Influence of fine particles run off on shear behavior of volcanic coarse-grained soil

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ABSTRACT

In Hokkaido, Japan, over 40% area has been covered by volcanic coarse-grained soils. Due to the extreme weather in Hokkaido, snowfall always reaches several meters. After winter, a large amount of snow melts into water simultaneously, and at the same time permeated into ground rapidly and continuously. Fine particles contained in soil, therefore, will be carried out of soil structure by water. Changes in soil structure should be expected. The main purpose of this paper is to examine influences of fine particles run off on the shear behavior and Soil-Water Characteristic Curve, SWCC, which plays a very important role in the determination of unsaturated soil property function, of the volcanic coarse-grained soil under unsaturated condition. A series of triaxial compression tests and soil-water characteristic test were performed for volcanic coarse-grained soil from which fine particles were removed by water flow previously. The experimental results show that the shear strength of volcanic coarse-grained soil decreases substantially under both saturated condition and unsaturated condition when fine content was removed. Fine particles run off also gives a strong influence to soil-water characteristic curve. It causes a rightward shift in soil-water characteristic curve.

Keywords: volcanic coarse-grained soil, fines run off, unsaturated soil, shear behavior, SWCC

1 INTRODUCTION

Volcanic coarse-grained soils which are generated due to dynamically occurred active volcanos eruption since the quaternary period are widely spread over Japan. In Hokkaido, the northern island of Japan, over 40% of its area has been covered by abovementioned volcanic coarse-grained soils.

These soils are usually used as construction material for their relatively stable mechanic property and its advantage of lightweight compared to other soils. Recent years, volcanic coarse-grained soils have attracted many researchers’ attention. A tremendous amount of researches about volcanic coarse-grained soils have been made. According to the previously conducted researches, volcanic coarse-grained soils showed a quite different behavior from other soils, such as sands or clays. That is so-called crushability which means soil particles crushes even at low stress state. This special behavior of volcanic coarse-grained soils leads to a result which is strength characteristics’ degradation (Sahaphol & Miura 2005). Hence, volcanic coarse-grained soils have been classified as “problematic soils”.

At current time, due to climate change, abnormal weather, like extremely heavy rain, is very common in snow melting season. Geotechnical disasters in Hokkaido, like slope failures or landslides, usually occur in the snow melting season. These have been considered caused by an increasing degree of saturation due to the melting water and the particles crushing induced by freeze-thaw action (Ishikawa & Miura 2011).

In addition to previous findings, there might be another reason, which is fine particles run off, takes credit for such geotechnical disasters. In snow melting period, a large amount of rainfall together with snow melting water permeated into the ground simultaneously. Fine particles contained in the volcanic coarse-grained soil ground would be carried out of soil structure by water flow. Changes in soil structure could be expected. Then strength of volcanic coarse-grained soils should change. Some researchers have been investigating the effect of fine particles on shear behavior (e.g. Sterpi 2003). They developed a seepage erosion model and evaluated the effect of fines on shear behavior of sand and gravel mixture. However, they used reconstituted soil from which fine content was simply removed through sieving as triaxial compression test material. Such reconstituted soil’s structure may be different from ones that were natural formed.

The objective of this paper is to investigate the effect of fine particles run off on the shear behavior of...
volcanic coarse-grained soil under different degree of saturation. To examine that, a series of monotonic triaxial compression tests for crushable volcanic coarse-grained soil specimens from which fine particles have been removed previously (referred as fines removed specimens hereafter) were performed under various degree of saturation by using an unsaturated triaxial test apparatus. SWCC test was also conducted by using same apparatus. The results were then compared with previous findings (Ishikawa et al. 2010) in which the shear behavior of volcanic coarse-grained soil with original grain size distribution (referred as original specimens hereafter) has been tested.

2 TESTING METHOD

2.1 Test materials

In this study, Kashiwabara volcanic soil was used as test material. This soil was sampled from natural deposits provided by Shikotsu caldera. Table 1 and Figure 1 show the index properties and the grain size distribution curves of the Kashiwabara volcanic soil respectively.

From Table 1 and Figure 1, it could be known that the soil has a fine content of about 1.9%. It is also worth to notice the low value of dry density of Kashiwabara volcanic soil. Extremely porous constituent particles caused its light dry density. Moreover, the porous particle is the reason for the high crushability of volcanic coarse-grained soil.

Table 1. Index properties of test material.

| Sample name | Kashiwabara volcanic soil |
|-------------|---------------------------|
| $\rho_s$ (g/cm$^3$) | 2.34 |
| $\rho_{d,max}$ (g/cm$^3$) | 0.623 |
| $\rho_{d,min}$ (g/cm$^3$) | 0.462 |
| $D_w$ (mm) | 1.25 |
| $F_r$ ($\phi75\mu m$) (%) | 1.94 |

Figure 1. Grain size distribution of Kashiwabara volcanic soil.

2.2 Test apparatus

Figure 2 shows a schematic diagram and a photo of a triaxial apparatus used in this study. A series of monotonic triaxial compression tests were conducted by employing axis translation technique (Hilfs 1956) along with pressure membrane method.

Various matric suctions were achieved by keeping pore air pressure ($u_a$) of 200 kPa constant and lowering pore water pressure ($u_w$) from 200 kPa during tests. Pore water pressure was applied to the specimens through a hydrophilic acrylic copolymer membrane filter (Versapor membrane filter, Air Entry Value, AEV=110kPa). The Versapor membrane was placed to the water plumbing path which was under the bottom of the soil specimen. On the top of the specimen, pore air pressure was applied through a hydrophobic polyflon filter. On the other hand, triaxial compression tests under saturated condition could be performed just by removing the Versapor membrane filter and the polyflon filter.

As shown in Figure 2, the axial loading was applied to soil specimen through a Direct Drive Motor, DDM. The axial stress ($\sigma_a$) was measured by using a load cell installed inside the triaxial cell, and the axial strain ($\varepsilon_a$) was measured by an external displacement transducer. The volumetric strain ($\varepsilon_v$) and the volume of drainage ($dV_o$) were measured through differential pressure transducers attached to pedestal and double tube burette respectively.

2.3 Specimen preparation for triaxial test

According to the Unified Soil Classification System, ASTM (2000) and American Association of State Highway and Transportation Officials, AASHTO (1986) classification systems, soil particle with a less than 75 $\mu m$ particle size was referred to as fines.

A special mold as shown in Figure 3 for the specimen preparation was newly manufactured; it is 70mm in diameter and 170mm in height. Inside the mold, an ASTM 200 (D=0.075mm) metal wire mesh was attached for removing the fines. By using this mold, cylindrical specimens were produced by
following the air-pluviation method (Figure 4). Initial dry density ($\rho_0$) was adjusted by changing the falling height to keep the dry density after consolidation ($\rho_{dc}$) similar to previous research (Ishikawa et al. 2010) which is about 0.53 g/cm$^3$. Fluctuation within ± 5% would be accepted. According to JGS 0520, to make experiment more accurate, the ratio between maximum particle diameter and specimen diameter should be less than 5. Soil particles bigger than 9.5mm in original soil, therefore, were removed previously.

As shown in Figure 5, the mold filled with test material was, then, put into an acrylic tank. A constant water flow induced by 1m hydraulic head was applied to remove the fine content. To shorten the preparing time and to simulate the mechanism of fine particle run off happened in real ground under extreme weather condition, 1 m hydraulic head was chosen. Such hydraulic head would cause a seepage velocity of about $2 \times 10^{-5}$ m/s at middle of the specimen. However the total amount of flushing water was not measured. It seems further investigation should be made. Several pre-tests have proved that as shown in grain size distribution curves on Figure 1, 24 hours water flushing would cause the fine content decreasing substantially to an almost constant value of about 0.5%. Afterwards, the mold was taken out of the tank. The soil specimen was dewatered by gravity at a room temperature of about 20°C for 24 hours for lowering degree of saturation to avoid strength loss caused by followed dry ice freezing process (JGS0520 2000).

Since volcanic coarse-grained soil is a kind of cohesionless material which means it can barely keep its cylindrical shape by itself, dry ice was used to freeze the soil specimen.

### 2.4 Monotonic triaxial test

Figure 6 indicates the flow for the monotonic triaxial test. Both tests under saturated condition and unsaturated condition were performed. For saturated condition, a double vacuuming method (Ampadu & Tatsuoka 1993) was used to saturate soil specimen. For unsaturated condition, by decreasing pore water pressure ($u_w$) to a preset value while keeping the pore air pressure ($u_a$) constant, matric suction ($s$) was applied until the drainage speed is less than 0.01ml/min. Here, matric suction is defined as $s = u_a - u_w$. All monotonic triaxial tests were conducted based on the standards of JGS 0524 (2000a) and JGS 0527 (2000b).
2.5 Soil-water characteristic test

The soil-water characteristic test was performed according to the test method for water retentivity of soils of the Japanese Geotechnical Society (2009).

After set soil specimen into pressure cell, quasi-saturated condition (had a degree of saturation of approximately 88.5%) was reached by adding de-aired water from the bottom of soil specimen. Afterwards, soil specimen was isotropically consolidated under a net normal stress \( \sigma_{\text{net}} \) of 49 kPa which was achieved by applying cell pressure \( \sigma_c \) of 249 kPa and both pore air pressure \( u_a \) and pore water pressure \( u_w \) of 200 kPa in fully drained condition till there were no changes in axial displacement or drainage volume. Then matric suction was applied to soil specimen. Drainage would happen after applying matric suction until equilibrium was achieved (drainage speed \( \leq 0.01 \text{ml/min} \)). The drainage volume was measured through a double tube burette and recorded automatically by computer. The soil-water characteristic curve, SWCC, could be drawn by repeating above procedures. Note that only drying process was conducted.

3 RESULTS AND DISCUSSIONS

3.1 Effect of fines run off on SWCC

Figure 7 shows the matric suction against degree of saturation obtained from triaxial compression tests under various matric suctions for both original specimens and fines removed specimens. This relationship could be seen as part of soil-water characteristic curves, SWCCs, during the drying process with a net normal stress of 49 kPa, although it is not the result from SWCC test.

Data gained from SWCC test for the fines removed specimen was also showed in Figure 7. Based on data from SWCC, it is reasonable to say that the data from triaxial tests is consistent with SWCC test. Therefore, analyses could be made based the data from triaxial tests.

In low matric suction range, degree of saturation decreases fast with increasing matric suction. As matric suction gets close to a value of 60 kPa, degree of saturation becomes, however, hard to change. It gets closer and closer to a certain value, which is called residual degree of saturation, \( S_{r0} \). The value of \( S_{r0} \) is about 24% for original specimens and is about 33% for fines removed specimens. Each residual degree of saturation was derived as shown in Figure 7. Blue and red lines are the fitted curves for experiment plots indicated by van Genuchten model (van Genuchten 1980). These curves gradually approach to residual degree of saturation in \( s \)-direction. It seems there was a rightward shift in soil-water characteristic curve after fines have been removed. The reason for the right shift is considered as follows. Since the coarse-grained particles are very porous, there are many opening intra-particle voids on the surface of constituent particles (Nakata & Miura 2007). Without fines clogging the voids in where water tends to be stored, hence the water retentivity of soil has increased. This shift causes a relatively large residual degree of saturation and consequently a different parameter \( \chi \). There are many methods suggested by researchers around the world to evaluate the magnitude of parameter \( \chi \). In this study, model shown in Equation 1 (Karube et al. 1996) was used for evaluating the magnitude of parameter \( \chi \).

\[
\chi = \frac{S_s - S_{r0}}{100 - S_{r0}}
\]

where \( S_{r0} \) is residual degree of saturation.

Table 2 shows calculated magnitudes of \( \chi \) at different matric suctions for both original specimens and fines removed specimens.

![Figure 7. Matric suction, \( s \) versus degree of saturation, \( S_s \).](image)

Table 2. Magnitudes of \( \chi \) under different conditions.

| \( s \) (kPa) | Fines removed | Original |
|-------------|---------------|----------|
| \( S_s \) (%) | \( \chi \)     | \( S_s \) (%) | \( \chi \) |
| 5           | 48.6          | 0.233    | 47.9      | 0.314   |
| 15          | 43.0          | 0.149    | 39.9      | 0.209   |
| 35          | 38.9          | 0.088    | 31.1      | 0.093   |
| 60          | 35.5          | 0.037    | 27.2      | 0.043   |

From Table 2, it is clear that the magnitude of \( \chi \) would decrease when fines were removed. According to Bishop’s theory:

\[
\sigma' = (\sigma - u_a) + \chi(u_a - u_w)
\]

where \( \sigma' \) is effective stress; \( \chi \) is a parameter related to the degree of saturation and ranging from 0 to 1; \( \chi(u_a - u_w) \) is suction stress, \( p_s \).

Using Equation 2, the shear strength equation is written as follows:

\[
\tau = c' + (\sigma - u_a)\tan \phi + \chi(u_a - u_w)\tan \phi
\]

where, \( c' \) is the effective cohesion, \( \phi \) is the effective internal friction angle.

Obviously, a smaller \( \chi \) value generates a smaller suction stress, \( p_s \), as shown in Figure 8. Suction stress is
the reason for strengthening in the shear strength under unsaturated condition. Since suction stresses in the fines removed specimens are smaller than ones in the original specimens at the same matric suction, the shear strength of fines removed specimens should get decrease. This phenomenon gives a viewpoint to explain the degradation in shear behavior after fine particles were removed.

It is not all clear, however, why such rightward shift in SWCC would generate when fines were removed. It looks like further research should be performed.

Figure 8. Suction stress, $p_s$, versus matric suction, $s$.

3.2 Shear behavior change due to fines run off

Figure 9 shows the relationship between axial deviator stress ($q$), volumetric strain ($\varepsilon_v$), and axial strain ($\varepsilon_a$) during CD test under various unsaturated conditions (different matric suctions) and various net normal stresses (effective normal stresses). The CD tests data of Kashiwabara volcanic soil (original specimens) which had been obtained from previous research (Ishikawa et al. 2010) also showed up in these figures as a comparison to the current research to explain the effect of fine particles run off.

From Figure 9, it is observed that at low net normal stress of 49kPa, volumetric strain increases with increasing axial strain at first. When axial strain reaches about 15%, the increment in volumetric strain tends to stop and starts turning to drop as axial strain increases continuously. At high net normal stress of 98kPa, the volumetric strain increases continually till axial strain reaches 25%. It is worth to notice that the volumetric changes in two types of soil samples (with and without fines content) tend to be the same even there was a huge difference in shear strength.

From the same figures, it can also be observed that there is a big change in the shear strength between soil specimens with and without fine content. It seems that soil will undergo degradation in shear strength regardless of matric suction when the fines are removed. Figure 10 shows the peak strength of soil specimens at two net normal stresses (49 kPa and 98 kPa) and under different unsaturated conditions against matric suction. For each matric suction, comparing to the original specimens, the shear strength of fines removed specimens has decreased sharply. Since there was almost no distinct change in the density after consolidation between testing specimens, it could say that the effect of fine particles run off on the density after consolidation could be neglected. Besides, while looking at each branch of these two data sets in Figure 10, it could also be found that the shear strength increases with increasing matric suction in low suction range. Conversely, once matric suction exceeds a specific value the shear strength will get dropped.

By using the Mohr-Coulomb failure criterion and the effective stress concept which was expressed as equation 4, effective cohesion, $c'$ and effective angle of friction, $\phi'$ were compared (Figure 8).

Figure 9. Shear behavior of Kashiwabara volcanic soil.

Figure 10. Peak strength versus matric suction, $s$. 

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internal friction, $\phi'$ could be calculated.

$$\tau = c' + (\sigma - u_w)\tan\phi'$$  \hspace{0.5cm} (4)

where, $c'$ is the effective cohesion, $\phi'$ is the effective internal friction angle.

As shown in Figure 11, $\phi'$ is 39.5° for original specimens and 38.9° for fines removed specimens. It seems that the value of $\phi'$ does not change much. The effective cohesion, however, changes from 22.9 kPa for original specimens to 7.7 kPa for fines removed specimens. It looks like the Mohr-Coulomb failure envelope shifts in a parallel manner from a high position to a low location. Such reductions in $\phi'$ and $c'$ could be considered as reasons for strength degradation in fines removed soil samples.

Assuming that the internal friction angle under unsaturated condition, $\phi$, is equal to the effective internal friction angle, $\phi'$, total cohesion, $c$, could be calculated by using results from CD test under net normal stress of 49 kPa. Figure 12 shows the calculation results. For both types of soil specimens, total cohesion increases as matric suction increases at the first. However, in high suction range, with matric suction increasing, the increment in total cohesion turns to stop and gets drop. In any case, the total cohesion of fines removed specimens is smaller than the total cohesion of original specimens. As discussed in previous section, this decrement in total cohesion could be considered caused by decrement in suction stress, $p_s$.

4 CONCLUSIONS

From current research, findings which were summarized as following could be obtained.

1. The fine content plays an important role in affecting shear behavior of volcanic coarse-grained soil.
2. Degradation in shear strength generate when fine particles were carried out of soil structure.
3. Fine particles run off gives effects to soil-water characteristic curve which in turn affects shear strength of volcanic coarse-grained soil.

The research findings indicate that fine content has a strong influence on the shear characteristic of a crushable volcanic coarse-grained soil in both saturated and unsaturated conditions even the content of fines does not take much large proportion.

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