CHAPTER 4

Results and Discussions

The results of field observations and laboratory tests of landslide and non-landslide areas.

4.1 Geotechnical soil properties

4.1.1 Permeability test

In-situ permeability tests. The perform on site permeability for landslide area ranges from 1.08×10^{-5} to 1.76×10^{-5} cm/s; with the average of 1.32×10^{-5} cm/s. While in yhe non-landslide areas, the permeability value was 8.56×10^{-6} to 9.55×10^{-6} cm/s; with the average value of 9.11×10^{-6} cm/s. The average permeability of the landslide site was higher than the non-landslide site. The values of hydraulic conductivity of landslide and non-landslide areas were low based on standard soil value. Generally, slopes with lower hydraulic conductivity are most prone to shallow failures due to the significant pore water pressure response to the rainfall. For the low permeability soils, the antecedent rainfall can be important in reducing soil suction and increasing the pore-water pressure

4.1.2 Grain size analysis

Table 4.1 and Figure 4.1 show the grain size distribution of the soil samples from landslide and non- landslide areas. The percentages of fine grains in the landslide soils range between 6% and 12%, while those in the the non-landslide soils ranged between 9% to 23%. Coarse-grained soils of the landslide area was higher than non-landslide areas. According to the Unified Soil Classification System (USCS), the soils from the landslide and non-landslide area were generally well-graded sand. No distinct variation in the particle size distribution with depth could be observed for soils from the landslide and non-landslide areas. It is generally explained that rainfall-triggered landslides in coarse grained soils are caused by increasing pore pressures and seepage forces during the periods of intense rainfall. Soil with more sand, high slope and intensive rainfall are most dominant factors of landslide (Patanakanog, 2001).

Table 4.1 Grain size distribution for the landslide and non-landslide areas.

Sample		Depth (m)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)
Landslide Area	LS_A1	0.50	2.16	88.30	3.51	6.03
	LS_A2	1.00	3.32	90.62	2.72	3.34
	LS_A3	1.50	3.23	90.51	2.14	4.12
	LS_B1	0.50	1.63	88.66	4.22	5.49
	LS_B2	1.00	1.17	87.27	4.21	7.35
	LS_B3	1.50	3.77	89.66	2.88	3.69
	LS_C1	0.50	9.88	79.19	4.11	6.82
	LS_C2	1.00	17.43	73.32	3.58	5.67
	LS_C3	1.50	2.90	87.84	4.02	5.24
Non-Landslide Area	N-LS_A1	0.50	5.19	80.96	5.67	8.18
	N-LS_A2	1.00	3.24	83.61	6.33	6.82
	N-LS_A3	1.50	2.45	74.17	7.92	15.46
	N-LS_B1	0.50	4.14	80.51	6.21	9.14
	N-LS_B2	1.00	2.04	78.66	8.54	10.76
	N-LS_B3	1.50	0.23	81.63	7.33	10.81
	N-LS_C1	0.50	2.68	81.24	5.43	10.65
	N-LS_C2	1.00	0.52	81.23	8.29	9.96
	N-LS_C3	1.50	11.10	79.70	3.76	5.44

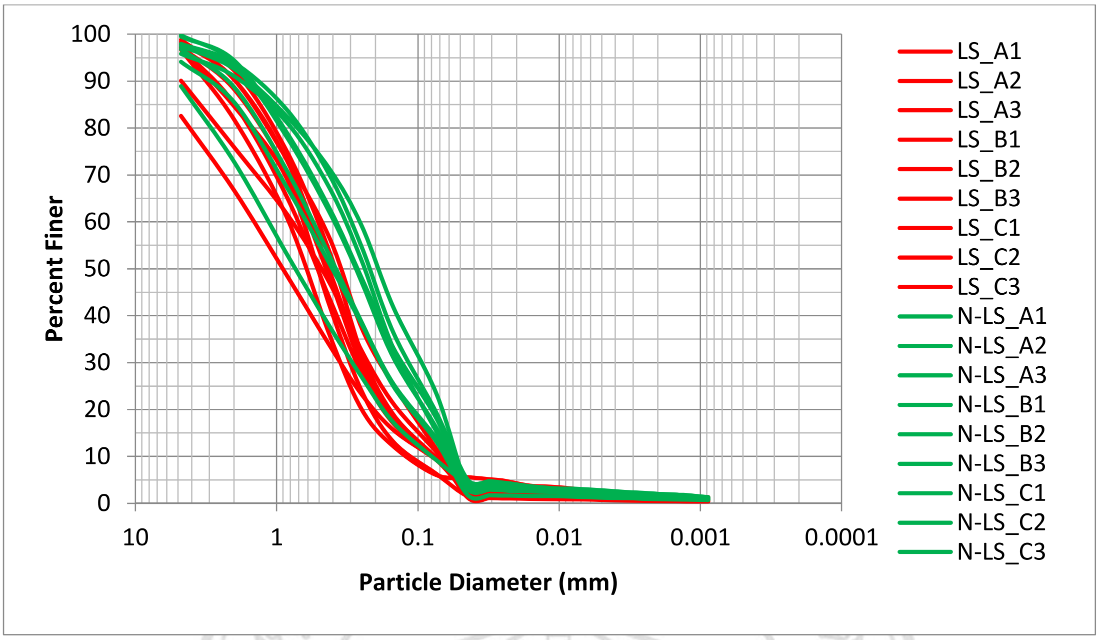

Figure 4.1 The grain size distribution curves for the landslide and non-landslide area.

4.1.3 Atterberg limits

The Atterberg limits values (Table 4.2) affect the general behavior of the soils in terms of slopestability. Figure 4.2 show the water content, liquid limit, plastic limit and plasticity index with various depth of soils from landslide and non-landslide areas. The water contents of soils in landslide area range between 19%-28.3%, higher than those in the non- landslide area which ranged between 16.9%-23.2%. Both areas were almost high in water content at depth of 1 meter. The amount of water may be increase or decrease stability. A sand castle for example, water must be mixed with sand in order to keep its castle shape. If too much water is added in to sand, it will be washed away. If water is inadequate, the sand shape change and it falls.

In the landslide area, the liquid limits of soils range from 19% to 28%, with an average of 23% and the plasticity indeces range between 6% to 16%, with an average of 11%. These values represent clayey sand with low plasticity (Fig. 4.3). In the non-landslide area, the liquid limit and the plasticity indeces of soils range from 25% to 34% with an average of 30% and 8–17% with an average of 13%, respectively. These values represent clayey sand with low and medium plasticity (Fig. 4.4). The liquid limit of soils from landslide was lower than that from non-landslide area and mostly decreased with depth. A high liquid limit usually indicates that the soil was able to absorb a large percentage of water. Giannecchini and Pochini (2003) found that the soils from landslide areas have a lower liquid limit than those from non-landslide areas, based on size distribution analysis. Hence, plastic limit of soils from landslide is lower than that from grain non-landslide area. The plasticity limit of soil was almost highest value at depth 1 meter. The plasticity index of the soil samples was determined using the Unified Soil Classification System (USCS) plasticity chart. The plastic index of landslide area was 6.2% to 16.2% and non-landslide area was 8.7% to 17.5%. The plasticity index of the landslide and non-landslide of soils decrease with depth. Generally, plasticity index of soils decreases with depth as the degree of weathering decreases.

Table 4.2 Water content, liquid limit, plastic limit and plasticity index of soils from landslide and non-landslide area.

Samples		Water content (%)	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)
Landslide Area	LS_A1	26.6	25.4	10.4	15.0
	LS_A2	22.6	21.8	11.1	10.7
	LS_A3	21.8	22.2	12.7	9.5
	LS_B1	24.1	26.8	10.6	16.2
	LS_B2	29.1	23.4	11.6	11.8
	LS_B3	24.9	19.0	11.6	7.4
	LS_C1	24.5	28.3	13.0	15.3
	LS_C2	29.6	23.5	13.7	9.8
	LS_C3	25.7	19.4	13.2	6.2
	Average	**25.4**	**23.3**	**12.0**	**11.3**
Non-Landslide Area	N-LS_A1	16.9	31.2	15.4	15.8
	N-LS_A2	23.2	29.5	17.6	11.9
	N-LS_A3	19.3	27.8	17.9	9.9
	N-LS_B1	22.3	34.1	16.6	17.5
	N-LS_B2	21.1	28.2	17.3	10.9
	N-LS_B3	19.7	32.8	18.0	14.8
	N-LS_C1	18.4	29.2	16.0	13.2
	N-LS_C2	19.3	28.4	18.5	9.9
	N-LS_C3	17.0	25.2	16.5	8.7
	Average	**19.7**	**29.6**	**17.1**	**12.5**

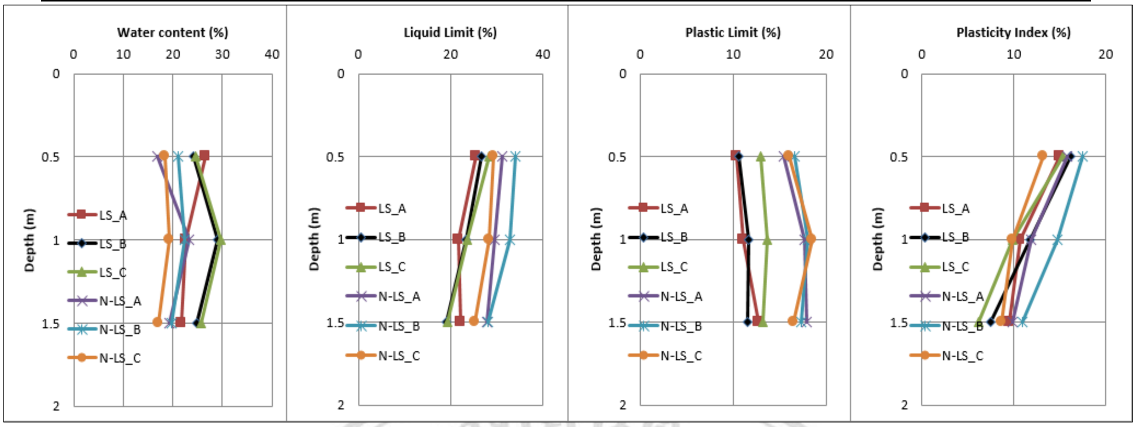

Figure 4.2 Water content, liquid limit, plastic limit and plasticity index with various depth of soils from landslide and non-landslide areas.

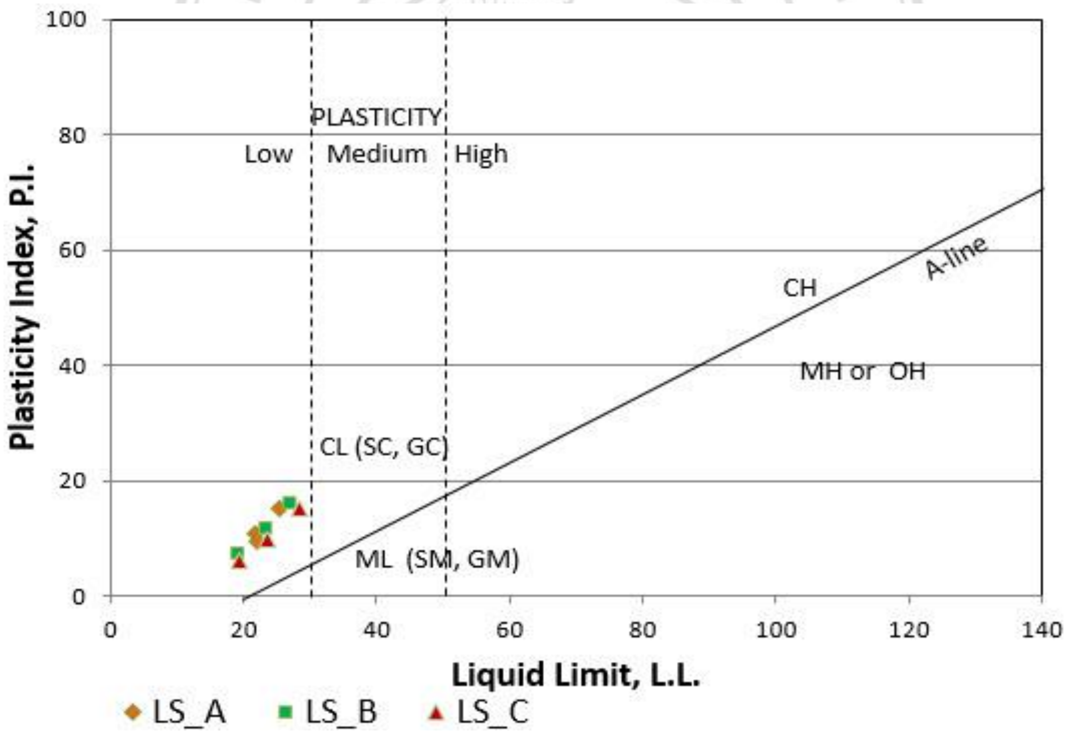

Figure 4.3 Plasticity chart (USCS) of soil samples in landslide area.

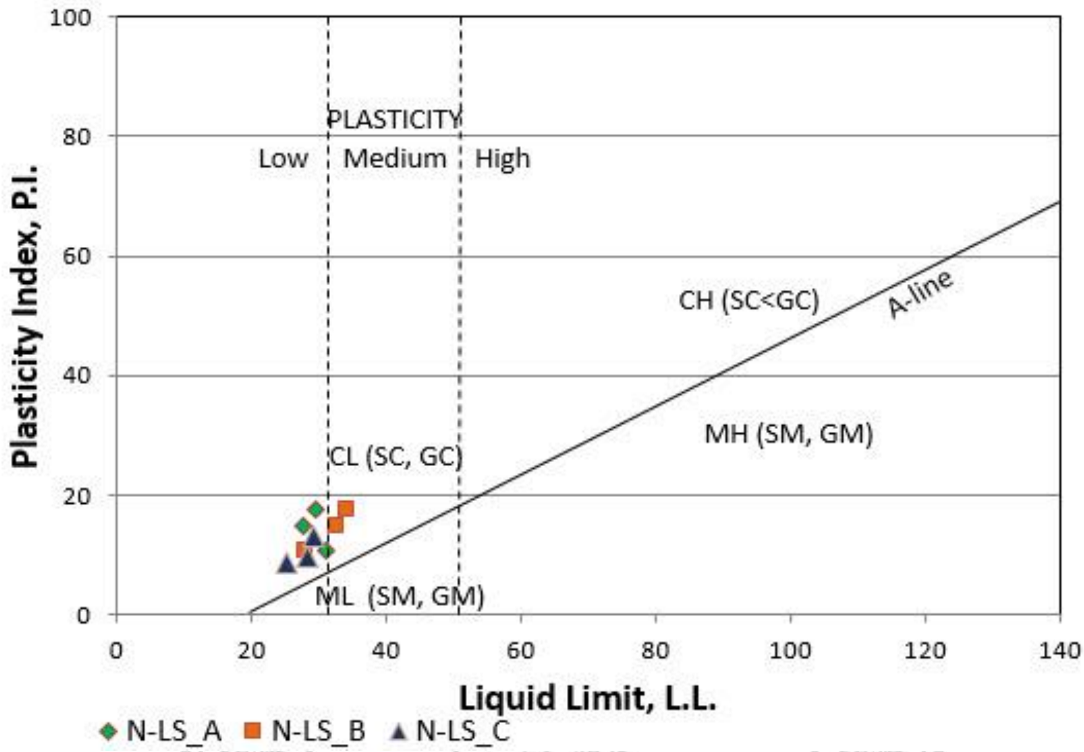

Figure 4.4 Plasticity chart (USCS) of soil samples in non-landslide area.

4.1.4 Shear strength (Direct shear test)

The shear strength of the soil was described by the function of normal stress on the slip surface, cohesion, and angle of internal friction. The shear strength was characterized by the angle of internal friction and cohesion. It depends on water content, bulk density, grain size distribution, and structural cohesion between soil particles. The angle of internal friction and cohesion are the two important physical properties of soil which determine the shear strength, safety factor as well as stability condition of the slope materials. Disruption in the stability of soil samples results in a lower value of shear strength due to the collapse of soil structure and increases the value of friction angle (Salih, 2012). The angles of internal friction of the soils are high indicating that the slope is unstable and can likely be collapsed (Guedjeo et.al., 2013).

Shear strength values were obtained from laboratory analyses of the landslide soils and non-landslide soils as presented in Table 4.3. The average cohesion of landslide soils of the study area is 4.0 kPa and the average friction angle is 44.4^{o}. The average cohesion and internal friction angle of soil samples from non-landslide area are 8.2 kPa and 32.90^{o} , respectively. Therefore, soil samples from the landslide area are low cohesion and high internal friction angle. The values of friction angle are higher for well-graded soils than for uniformly graded soils. This is due to the fact that the well-graded soils allow smaller particles to fill the gaps between larger particles, as a results, it is possible to form denser packing that offers greater resistance to shearing. Water is an important factor in slope stability, contributing both to high shear stress and low shear strength. The angle of internal friction and cohesion from this study were used to calculate the factor of safety by CHASM software.

Table 4.3 The results of direct shear test.

Sample		**Cohesion (kPa)**	**Friction angle**
Landslide	LS_A	4.0	39.80°
	LS_B	2.5	45.00°
	LS_C	5.5	48.36°
	Average	4.0	44.38°
Non-Landslide	N-LS_A	12.5	38.66°
	N-LS_B	6.4	31.61°
	N-LS_C	5.7	28.61°
	Average	8.2	32.90°

The two main parameters that control shear strength of the soils are the cohesion and the friction angle. The shear strength parameters were plotted against the clay content and the graphs were used to determine the correlation between the two parameters. Fig. 4.5 shows a graph of the clay content and the cohesion in the samples from landslide and non-landslide areas. In both areas, the cohesion increases with increasing clay content. As more clay is introduced into the sandy materials, the clay particles fill the void spaces in between the sand particles and begin to induce the sand with interlocking behavior. This explains why clayey sand soils which are expected to exhibit low cohesion have high cohesion values when the clay content increases

(Shanyoug et al, 2009). A graph of clay content and friction angle is presented in Fig. 4.6. Friction angle in landslide areas is higher than non- landslide areas. Because clay content of soil from landslide areas is lower than that from non-landslide area. The friction angle decreases with increasing clay content in the samples of the non-landside areas. Similar observations of decreasing friction angle of sandy soils with increasing clay content were reported by Naser (2001), Tiwari and Marui (2005) and Yin (1999). Thus, clay content also promotes an increases in cohesion and a decreases in the friction angle.

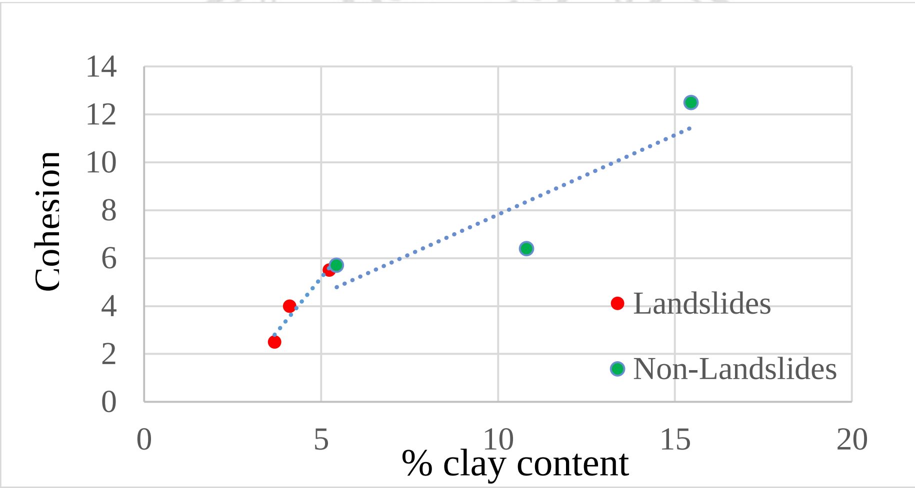

Fig. 4.5 Variation of clay content with cohesion.

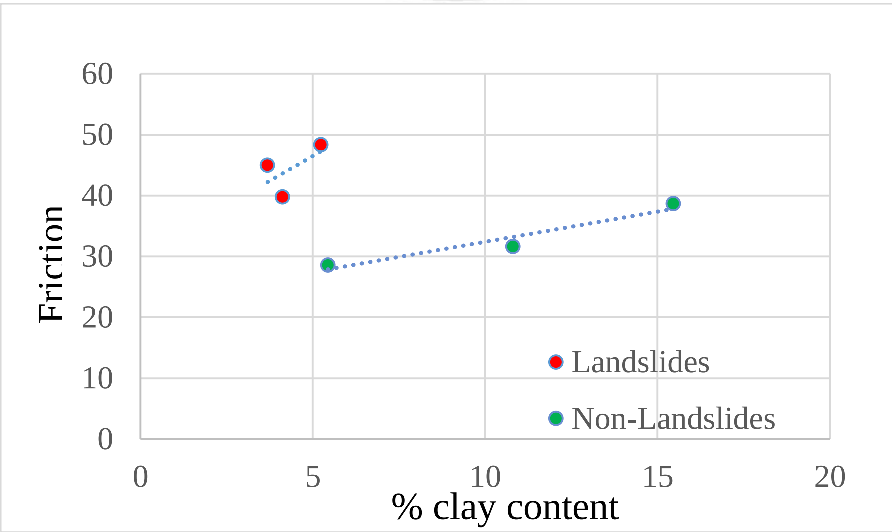

Fig. 4.6 Variation of clay content with friction angle.

4.2 X-ray diffraction mineralogical analysis

Granite is made up of quartz, mica and feldspar. As quartz is resistant to chemical weathering, it may be removed only as mineral grains of quartz. Feldspars and micas are susceptible to chemical weathering and break down to form clay minerals. The X-ray diffraction study confirmed that the soil from the landslide area consisted of quartz, feldspar, muscovite, kaolinite, illite and montmorillonite. Soil samples from the non-landslide area consist of quartz, feldspar, muscovite, kaolinite. Quartz content in soils is higher in the non-landslide area than in the landslide area. Feldspar minerals such as albite and microcline are higher in the landslide area than in the non-landslide. Hence, clays may be composed of the mixtures of finer grained clay minerals and clay-sized particles of other minerals such as quartz, carbonate, and metal oxides. Figure 4.7 shows the representative XRD diffraction pattern of the soils from the landslide area (sample no. LS_A2) and from the non-landslide area(sample no. N-LS_A2). Quartz, feldspar and muscovite are the primary minerals indentified by the XRD data and the important clay minerals are kaolinite, montmorillonite and illite. Quartz is identified by its typical 3.34 Å peak. Muscovite can be identified by 9.9 Å and 4.9 Å, feldspar by 3.24 Å, kaolinite by 7.1 Å, illite by 10 Å, and montmorillonite by 15 Å peaks. Quartz, feldspar, muscovite are present in the clay fraction in all soil samples. Feldspar minerals such as albite and microcline are abundant after quartz.

Table 4.4 shows mineral content of the soils calculated using X-ray diffraction analysis. Clay minerals detected in this study include illite, kaolinite and montmorillonite. Semi-quantitative mineral analysis indicated 6.2% to 17.8% of montmorillonite in the landslide area and none in the non-landslide soils. The proportion of kaolinite found in soil samples from the landslide areas are 5.9%-9.8%, and three soil samples from the non- landslide area are 3.4%-6.7% at the top of the slope.

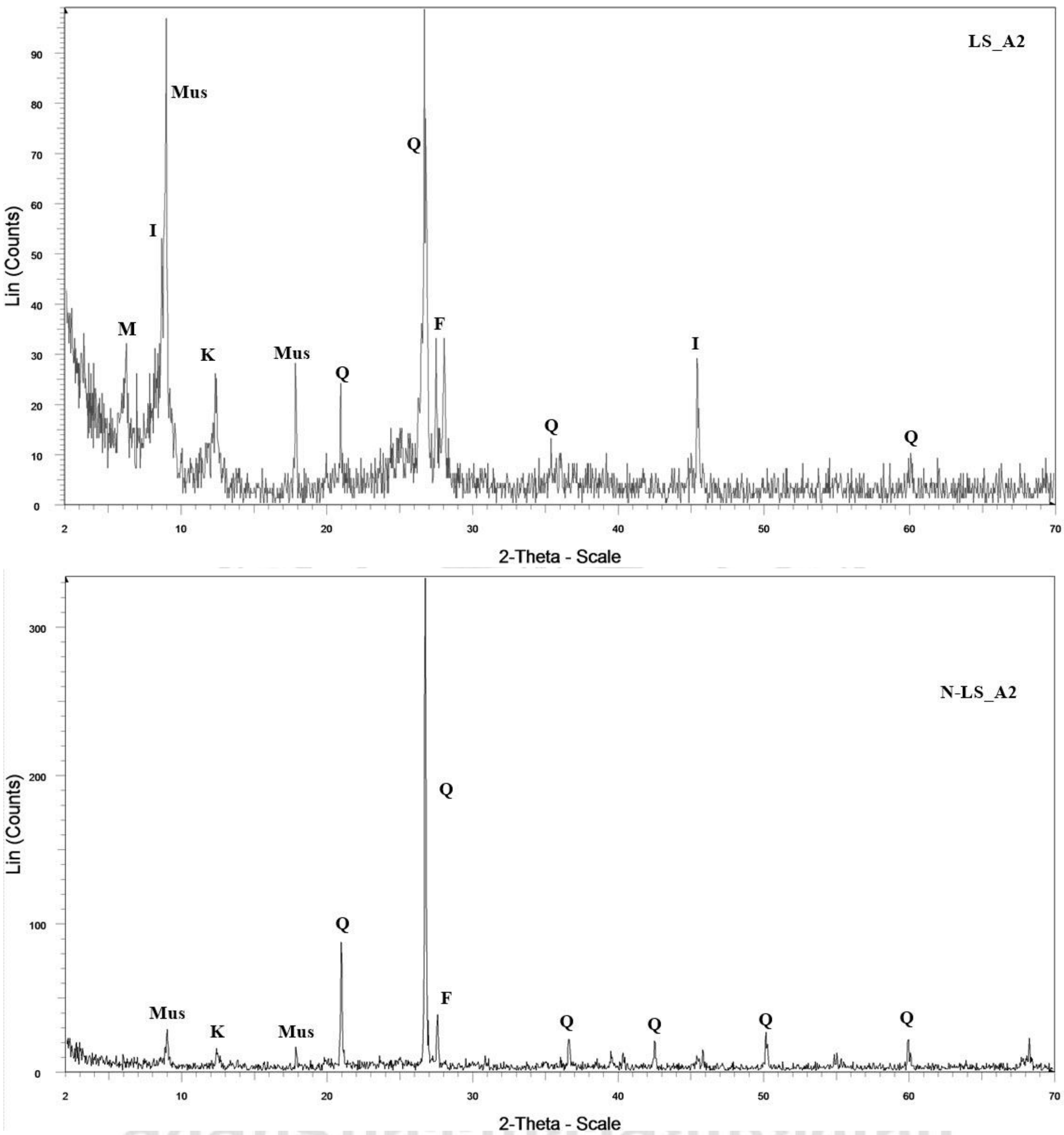

Figure 4.7 shows the representative XRD diffraction pattern from the soils of landslide sample no. LS_A2 and non-landslide sample no. N-LS_A2 (Q=Quartz, F=Feldspar, Mus=Muscovite, K=Kaolinite, I=Illite, M=Montmorillonite).

Kaolinite does not absorb water and does not expand when it comes in contact with water. However, their overall structure is soft and weak, when soak with and hence contributes to landslide. The most important aspect of montmorillonite is its ability for H_2O molecules to be absorbed between the sheets. The force of bonding between cations and the sheets is not very strong and depends on the amount of water

Table 4.4 Semi-quantitative XRD analysis of mineral constituents in the soils.

Minerals / Sample	Quartz (%)	Feldspar (%)	Muscovite (%)	Kaolinite (%)	Illite (%)	Montmorillonite (%)
LS_A1	35.3	11.3	23.1	8.8	13.4	8.0
LS_A2	30.6	9.7	27.8	7.6	15.3	9.0
LS_A3	28.9	13.2	28.2	5.7	15.4	8.6
LS_B1	26.5	23.6	25.2	8.9	8.3	7.3
LS_B2	22.7	36.8	14.5	9.3	14.4	8.8
LS_B3	21.1	17.8	35.1	7.9	12.0	6.2
LS_C1	50.5	19.1	-	9.8	20.6	-
LS_C2	25.0	18.1	22.2	7.8	9.1	17.8
LS_C3	39.7	17.2	19.7	5.9	10.9	6.7
N-LS_A1	85.3	5.2	6.0	3.4	-	-
N-LS_A2	80.0	8.8	7.2	4.0	-	-
N-LS_A3	82.5	10.8	-	6.7	-	-
N-LS_B1	88.5	6.2	5.3	-	-	-
N-LS_B2	78.7	4.7	16.6	-	-	-
N-LS_B3	88.5	6.2	5.3	-	-	-
N-LS_C1	81.1	9.8	9.0	-	-	-
N-LS_C2	70.7	15.0	14.3	-	-	-
N-LS_C3	81.8	8.3	9.9	-	-	-

present. In dry montmorillonite, the bonding is relatively strong. The montmorillonites are expanding clays when they become wet, because of water enters the crystal structure and increases the volume of the mineral. The water has virtually no strength, almost any load will cause layer to slide easily over other layer and is prone to slide when they are wet. Montmorillinite can expand by several times its original volume when it comes in contact with water. It reduces the cohesion in soil and greatly affects its shear strength behavior.

Soils in the granite areas where landslides took place have lower clay mineral content relative to those from non-landslide areas. Therefore, clay mineral content can serve as a sensitive factor influencing landslides, together with the mechanical properties. The content of clay minerals is high in landslide soils, esspecially montmorillonite and kaolinite. It is believed that this area is more vulnerable to landslides when compared with other areas because of its content of montmorillonite and kaolinite, even though there might be light precipitation during the rainy season.

4.3 Slope stability analysis (Combined Hydrology And Stability Model)

To study the effect of rainfall on the stability of soil slopes, a method that combines hydrological information and slope stability analysis is required. By using these models, the effect of water infiltration on soil strength and slope stability can be determined. This model has been used for various environmental conditions. The results show that the position of groundwater table, soil friction, soil cohesion, rainfall intensity and rainfall duration have significant effects on the instability of landslides. Groundwater table position and soil strength properties are found to be the primary factors controlling the instability of slopes, while rainfall intensity plays a secondary role. The soil strength reduction as moisture content changes from unsaturated to saturated after wetting by rainfall. On the other hand it is shown that increasing soil saturation, which is a direct effect of rainfall accumulation, decreases the factor of safety. The results also demonstrate. The effect of rainfall duration on the slope instability. Figure 4.8 shows the variation of the factor of safety in 48 hours. Factor of safety with the lower value of 1 (<1) indicates the unstable slope and sliding surface. The result of landslide area simulation, the factor of safety decreases from 1.91 to 0.97. It startes to slide at the 39^{th} hour, while the rain stopped 15 hours earlier . In the non-landslide area, a simulation of 48 hours showed that the factor of safety decreases from 2.32 to 1.38, indicating a relatively stable slope.

The soil samples from landslide and non-landslide areas show negative pore water pressures resulting in the increase of the shear strength. While rainfall proceeds the water pressures become positive and the shear strength decreases. Hence, the factor of safety decreases and the slope becomes unstable and slides in take place the landslide area. However, the factor of safety for the non-landslide area tends to decrease as well in the simulation. Hence , if with heavy rainfall or long period rainfall, the slope in the non-landslide study area may possibly fails.

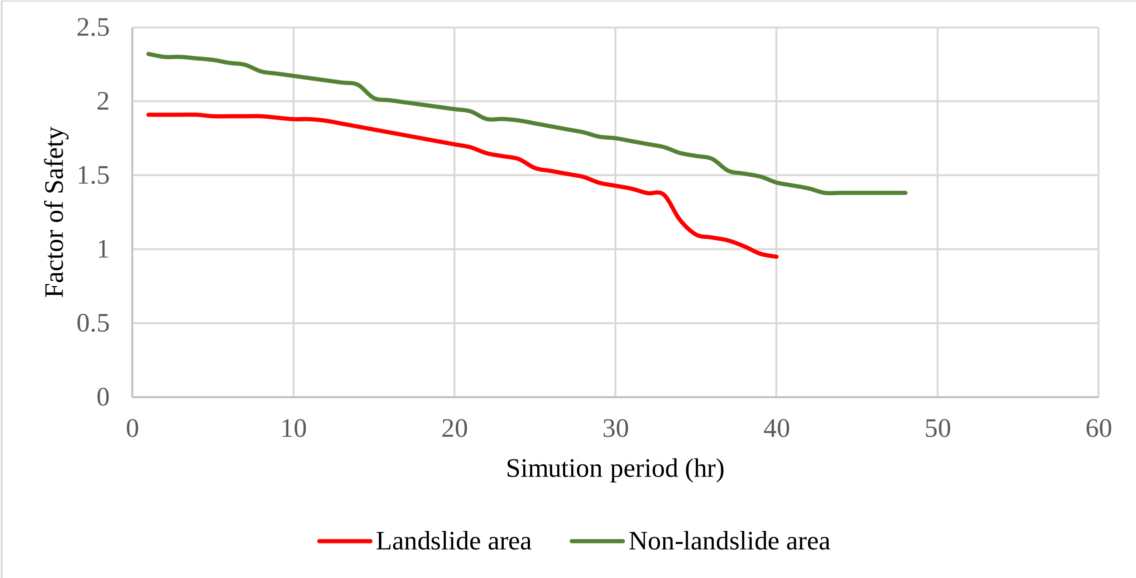

Figure 4.8 The variation of factor of safety with time for 48 hours simulation of landslide and non-landslide areas.