Soft rock slope weathering due to rainwater

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ABSTRACT

Among various types of chemical weathering, rainwater plays a vital role in degradation of soft rock slopes affecting its geotechnical properties. As conducting laboratory tests every year to determine shear strength of widespread mountainous slopes is critical and expensive, a necessity of an empirical relationship is realized. This paper presents a laboratory developed relationship between shear strength and shear wave velocity for the weathering of soft rocks. Acidic nature of rainwater is simulated by laboratory reproduced weathering process on artificial soft rocks made by silica sand, gypsum and CaCO\textsubscript{3}. A negative ageing effect on the geo-material by deterioration of binding minerals is elucidated from decreasing trends of shear strength and shear wave velocity. It is revealed that the more is the acid contents in rainwater, the more is the decomposition of soft rocks. Moreover, field tests were conducted to acknowledge a general profile of the weathered rock slope.

Keywords: soft rock, chemical weathering, rainwater, pH, shear strength, shear wave velocity.

1 INTRODUCTION

Both mechanical and chemical weathering are responsible for an intact rock to weaken and come to a residual state. However, chemical weathering is more vulnerable when the rock contains some micro cracks by mechanical weathering. The micro cracks within the rock allow rainwater to penetrate deep inside enhancing deterioration of rock minerals. For example, Micro-sheets on granitic mountain at Hiroshima, Japan, are loosened and disintegrated by widening or neo-formation of micro cracks probably in combination with stress release, temperature change, and changes in water content. The loosened zones thicken with time and finally slide due to heavy rainfall when it is immediately saturated (M. Chigira, 2000).

Hot, humid and wet environment is the best for chemical weathering. For example, the summer monsoon season in Nepal covers about 75\% of annual precipitation from June to September. It rains almost every day resulting in a hot and wet weather which is a favorable condition for chemical weathering. According to A. D. Regmi et al. (2012), geological structure, rock weathering and formation of clay minerals are major causes for triggering many landslides in Nepal.

A number of researchers have already studied on mechanical weathering and developed an empirical relationship between shear strength and shear wave velocity (K. Gyawali et al., 2014). M. Aziz et al. (2010) compared deterioration of granular soil under saturated and dry conditions. J. Chen et al. (2000) studied lichens induced chemical weathering of rocks due to the excretion of various organic acids from lichens. L. Pitzurra et al. (2003) has reported carbonate rock weathering caused by microbial growth and air pollution. The geotechnical researches on rainwater induced rock weathering are still lacking which could include various acid reactions with rock minerals.

The effects of rainwater on soft rock slope with the consideration of shear strength and shear wave velocity after decomposition are the major interests of this study simulating chemical weathering such as Hydrolysis, carbonation and acid rain precipitation.

2 METHODOLOGY

2.1 Materials

Gypsum, CaCO\textsubscript{3} and silica sand no. 7 were chosen for the sample preparation. The materials proportion is presented in Table 1.

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Table 1. Materials composition.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Gypsum</th>
<th>CaCO₃</th>
<th>Silica sand no 7</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent</td>
<td>6%</td>
<td>8%</td>
<td>71%</td>
<td>15%</td>
</tr>
</tbody>
</table>

Gypsum and CaCO₃ both work as binding minerals. However, it is observed that when gypsum amount is increased, the sample becomes strong and when CaCO₃ is increased, the sample becomes weak. Both binding minerals were used to make moderate strength sample. The above proportion was obtained by hit and trial methods. Gypsum is moderately water-soluble (~2.0–2.5 g/l at 25°C). CaCO₃ is soluble in dilute acid.

2.2 Sample preparation

The dimension of the sample was 18cm height and 10cm diameter. At first, the dry materials gypsum and CaCO₃ were mixed together by a metal spoon. Then silica sand no. 7 was added and mixed together until the uniform distribution of materials was reached as shown in Fig. 1. Hand mixing was also done if non-homogenous mixture was observed. After that the calculated amount of water was added and mixed quickly only by a metal spoon. The adding water and wet compaction should be performed within 25 minutes to avoid drying in the last layer. The sample was prepared in 5 layers following the modified under compaction method (R. S. Ladd, 1978) with increasing no. of blows from top to bottom. The mould used for sample preparation is shown in Fig. 2.

2.3 Weathering Process

A laboratory weathering process was conducted in 20 liters plastic bucket filling about 15 liters pure distilled water as shown in Fig. 3. A metal stand like in Fig. 3 was used for supporting the weathered sample and easy transferring the sample from the water bucket to machine. Three types of weathering conditions were considered which is given in Table 2.

Distilled water was used for all three cases. For pH-5 and pH-4 cases, HCL acid (concentration, 35%) was added everyday once to come to initial pH-value 5 and 4 respectively. After adding acid, the acid water solution was stirred properly with a wooden stick avoiding the movement of the sediments settled at the bottom of the bucket. The pH-value was recorded each time with a pH-meter. Next day, the pH-value was found to around pH-7 (neutral) indicating that there has been a chemical reaction with calcite minerals.

Table 2. Test conditions.

<table>
<thead>
<tr>
<th>Cases</th>
<th>Name</th>
<th>Simulation</th>
<th>Chemical process</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Water only</td>
<td>Pure water</td>
<td>hydrolysis</td>
</tr>
<tr>
<td>2</td>
<td>pH-5</td>
<td>Clear rain water</td>
<td>Carbonation</td>
</tr>
<tr>
<td>3</td>
<td>pH-4</td>
<td>Acid rain</td>
<td>Carbonation</td>
</tr>
</tbody>
</table>

2.4 Test procedure

Unconfined compression tests were performed to measure axial stress on the samples from fresh to weathered as in Fig. 4. The top cap is very flexible allowing a self-adjusting with the top surface the sample and the pedestal is not fixed to machine. A strain control loading was applied at the rate of 0.1mm/min.

External vertical displacement was measured by EDT (External Displacement Transducer) whereas initial young’s modulus was measured by two LDTs (Local deformation transducers) because the axial strain of the specimen obtained by EDT includes the effects of bedding error. The LDTs can measure the strains less than 0.0005% without any second stage amplification. Two 12cm LDTs were attached at two sides of the sample. A small portion was cut to prepare a spot for hinge attachment as shown in Fig. 5. A gypsum paste was applied and leveled to make a smooth surface. After having dried gypsum spots, four pseudo hinges were attached to those spots with the help of super setting glue Fig. 6 (S. Goto et al., 1991; K. Hayano et al., 2001).
3 LABORATORY TEST RESULTS AND DISCUSSIONS

3.1 Stress vs. strain

The axial stress vs. axial strain diagram for pH-4 case (Fig. 7) depicts that there is a significant decrease from fresh to 2-days of weathering and then gradual decrease is noticed up to 10 days of weathering. It might be because of combined effects of chemical weathering and deduction of suction for the initial days of weathering. But in this research, the suction parameter is not taken into consideration; instead dissolution of binding materials is adopted. This process is easily demonstrated by the change in surface roughness with accompanying decrease in diameter of weathered samples (Fig. 8).

In addition, the stress vs. strain curves is important to determine peak unconfined compression stress that the sample can withstand. The peak unconfined compression stresses from fresh to 10-days of weathering for all three cases are presented in Fig. 9.

Fig. 7 Stress strain curve for pH-4 series.

Considering the equation of motion (1) of rock mass, the difference between peak axial stress and residual stress determines the acceleration of rock fall. Keeping Equation (1) in mind, for the fresh sample, this difference is larger than the other weathered samples. Hence, the fresh sample might possess a high chance to fast rolling down if the shear failure is occurred in real scenario.

Equation of motion:
Mass of rock * acceleration = external force – remaining residual strength. (1)

Shear strength (τu) = \( \frac{q_u}{2} \) (equation, 2).

where, \( q_u \) = Unconfined compression strength

Shear strength vs. number of weathering days relationship is just similar to Fig. 9 which shows a reducing trend of shear strength for all three series.

A noticeable deduction of axial peak stress from fresh to two days weathered samples is illustrated for all three cases. However, for water only and pH-5 series, after 6-days of weathering, peak stresses of samples tend to be stabilized whereas pH-4 series is still tending to weather. The weathering trend for water only and pH-5 looks similar having not much difference in stresses. Up to four days, there has been found no distinguishable difference in weathering trends for all three cases. It might be because gypsum has low rate of solubility (~2.0–2.5 g/l at 25°C) which would happen in first four days. After four days, reduction in strength might be only due to reaction of CaCO3 with acid. Hence, pH-5 solution not being so strong, tended to be stabilized. Particularly, at 10 days of weathering, the difference of axial peak stresses (qu) from water only to pH-4 cases indicates the real chemical effects.

3.2 Shear strength vs. number of weathering days

Shear strength is determined by taking the half of peak axial stresses (qu) (equation, 2).

Shear strength (τu) = \( \frac{q_u}{2} \) (2)

where, \( q_u \) = Unconfined compression strength

Fig. 8 Weathering samples from fresh to 10-days of pH-4 series.
3.3 Shear wave velocity vs. number of weathering days

Shear wave velocity of the sample is calculated statically by using equations (3), (4), (5) and (6). For determination of initial Young’s modulus, axial stress vs. LDT strain curves are considered in the range of ~0.001%. Axial stress and strain curves for EDT and LDT are shown in Fig. 10.

Shear wave Velocity (Vs) = $\sqrt{\frac{G_{\text{max}}}{\rho}}$, m/s \( (3) \)

Maximum Shear Modulus ($G_{\text{max}}$) = $\frac{E_0}{2(1+\nu)}$ \( (4) \)

Initial Young’s Modulus ($E_0$) = $\frac{\text{Stress}}{\text{True LDT Strain}}$ \( (5) \)

where, $E_0$=Initial Young’s modulus at small strain
$\nu$ = Poisson’s ratio
$\rho$=Dry mass density of tested sample

True LDT strain = -$\log_{10} \left( \frac{L-\Delta d}{L} \right) \times 100\%$ \( (6) \)

Considering Fig. 11, shear wave velocities are decreasing with increasing days of water submersion for all cases studied. After 6-days, shear wave velocities of pH-4 series seem to decrease more distinctly than the other two series. At 10 days of weathering, shear wave velocities of all three cases are in the range of 150 to 300 m/sec. In laboratory, it was felt difficult to control water content of all weathered samples in the case of unconfined compression tests. The measurement of shear wave velocities is affected by water content of weathered samples. The weathered circumferential surface of the sample was not found to be uniform, hence, the average of varied initial Young’s Modulus measured by two LDT strains was determined.

3.3 Shear strength vs. shear wave velocity

A relationship between Shear strength and shear wave velocity for all three series is portrayed as in Fig. 12. Negative aging effects of weathering on soft rocks induced by water have been easily recognized from this relationship. The water only and pH-5 curves are stuck earlier whereas pH-4 curve is tended to weather more. It can be concluded that with more acidic water solution, larger weathering is perceived. ‘pH-value 4’ is 10 times more acidic than pH-5.

K. Gyawali et al. (2013) has showed the logarithmic relationship between shear strength and shear wave velocity for wide range of samples from naturals to cement treated artificial rock samples under the mechanical weathering process. According to K. Gyawali et al. (2013), both shear strength and shear wave velocity are decreasing following constant linear slopes of weathering for different composition of rock samples studied. Fig. 12 also somehow resembles with
the result of K. Gyawali et al. (2013). However, second degree polynomial trend line is fitted for water only series and two different sloped lines are adjusted for pH-4 and pH-5 series (Fig. 12) which shows a sudden drop from fresh to two days of weathering and then slow rate of weathering after two days for all three trends. In this research, authors have started weathering with low strength fresh rock sample of about 80KPa to study rainwater induced weathering without mechanical weathering concerning only one summer monsoon season. However, particularly considering pH-4 case, the fresh sample has lost about 80% of its shear strength after 10 days of weathering and about 50% after two days of weathering. Similarly, in the cases of water only and pH-5, the shear strength lost is about 62% from fresh to 10 days of weathering.

4 FIELD TEST RESULTS

Mechanical properties such as shear strength and shear wave velocity and extent of weathered material are essential parameters for the risk assessment of the weathered slope and to ensure reasonable design of retaining structures. To investigate the geotechnical properties of a real weathered slope, seismic refraction test and Portable Dynamic Cone Penetration (PDCP) test were conducted at Ohya landslides area, Shizuoka, Japan on 2014/06/19, (M. Aziz et al., 2009). The location of study area is shown in Fig. 13.

4.1 Seismic refraction test (SRT)

The analysis of seismic refraction test is shown in Fig. 14 which reveals that the shear wave velocity in the surface weathered layer is in the range of 180m/sec and that of underlying layer is about 400m/sec. The general soil profile to the length of extent of geophones used is obtained by intercept time method (D. Palmer, 1986) which is depicted in Fig. 14. The thickness of weathered layer is found to be of shallow extent ranging from 0.25m to 0.7m. There might be a chance of shallow landslides with another rainfall.

Seismic refraction test was accompanied with Portable dynamic Cone Penetration (PDCP) test. The PDCP field data, $N_d$, is presented in Fig. 15 ($N_d$=No. of drops of 5kg hammer from 50cm height of fall for 10cm penetration of standard 600 cone). For the calculation of equivalent SPT-N, equivalent unconfined compression stress, $q_u$, and equivalent shear wave velocity, $V_s$; the empirical correlations (JGS-1433, 1995) are used. From the PDCP test (Fig. 15), the thickness of weathered layer has been found to be 0.8m which is comparable to the thickness calculated from seismic refraction test analysis.
4.3 Comparison between field and laboratory tests

Although, materials used for laboratory tests and field residual soils are different, a general comparison in mechanical properties and deterioration response can be analyzed. From the seismic refraction tests, the shear wave velocities for the weathered layer and bedrock were found to be 180m/sec and 400m/sec respectively. If the laboratory test results are considered, the weathered layer in field is comparable to ten days’ weathered samples and the bedrock resembles with laboratory prepared fresh sample which is not much strong. Therefore, it is obvious that surface residual layer of Ohya slope studied is highly weathered and the bedrock is also in the process of weathering.

5 CONCLUSIONS

A laboratory developed relationship between shear strength and shear wave velocity is anticipated to be helpful for predicting stability of a weathered slope and deciding the necessity of retaining structure to prevent future landslides. Such type of relationship is expected to be useful for field the monitoring purpose of rock slopes that are undergoing weathering process. On the basis of laboratory and field tests following conclusions are drawn.

- Unconfined compression stress, Shear Strength and shear wave velocity are reducing with increase in a number of days of weathering in all three cases studied. There is a significant decrease in shear strength from fresh to 2-days of weathering.
- The more acidic rainwater is, the more the weathering of soft rock is. Weathering trends are similar for water only and pH-5 cases which mean that naturally occurred clear rainwater of pH-value, 5, is not much harmful.
- No significant difference in shear strength deduction is found for all three cases within 4 days of weathering.
- Weathering features and shear wave velocity measured by seismic refraction test and PDCP are helpful to know the stability of slope correlating with the empirical relationship developed by lab tests.
- Authors used very low percentages of Gypsum and CaCO₃ to make the sample of relatively low strength. Further studies will be required to investigate whether weathering trend varies with amount of binding materials the rock sample contains and of higher strength or not.
- Finding weathering trend in the case of natural rocks which are susceptible to degradation would be very interesting to view in future researches.

REFERENCES