during sampling.

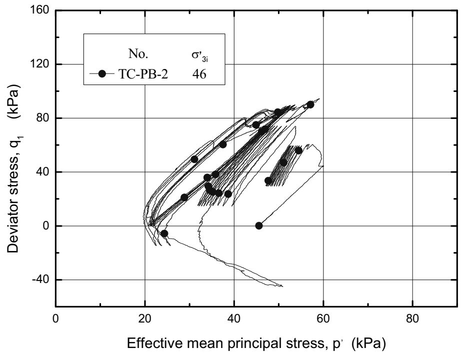
Figure 6 c) shows the R-γ_α relationships in TC-PU-group on shear band, where R is shear stress ratio on shear band, and γ_α is nominal shear strain. R-γ_α relationships were fairly similar to each other. Refer



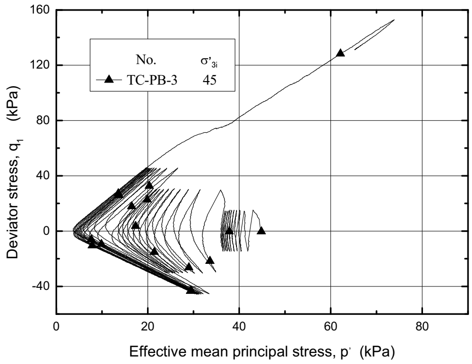
a) Stress-strain relationships in TC-PB-group



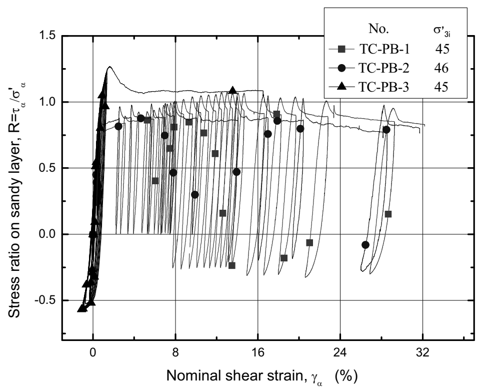
b) p'-$q_1$relationship in specimen TC-PB-1



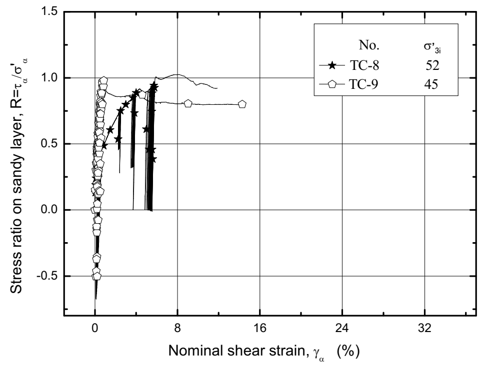
c) p'-$q_1$relationship in specimen TC-PB-2



d) p'-$q_1$relationship in specimen TC-PB-3



e) R-γ_α relationships in TC-PB-group specimens



f) R-γ_α relationships in TC-group specimens

Figure 7. Test results on TC-PB-group and TC-group specimens

to Deng *et al.* (2007) for the details on measurement of shear band orientation and the calculation of nominal shear strain γ_α.

As shown in **Figure 6 d)**, the shear band in specimen TC-PU-1 was not on the sandy layer. In addition, the peak of stress ratio R_{max} was over 1.6 which was much higher than that of specimens in TC-PB-group as shown later (**Figure 7 e)**). These two facts suggest that the sandy layer in this group was not deeply weathered and had high strength, so it did not fail during the earthquake.

Test results on TC-PB-group specimens

Figure 7 shows undrained cyclic loading test results on TC-PB-group specimens.

In **Figure 7 a)**, under similar test conditions, specimens TC-PB-1 and TC-PB-2 exhibited a peak deviator stress of about 80 kPa. In the subsequent cycles, no significant accumulation of excess pore water pressure can be seen in **Figures 7 b) and c)**. For all the three tests, although the excess pore water pressure increased dramatically before exhibiting a peak deviator stress, the effective stress path did not pass the origin as shown in **Figures 7 b), c)** and **d)**. These results were possibly affected by the membrane compliance as described in Deng *et al.* (2007).

In **Figures 7 e)** and **f)**, R-γ_α relationships in TC-BP-group specimens and TC-group specimens (TC-8 and TC-9) are plotted respectively. TC-PB-group specimens exhibited similar R-γ_α relationships to those of TC-group specimens, except that their mobilized residual stress ratios were higher than those of TC-group specimens which were retrieved very near the failed slope.

The pattern of shear band formation observed in the current study was different from the one observed in the previous prismatic specimens TC-8 and TC-9. In this TC-PB-group, the shear band (**Figure 8**) was thin and always located on the lower boundary which was between the sandy layer and the bottom softrock, except for a small part of shear band in TC-PB-3 (**Figure 9**) that was formed along the upper boundary between the sandy layer and the upper softrock as the bottom boundary touched the pedestal. In the previous tests of TC-group (**Figure 10**), on the other hand, the shear band was much thicker and contained some crushed blocks.

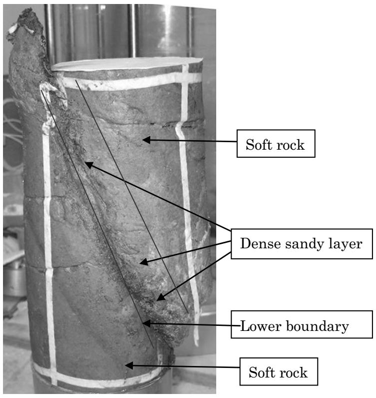


Figure 8. Failure in TC-PB-1

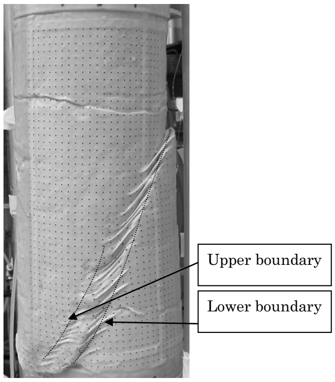
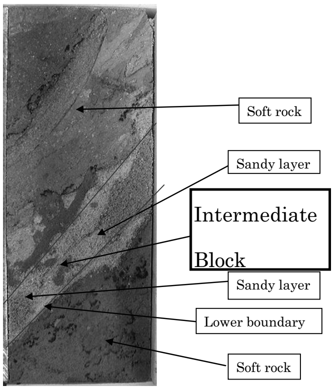


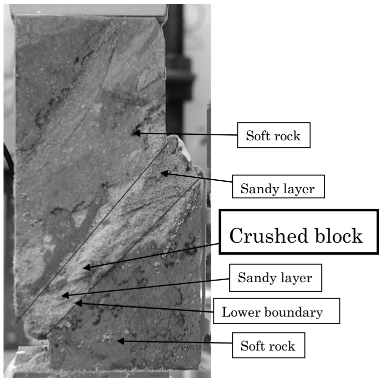
Figure 9. Failure in TC-PB-3

Monotonic loading test results on H-group specimens

Figure 11 shows monotonic loading test results on H-group specimens. In **Figure 11 a)**, no significant strain soft was observed. As the bottom rock block of specimen H-5 touched the top cap and pedestal after the axial strain exceeded 1.7%, its peak deviator stress was much higher than those the other specimens that were tested under similar conditions. In **Figure 11 c)**, the peak value of the shear stress ratio that was mobilized on the sandy clay layer varied within a range of 0.6 to 0.9, and its residual value is only slightly lower than the peak value. **Figure 11 d)** summarizes $\sigma'_\alpha - \tau_\alpha$ relationships in monotonic loading tests in H-group. The failure envelopes for the peak and residual stress states were also drawn in the figure. As a result, the strength parameters as listed in **Table 2** were obtained.

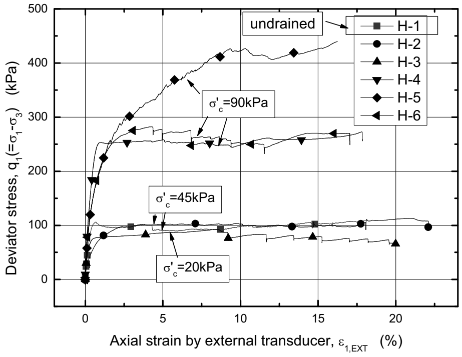


a) before shearing

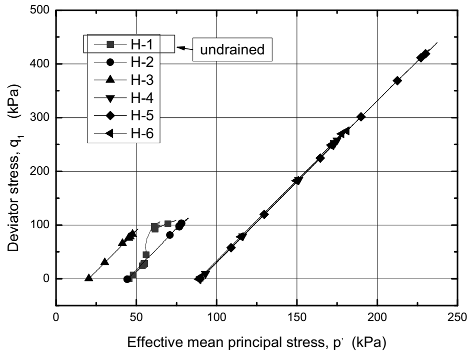


b) after shearing

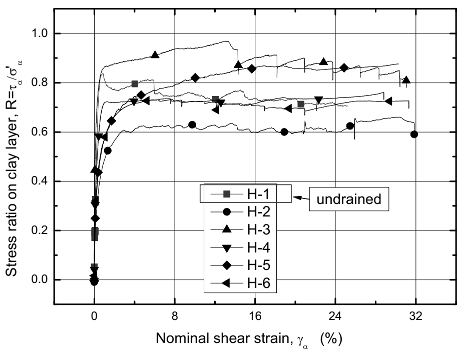
Figure 10. Crushing of intermediate blocks in specimen TC-5



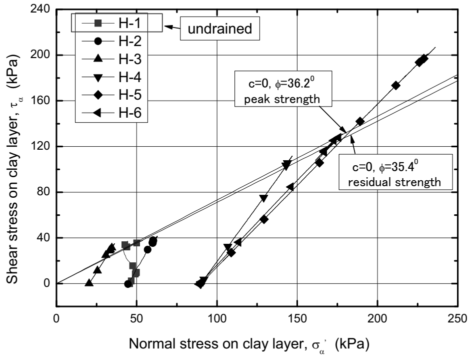
a) Stress-strain relationships



b) p'-q_1 relationships



c) R-γ_α relationships



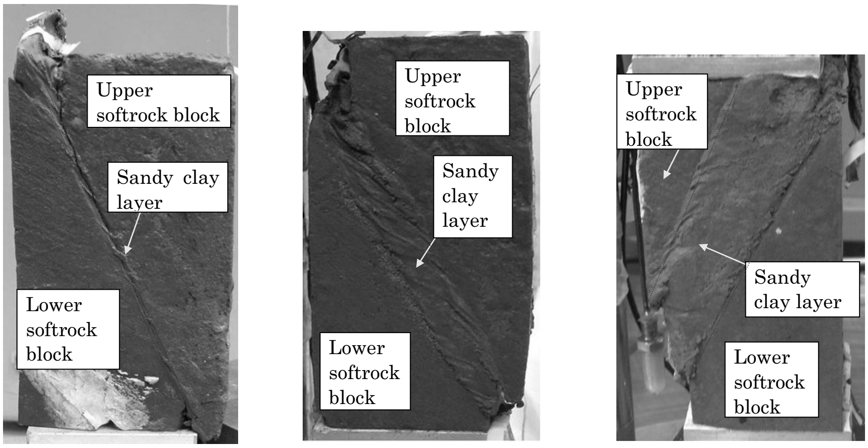
d) Shear stress-normal stress relationships on sandy clay layer

Figure 11. Test results on H-group in monotonic loading

Table 2. Strength parameters of H-group specimens in monotonic loading

	ϕ_{peak} (deg.)	c_{peak} (kPa)	ϕ_{res} (deg.)	c_{res} (kPa)
Saturated specimens	36.2	0	35.4	0

Strain localization occurred within the whole region of the sandy clay layer having a width in the range of 3 mm to 32 mm (**Figure 12**) that had irregular interfaces with the soft rock blocks. Their stiffnesses were different from each other: increasing in the order the sandy clay layer, the upper softrock block, the lower soft rock block. The sandy clay layer can be pinched by finger easily, while the lower softrock block can not be pierced even by a scoop.



a) H-1 b) H-2 c) H-3

Figure 12. Sandy clay layers in H-group

Cyclic loading test results on H-group specimens

Neither specimen H-7 nor specimen H-8 liquefied as shown in **Figure 13**. As is the case with the test results on TC-PB-group as shown in **Figure 7**, the test results on specimens H-7 and H-8 were possibly affected by the membrane compliance as described in Deng *et al.* (2007).

Summary of test results on specimens retrieved from Yokowatashi

The previous test results on prismatic specimens (Deng *et al.*, 2007) and the current test results on cylindrical specimens are summarized in this section.

The strength was likely to be affected by the soil type, degree of weathering and degree of erosion. The softrock specimens of R-group in Deng *et al.* (2007) and R-P-group in this paper, which did not contain the sandy layer, had a peak strength of over 3 MPa in unconfined compression tests or TC tests. The specimens, with slightly weathered sandy layer (TC-PU-group), had a peak strength of over 500 kPa under an initial effective confining stress of 20 kPa, and the corresponding shear stress ratio mobilized on the sandy layer was over 1.6. The specimens in TC-PB-group, which had been deeply weathered while having a few cavities in the sandy layer, mobilized the peak stress ratio of 1.3 in undrained tests. Specimens in TC-group in Deng *et al.* (2007), which contained deeply weathered sandy layer and many visible cavities, were the weakest among the five groups tested in this present study, so the failure occurred along this sandy layer.

The failure patterns were different among the six groups. The R-group and R-P-group specimens failed in the test like a common softrock. In two cases of specimens in TC-PU-group, the shear band was mostly formed within the sandy layer. The shear band of specimens in TC-PB-group was formed along the boundary between the sandy layer and the lower softrock when the boundary did not touch

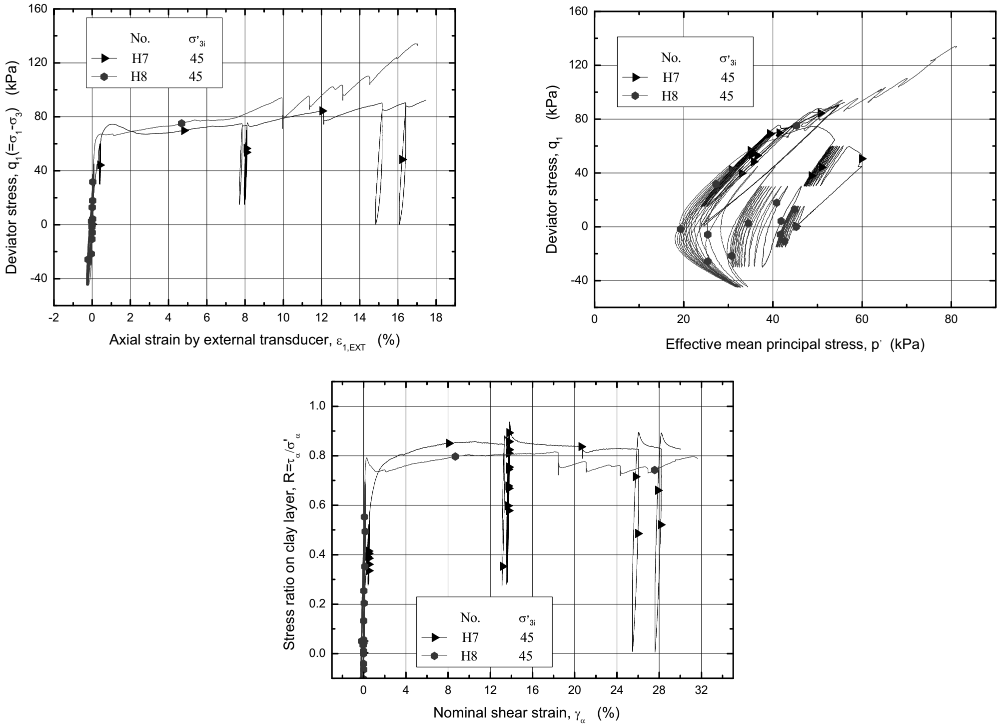


Figure 13. Cyclic loading test results on H-group

the pedestal. For the specimens in TC-group and PSC-group which contained many visible cavities, the shear band was very thick and crushing of intermediate sandy softrock blocks were observed.

The failure pattern seems to contribute to the large residual displacement of slope that was induced by the earthquake. It is reasonable to extrapolate that in the failed slope there were more cavities in the saturated sandy layer. So, when these cavities, that were sandwiched between adjacent softrocks, having low permeability were compressed during sliding, the pore water pressure could increase significantly.

Summary of test results on specimens retrieved from Higashi-Takezawa site

The H-group specimens also had a weak sandy clay layer which was 3 to 32mm thick according to the measurement after failure. The shear band with an irregular interface was always formed within this sandy clay layer.

The peak strength of H-group was c=0, $\phi = 36.2^{\circ}$ which was weaker than that of the TC-group from Yokowatashi site. As the dip angle was 18°~20°, the slope was stable under normal condition when there was no earthquake and the ground water level was not extremely high. The increment of strain induced by cyclic loading was very limited, and full liquefaction did not occur under undrained cyclic loading conditions.

CONCLUSIONS

The following conclusions can be drawn from the test results presented in this paper:

1) For the specimens retrieved from Yokowatashi site, the strength was affected by material type and

degree of weathering. The TC-group specimens which were retrieved very near the failed slope were the weakest among the tested specimens.

2) For the specimens retrieved from Yokowatashi site, the failure pattern was affected by the material type, the degree of weathering and the existence of cavities. The TC-group specimens had a very thick shear band, while the TC-PU-group specimens which were retrieved from the locations far from the failed slope had a thin shear band along the boundary between the sandy layer and the lower softrock.
3) For the specimens retrieved from Higashi-Takezawa site, the strength was lower than that of the specimens retrieved from Yokowatashi site. In both cases, a weak layer was found on the shear band formed in the tests.
4) In the cyclic loading tests, full liquefaction did not occur. This may be affected by the effects of membrane compliance.

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