# Influence of Weathering on Physical and Mechanical Properties of Mudstone

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## Abstract

Majority of the landslides in Niigata prefecture, Japan are occurred at Neogene sedimentary soft rocks. Weathering of such rocks is an important geological, environmental and engineering process. In order to study the chemical and physical weathering and their impact on the shear strength of the soil mass, soil samples were collected from ground surface to 15 m depth at two different drainage wells in the Mukohidehara landslide area. We carried out several laboratory tests like Atterberg's limits, particle size analysis, X-ray diffraction analysis, slake durability test, X-ray fluorescence analysis. We also conducted drained simple shear test, and drained ring shear tests on the soil samples to measure the strength characteristics.

Test results showed that fully softened shear strength of the less weathered rock sample was very close to the peak shear strength of the disintegrated sliding surface sample. Because of insignificant difference in mineralogical composition, residual shear strengths of the soil and rock samples from different depths were very close. The research results suggested that physical weathering in terms of slaking plays major role in the reduction of shear strength of mudstone. They also suggested that chemical weathering was not significant compared to the physical weathering at the shallow depths in the mudstone formations.

**Keywords:** mudstone, weathering, slaking, shear strength

## Introduction

Niigata prefecture is well-known in Japan for a large number of landslide occurrences. Majority of the landslides in Niigata are occurred at Neogene sedimentary soft rocks, especially at mudstone strata. Weathering of such soft rocks is important geological, environmental, and engineering processes (Okamoto et al., 1981). Weathering processes of physical break down and chemical alteration lead to weaken the shear strength of rocks and form thick sequences of weathered materials whose physical and geotechnical properties have been highly altered. Such alteration processes cause the decrease in particle size, the change of mineral composition and the decrease of inter particle bonding strength (Lerouil, 2001). These processes eventually result into a gradual decrease in stability of the slope, which ultimately causes the landslide activation accompanied by a slow rate displacement.

It is necessary to evaluate durabilities of such rocks against weathering, their effects on physical and mechanical properties, and ultimately the stability of the natural and cut slopes.

Physical weathering processes including the slaking are studied by many researchers (Nakano, 1967; Franklin and Chandra, 1972, Matsukura and Yatsu, 1982). Nakano (1967) conducted a research on breaking of tertiary mudstone with slaking and observed the changes in soil properties. However, he did not mention the effect of slaking in shear strength.

Due to geological and environmental activities, mudstones of landslide areas are subjected to gradual weathering processes that lead to weaken the shear strength of the rocks. It is necessary for the long-term evaluation of the slopes to know how the stabilities of the mudstone slopes are changed in accordance with weathering processes. The main objective of this research is to study the effect of weathering on the physical and mechanical properties of soils and rocks from landslide areas

pp. 467–479 

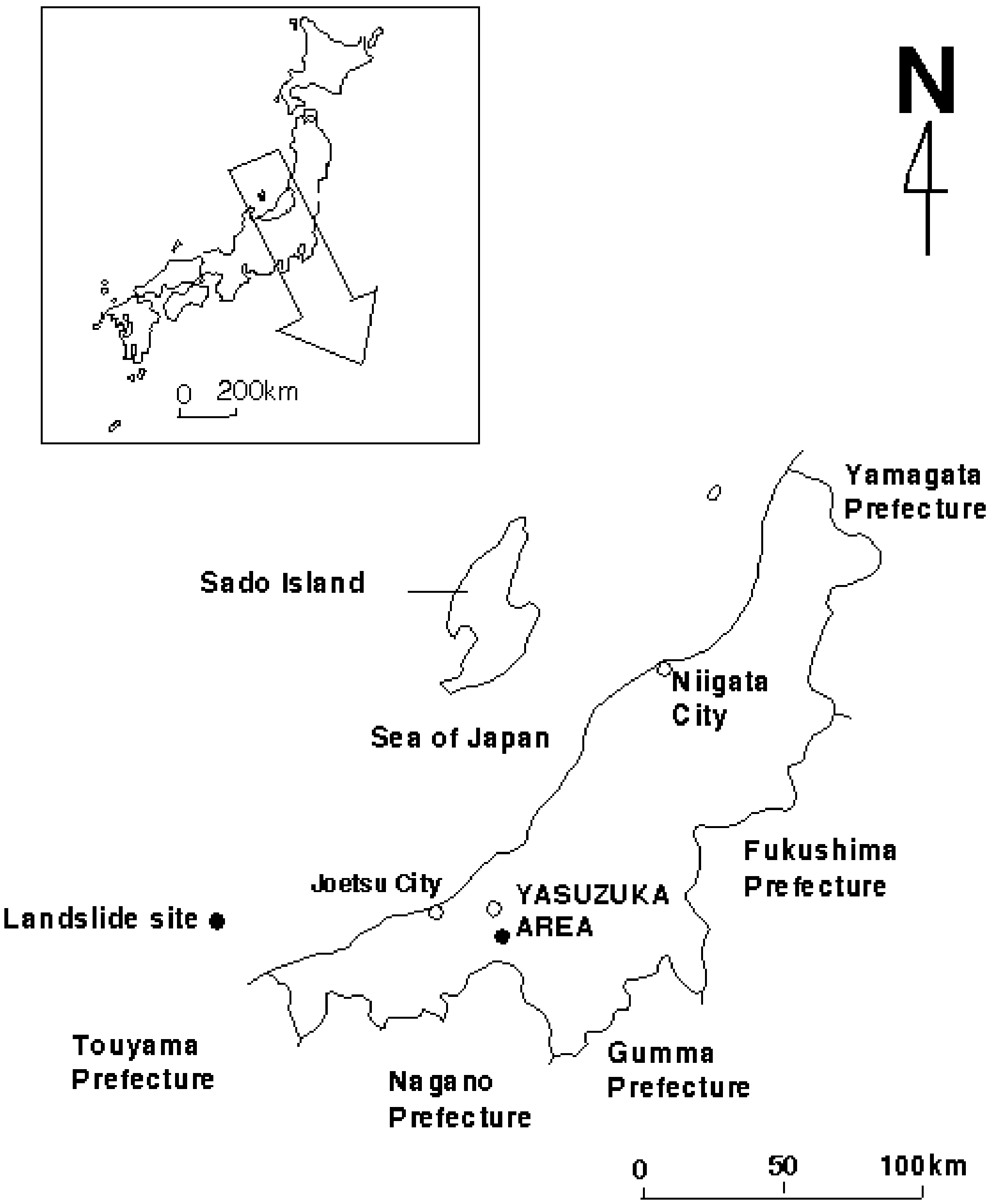


**Fig. 1.** Location of the study area

## Overview of the study area

The study area covers the Yasuzuka area of the east part of Joetsu City in Niigata Prefecture, Japan (Fig.1). This area consists of gentle hills, where the middle Miocene to Quaternary mudstones and sandstones are widely distributed. The mudstones and sandstones in study area are comparatively fragile. The fragility is due to the deformation by parallel folds extending the NE-SW direction at the interval of 2–5 km and forming the basin and range structure. The rock masses near the fault lines are highly fractured and also many tension cracks are distributed around anticlinal axes. Fractures and cracks lead most of the rock masses to undergo weathering under the circulation of ground waters. Therefore, there are numerous landslides in the study area and most landslides occur on the weathered mudstones and soil deposits. For this study, samples were collected from the Mukohidehara landslide which lies on the Sugawa formation in the study area (Fig.2).

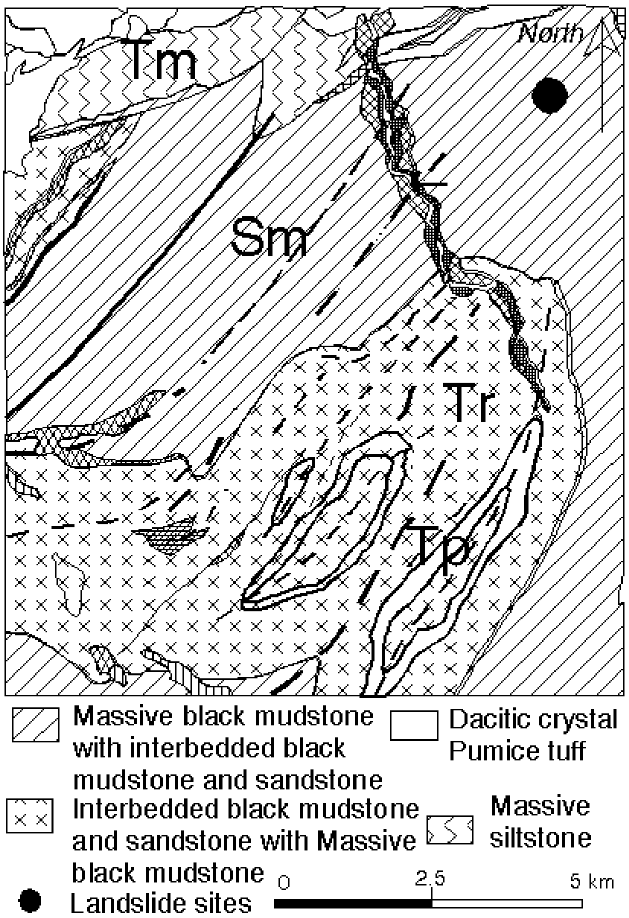


**Fig. 2.** Geology of the study area

## Samples and Experimental Methods

### *Sample Collection*

Construction of drainage wells in the Mukohidehara Landslide provided an opportunity to collect soil and rock samples from different depths in vertical profiles. Soil samples were obtained from about 0.5 m depth from the main scarp and the sliding surface in the landslide. Less weathered or unweathered intact rock samples were obtained from above and below the sliding surface. After bringing the samples to the laboratory at minimum possible disturbance, the intact rock block samples were trimmed, cut or reconstituted, as per several requirements of different tests.

### *Mineral Composition*

Mineral composition of samples was determined by X-ray diffraction (XRD) based on Moore and Reynolds (1997). XRD is particularly effective for identification of clay minerals, which are often of great geotechnical significance and are difficult to identify by any other means (Ward et al, 2005). Three types of samples were analyzed in each case, whole rock samples, normal air-dried sample for extracted clays, and ethylene glycol saturated samples for extracted clays. Three types of clay minerals, smectite, kaolinite and illite, were identified for the samples from the study area.

### *Grain Size Distribution*

In general, the increases of sand content in the mudstone soil lower water content and specific surface area, and heighten uniaxial compressive strength and permeability (Wetzel and Einsele, 1991). Samples were first hydrated with water for about 10 days and then dried and gently broken by mortar and pestle, before doing the hydrometer analysis as described in ASTM 422-98 (ASTM, 2000).

### *Slaking Tests:*

The slaking process can penetrate deep into the rocks under the presence of channels (Shakoor and Rodgers, 1992) and can rapidly change the physical properties of rocks by breaking the bond between the particles (Bell et al, 1997). The slake durability tests were carried out to determine the effects of alternate drying and wetting on the durability of soil and rock. Two types of tests, namely, dynamic slake durability tests (Franklin and Chandra, 1972) and alternate drying and wetting tests were carried out. The slake durability index ($S_d$) is expressed by the percentage ratio of final and initial dry weights of material.

### *Bulk Chemistry*

The major elemental oxides of the whole rock and soil samples were measured by XRF analyzer. In order to assess the role of chemical weathering, Chemical Index of Alteration (CIA) was calculated using the method by Nesbitt and Young (1982). The CIA is defined as the ratio of $Al_2O_3$ and ($Al_2O_3$+CaO+$Na_2O$+$K_2O$) in molecular proportions and is expressed in percentage. Higher value of CIA shows higher degree of chemical weathering.

### *Physical and Strength Properties of Soil*

Atterberg limits

The Atterbergs limits were determined on powdered samples using ASTM procedures D 4318-98 (ASTM, 2000) for liquid limit and plastic limit. Intact rock samples were first hydrated with water for 10 days and then dried and gently broken by mortar and pestle before measuring the Atterberg limits.

Simple Shear Test

Simple shear tests were carried out for intact (undisturbed), slaked and remolded samples. Intact samples were carefully trimmed off to a size of 100 mm diameter and 25 mm thickness. Then, the samples were subjected to slaking through alternate wetting and drying for four times at an interval of a day. The slaked samples, at the first and fourth cycle, were then used for shear strength measurement using the simple shear testing device. Likewise, remolded samples were prepared by mixing distilled water equal to Liquid limit to the disintegrated soil or rock samples and kept hydrated for 72 hours. Thus prepared samples were then consolidated under the normal stress of 300 kPa until 100% consolidation and then sheared at the normal stresses of 100, 150, 200, and 250 kPa.

Ring Shear Tests

Ring shear apparatus as described by Tiwari and Marui (2005) having outer ring of 200 mm diameter, inner ring of 130 mm diameter, and thickness of 35 mm was used for the residual shear strength measurement. Samples passing from 425mm size sieve were mixed with water content equal to the liquid limit and kept hydrated for 72 hrs to ensure 100% saturation. After feeding into the annular space in between the outer and inner rings, samples were consolidated at the normal stress of 250 kPa until 100% consolidation. Then, reducing load multi-stage ring shear tests (Tiwari and Marui, 2004) were performed at the normal stresses of 250 kPa, 200 kPa, 150 kPa, 100 kPa, 50 kPa, 25 kPa, 12.5 kPa and 6 kPa with a shearing speed of 0.1 mm/min. This shearing rate was calculated based on the consolidation data as per the ASTM Standard D 6467 99 (ASTM, 2000).

## Test Result and Analysis

### *Water content and density*

Fig.3 shows the depth-wise variation of water contents and bulk densities at both well 1 and well 2 of the Mukohidehara landslide. Although water content of the soil and rock at well 1 was slightly higher than that in well 2, samples in both wells exhibited a consistent trend of variation in water content and bulk density. Low water content at the surface soil and high water content at the sliding surface were expected, as the former was attributed to the partial saturated condition whereas the later was attributed to the existence of high amount of disintegrated and slaked particles. At the unsheared mass, water content exhibited a decline of 1.5%/m in depth. Bulk densities of the surface soil, the soils from sliding surface and from the depth of 4 m (ground water fluctuation level) at well 1 showed comparatively low values from 18 to 19kN/m$^3$. The minimum and maximum groundwater table at well 1 in 1995 and 1996 were −2.60m to −3.30m and −3.40m to −4.00m respectively and at well 2 in 1996 was −3.054m to −3.75m (Investigation report of the Mukohidehara Landslide 1997). At the unsheared and less weathered rock portion, bulk density was inclined with approximately 1kN/m$^3$/m in depth

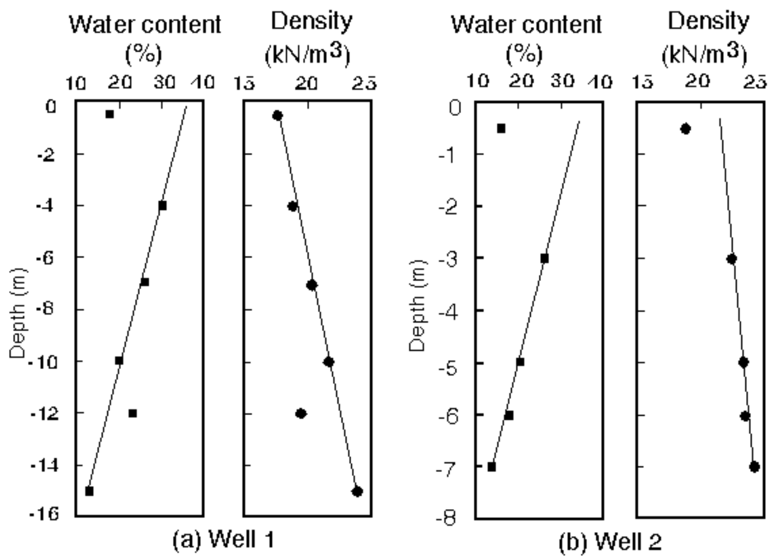


**Fig. 3.** Depth-wise variation of water contents and bulk densities at both wells

**Table 1.** Particle size distribution, USCS classification and second cycle slake durability value of specimen for both wells, $Sd_2$: Slake durability value after second slaking cycle

| Well 1 | | | | | | |
|---|---|---|---|---|---|---|
| Depth (m) | sand % | silt % | clay % | fine % | USCS | (Sd2%) |
| -0.5 | 11 | 51 | 38 | 89 | CH | 11 |
| -4 | 15 | 44 | 41 | 85 | CH | 33 |
| -7 | 17 | 49 | 34 | 83 | CH | 80 |
| -10 | 12 | 46 | 42 | 88 | CH | 50 |
| -12 | 4 | 52 | 44 | 96 | CH | 14 |
| -15 | 9 | 48 | 43 | 91 | CH | 65 |
| Well 2 | | | | | | |
| Depth (m) | sand % | silt % | clay % | fine % | USCS | (Sd2%) |
| -0.5 | 17 | 47 | 36 | 83 | CH | 16 |
| -3 | 17 | 45 | 38 | 83 | CH | 80 |
| -5 | 20 | 42 | 38 | 80 | CH | 84 |
| -6 | 26 | 39 | 35 | 74 | CH | 85 |
| -7 | 24 | 42 | 34 | 76 | CH | 86 |

until close to 24 kN/m$^3$. The bulk densities at both wells exhibited the similar depth-wise variation.

## *Grain size distribution*

The particle size distribution of different soils based on the sieve and hydrometer analysis and Unified Soil Classification System (USCS) is shown in Table 1. Proportions of sand and silt were not of much importance for this research compared to the proportions of clays. Therefore, here we describe variations in the proportion of clays in detail. Clay fractions in Well 1 were measured to be 34 to 44%. There was no consistent pattern of clay fraction variation. However, the depth-wise clay fractions were close in amount no matter where the samples were collected. The trend of clay fraction variation in the well 2 was similar to that in the well 1, although it showed approximately 4 to 5% less clay fraction than that in the well 1.

## *Mineralogical Analysis*

Proportions of various minerals of the soil and rock samples identified by x-ray diffraction patterns and calculated by the semi-quantitative method by using the area method proposed by Iwamitsu et al. (1995) as shown in Fig.4. As the main objective of this study is to observe the effect of various soil properties on the strength properties of the soil and rocks, variations in clay minerals were observed in detail. Fig.5 shows the depth-wise variation in predominant clay minerals such as smectite and kaolinite. In both wells, proportion

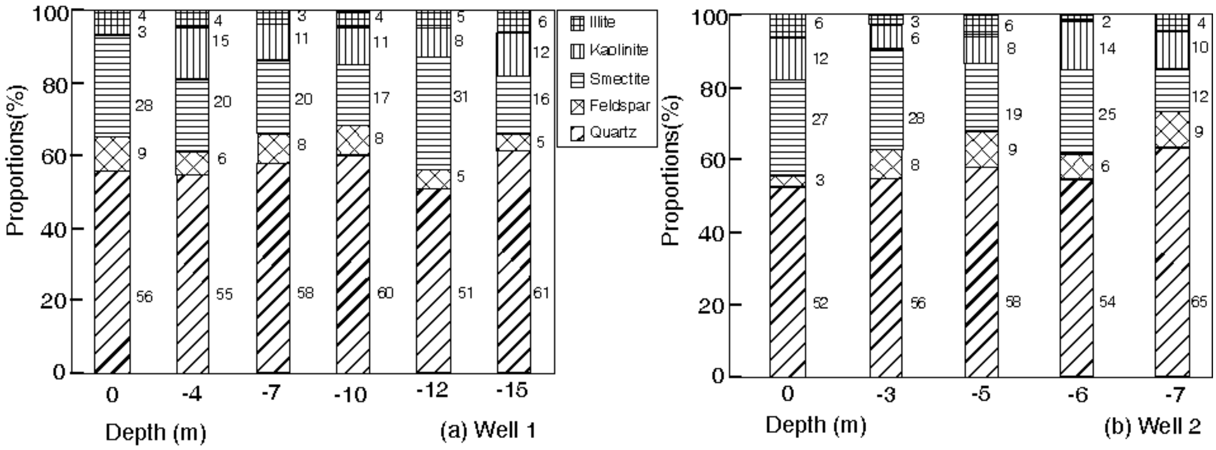


**Fig. 4.** Depth-wise variation of mineralogical composition at both wells

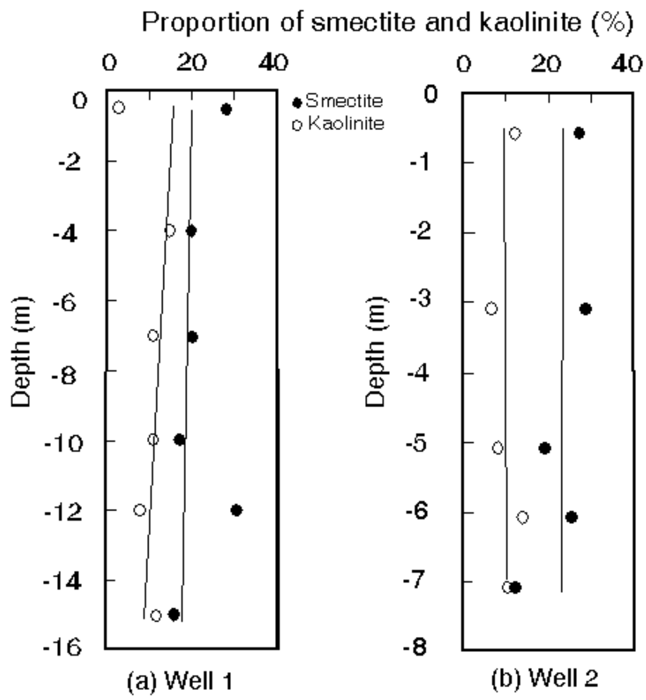


**Fig. 5.** Depth-wise variation of smectite and Kaolinite at both wells

of smectite was quite high at the surface and sliding surface (well 1) compared to the unsheared portion. Approximate proportions of smectite were measured to be 16 to 31% in well 1, and 12 to 28% in well 2. Proportion of kaolinite in the soil samples from well 1 and well 2 were 3 to 15% and 6 to 12% respectively. Results from the mineralogical study show that depth-wise variation in clay mineralogical composition was not significant in both wells.

## *Plasticity*

Fig.6 shows the depth-wise variations in liquid limit and plasticity index of the soil and rock samples at both wells. The test results show that the depth-wise consistency limits of the soil and rock samples were not significantly different in both wells. Fig.7 exhibits the depth-wise variation in activity. The activity shows the influence of mineral composition on physical properties of soil. The depth-wise activity values were not considerably varied in both wells, owing to the similarities in the proportions of clay fraction and plasticity

**Table 2.** Summary of major element compositions and CIA

| Well 1 Depth (m) | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | MnO | MgO | CaO | $Na_2O$ | $K_2O$ | $P_2O_5$ | CIA |
|---|---|---|---|---|---|---|---|---|---|---|---|
| -0.5 | 66.87 | 0.73 | 17.58 | 8.39 | 0.05 | 2.06 | 0.95 | 1.37 | 2.26 | 0.17 | 73.3 |
| -4 | 68.43 | 0.73 | 17.04 | 6.25 | 0.05 | 2.30 | 1.50 | 1.32 | 2.17 | 0.10 | 70.1 |
| -7 | 68.96 | 0.72 | 17.02 | 5.63 | 0.04 | 2.07 | 1.01 | 1.84 | 2.31 | 0.12 | 69.8 |
| -10 | 67.65 | 0.72 | 17.42 | 5.77 | 0.05 | 2.32 | 1.10 | 2.22 | 2.35 | 0.13 | 68.0 |
| -12 | 67.45 | 0.74 | 17.68 | 6.65 | 0.05 | 2.42 | 0.70 | 1.57 | 2.51 | 0.10 | 72.9 |
| -15 | 69.12 | 0.68 | 17.36 | 5.20 | 0.04 | 2.02 | 1.30 | 1.96 | 2.36 | 0.12 | 68.1 |
| **Well 2 Depth (m)** | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | MnO | MgO | CaO | $Na_2O$ | $K_2O$ | $P_2O_5$ | CIA |
| -0.5 | 65.85 | 0.79 | 18.59 | 8.43 | 0.10 | 2.03 | 0.34 | 0.88 | 2.25 | 0.16 | 75.8 |
| -3 | 66.87 | 0.66 | 17.58 | 8.39 | 0.09 | 2.08 | 0.93 | 1.39 | 2.24 | 0.15 | 70.5 |
| -5 | 69.53 | 0.58 | 17.42 | 4.69 | 0.04 | 2.16 | 1.53 | 1.81 | 2.35 | 0.09 | 67.7 |
| -6 | 66.53 | 0.72 | 17.62 | 6.83 | 0.06 | 1.98 | 1.50 | 1.79 | 2.21 | 0.15 | 68.5 |
| -7 | 69.55 | 0.61 | 17.55 | 5.64 | 0.07 | 1.92 | 1.50 | 1.51 | 2.36 | 0.10 | 69.3 |

index.

### *Chemical composition*

Major element oxides of subsurface locations in both wells are summarized in Table 2. The depth-wise variations in $Al_2O_3$ and Chemical Index of Alteration (CIA) are of particular interest, which reflect the extent of chemical weathering at present condition. The proportion of $Al_2O_3$ was high at the soil sample collected near the surface as opposed to the samples collected from the subsurface locations, although the soil sample from the sliding surface of well 1 also exhibited comparatively high $Al_2O_3$ proportion than the unsheared zone (Fig.8). In order to compare the extent of chemical weathering in samples from in each well, the values of $Al_2O_3$ and CIA in samples were normalized with the value of $Al_2O_3$ and CIA in the deepest sample respectively. CIA was higher at the shallower depth with an insignificant trend line (Fig.9). The value of CIA in the entire samples ranged from 68 to 76, which is close to the value exhibited by the median of completely weathered (100) and unweathered (50) rocks. The values of CIA in mudstone and shale vary from 70 to 75 (Nesbitt and Young, 1982). As the result, it is unlikely that the extent of chemical weathering in each well is significant parameter in this study.

### *Shear Strength*

Fig.10 shows the depth-wise variations in residual, fully softened, and peak friction angles at both wells. The depth-wise variation in residual, peak and fully softened cohesion in both wells are also presented in Fig.11. No general trend was observed in the depth-wise variations of residual friction angle of the sample in well 1. After 4 m depth (ground water fluctuation level), the residual friction angle was in increasing trend but reduced at sliding surface (at 12 m). The trend of depth-wise fully softened friction angle variation was similar to the trend for the variation of residual friction angle. There was a slight increase in fully softened friction angle with depth, although sliding surface soil exhibited comparatively lower fully softened friction angle which was close to the residual friction angle. Fully softened cohesion showed increasing trend with depth and was unlike trend of the residual state. In addition, fully softened cohesion at the sliding surface was very small.

Both wells exhibited the similar pattern in the depth-wise variation of peak shear strength. In general, drained peak friction angle showed a trend of increment with depth, except at the sliding surface, where soil samples exhibited considerably low friction angle. In comparison to the peak friction angle, peak cohesion showed higher rate of depth-wise increment. Fig.11 shows peak cohesion was abruptly increased right below the ground water fluctuation zone. Otherwise, the trend of depth-wise peak cohesion increment was consistent.

There was not so big difference between the values of peak, residual, and fully softened shear strength parameters for the sample from the sliding zone as well as the sample near the ground surface (Well 1).

## Discussion

The slake durability test results for all of the samples, at five different cycles of slaking as shown in Fig.12. As expected, in both wells, samples near the surface show higher degree of slaking with substantial decrease in amount of samples during subsequent cycles. Samples from sliding surface also exhibited very high slaking sensitivity. In case of the other samples from well 1, sensitivity to slaking at the second cycle was in

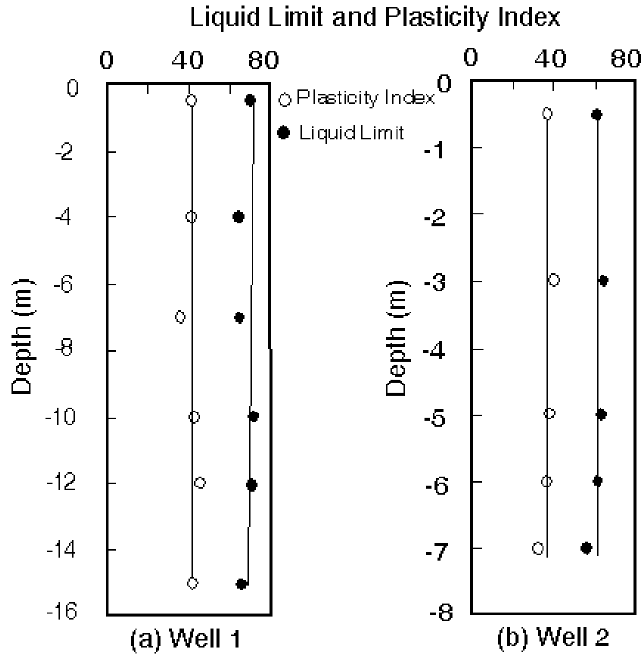


**Fig. 6.** Depth-wise variation of Liquid Limit and Plasticity Index at both wells

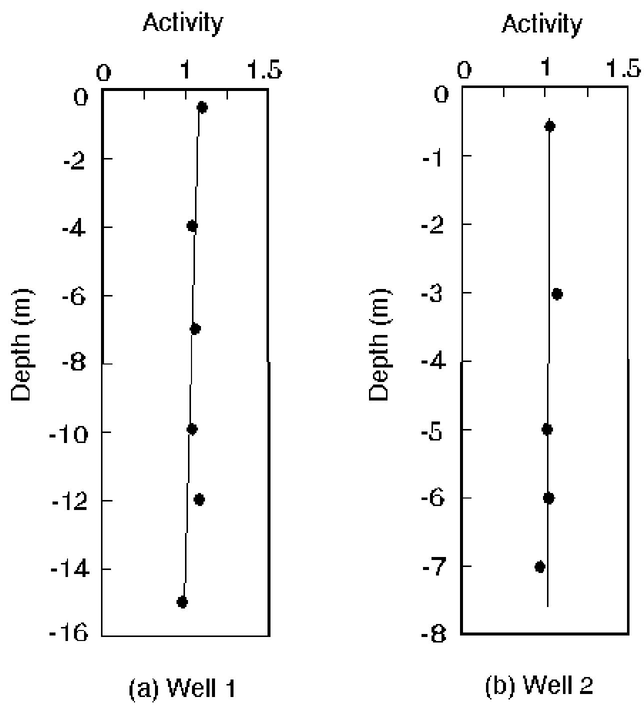


**Fig. 7.** Depth-wise variation of Activity at both wells

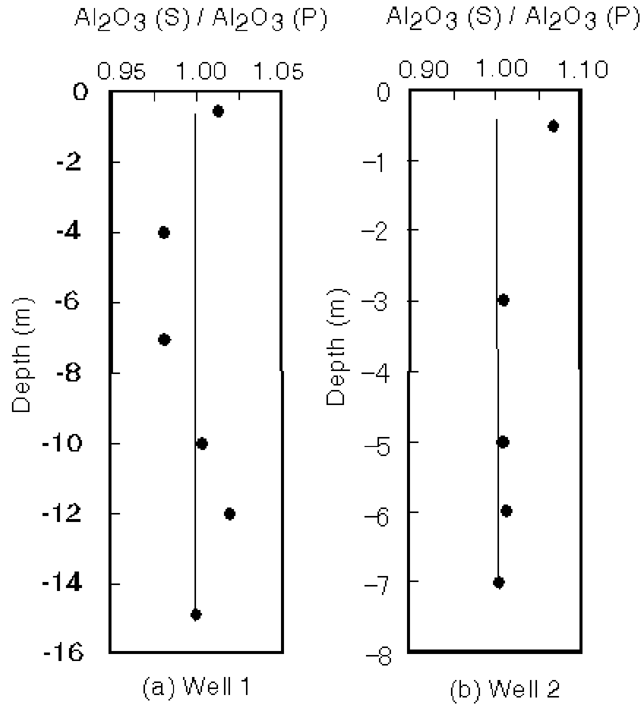


**Fig. 8.** Depth-wise variation of normalized aluminum oxide, S: Sample rock, P: Parent rock

decreasing trend with depth, although the sample from 7 m depth exhibited highest durability. There was nothing obvious in that sample to exhibit such characteristics. In general, the slake durability values of the samples from well 2 were higher than that in well 1. The weight loss values from the first to fifth cycle ($Sd_1$ to $Sd_5$) were in relatively narrow range in the well 2 (50 to 72%) compared to the well 1 (54 to 100%). That reflects higher strength of samples at well 2 against weathering. Slake durability characteristics of sample from 7 m depth in well 1 was similar to that in the sample below the ground water fluctuation zone in well 2. Test results showed that after a number of slaking, which depends on the degree of weathering at present condition, physical weathering occurs, which ultimately disintegrates the rock thus decreasing the density. This physical weathering with slaking reduces the shear strength of the rock sample significantly as shown in Fig.13. Significant reductions in shear strengths were observed from intact to the first slaking cycle and the $4^{th}$ slaking cycles. The shear strength of rock at the $4^{th}$ slaking cycle was very close to the fully softened shear strength of samples as well as the shear strength of sliding surface soil of the corresponding well. This shows that there is a significant decrease in peak shear strength with slaking, as a result of a decrease in density (Nakano, 1967) and increase in water content (Chandler, 1972, Morgenstern and Eigenbrod, 1974). As the soil samples at the ground water fluctuation zone were subjected to a number of alternate drying and wetting cycles, which is responsible for the considerable amount of slaking, peak shear strength of that depth became considerably low compared to the depth right below this zone. However, such slaking phenomenon does not alter fully softened and residual shear strength, as there is no variation in chemical and mineralogical composition of soil with slaking. The zone that lies at the ground water fluctuation depth is significantly weathered as opposed to any other zone in the soil mass below it, and thus has high potential to slope instability problems.

Although physical weathering was significant at the ground water fluctuation zone, there were no significant alterations in the chemical compositions at that zone relative to the adjacent depth or below it. Proximate values of CIA throughout the studied depth are an evidence of significantly less chemical weathering of the rock mass compared to the physical weathering. However, the value of CIA at the soil samples from the ground and sliding surface were notably high. This can be attributed the frequent contact of the disintegrated mudstone with ground and surface water of different chemical composition, which are potential to alter chemical composition of the soil. In the present case, such chemical reaction increased the amount of $Al_2O_3$ in the ground and sliding surface soil samples. This shows that physical disintegration is much more important than the chemical weathering. This idea is also supported by Taylor and Spears (1970), and Wetzel and Einsele (1991). Chemical weathering takes place after the physical weathering. Time taken for the completion of chemical weathering has wide range, depending upon several factors (Chigira, 1990).

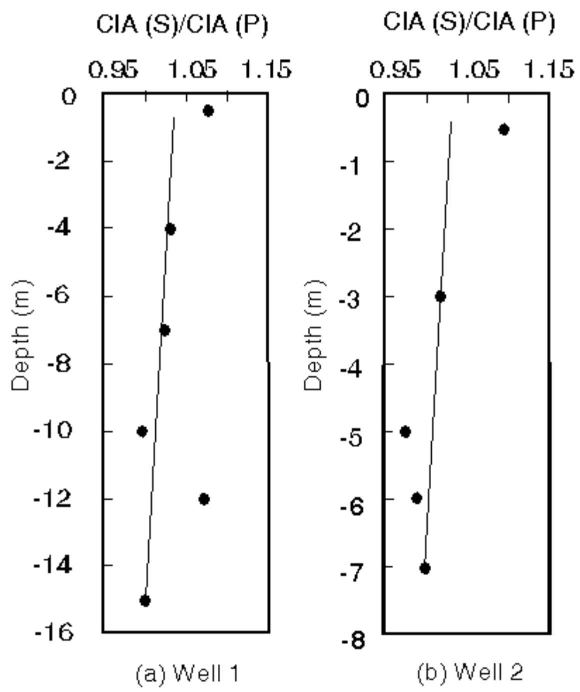


**Fig. 9.** Depth-wise variation of Normalized CIA, S: Sample rock, P: Parent rock

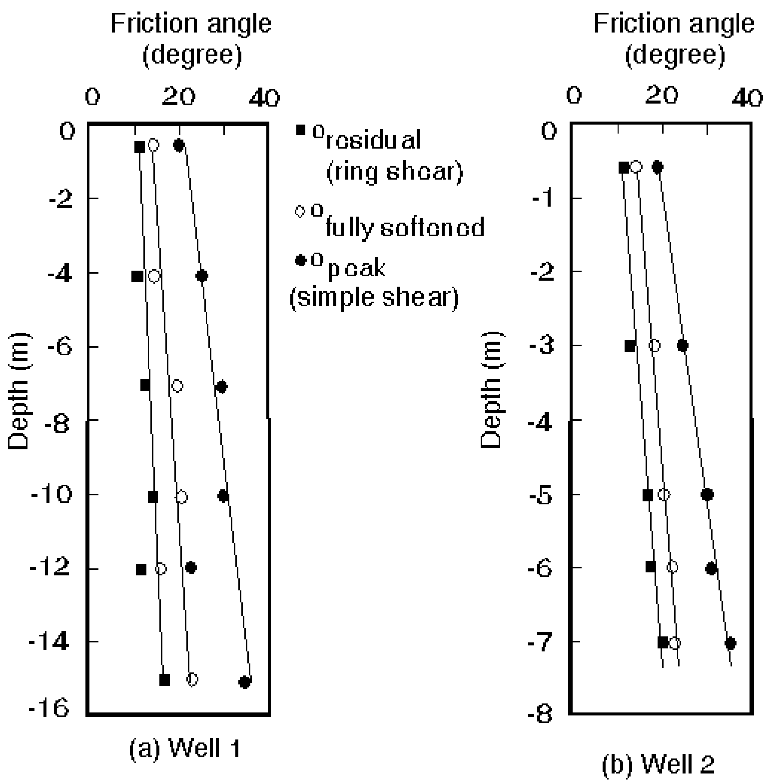


**Fig. 10.** Depth-wise variation of friction angles

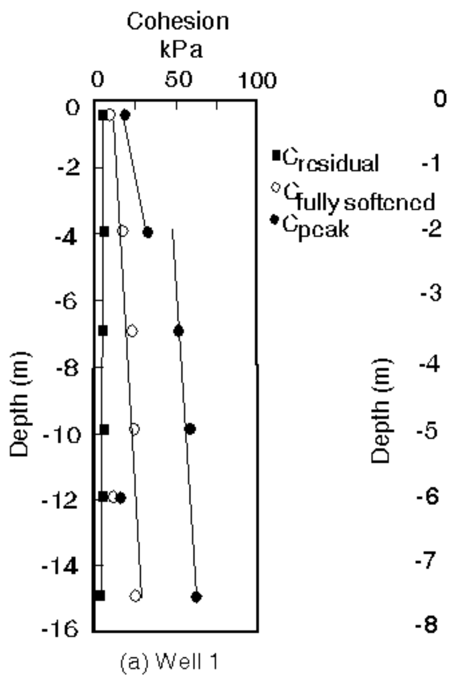


**Fig. 11.** Depth-wise variation of cohesion

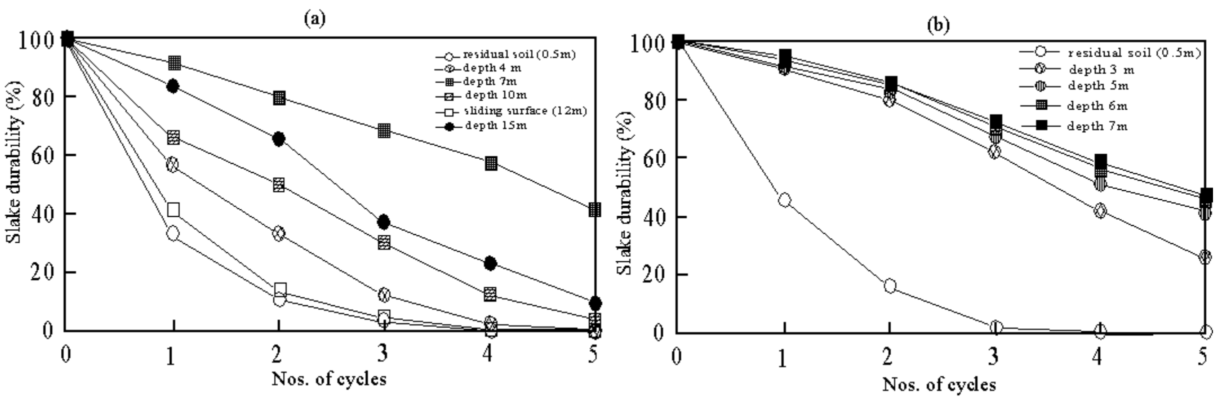


**Fig. 12.** Depth-wise variation of slake durability with increasing nos. of cycles (a) Well 1 (b) Well 2

## Conclusion

Construction of 3 m diameter drainage wells at the Mukohidehara Landslide provided an excellent opportunity to collect the soil and rock samples associated with mudstone from various depths. We observed their physical as well as other engineering properties that are directly or indirectly related to the slope stability. The test results and their analytical discussions suggest the fact that physical weathering is significant in the mudstone areas, especially up to the depth of ground water fluctuation. Below that depth, both physical and chemical weathering effects are less significant, although there is a slight decrease in weathering index (CIA) with increase in depth as a result of the increase in bulk density. Mudstones near the ground surface and at the sliding surface are highly disintegrated and eventually have significantly low bulk density, chemical weathering might also be significant as a result of chemical and mineralogical alteration through the action of the surface and ground water. The effect of chemical weathering on increase or decrease of shear strength is a subject of further research. However, the present study showed that physical weathering of soil and rock samples associated with mudstone always reduces the shear strength of the soil and rock, which eventually reduces the slope stability.

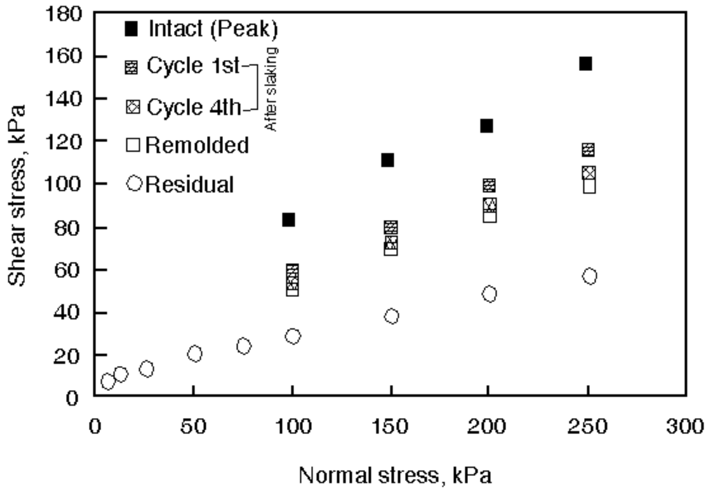


**Fig. 13.** Shear strength envelopes in intact, slaked and remolded conditions, specimen (4 m depth), well 1.

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