CHAPTER 2

Literature Review

2.1 Landslide in Thailand

Tingsanchali (1989) studied on a huge 1988 landslide in southern Thailand and proposed that the two principal methods for controlling debris flows were structural control and non-structural control measures. The suitability of these two methods or their combinations depends on the size and the characteristics of the area considered, the socio-economic condition, and the financial and political factors. According to Aung (1991) most failures took place on slope with gradient between 10 to 30 degrees and extended from the ground surface to the depth of 1 to 3 meters into the residual soil. These observations indicated that failures were mostly of surface erosion or earth flow types. He also constructed the landslide susceptibility map in the area west of Amphoe Phi Pun, Nakhon Si Thammarat province.

Nutalaya (1991) concluded that the followings were the factors causing landslides during the rainstorm event of 20th-23rd November 1988, Khao Luang Mountain Range. These factors included deforestation of the areas which significantly caused the erosion of steep slopes; steep stream gradient (over 35 per cent) and sharp change in gradient which occurred when the mountain streams met the flat valley floor resulted in the deposition of alluvial fans, and deeply saturated residual sand on the granitic rocks.

Tantiwanit (1992) conducted the study on the characteristics of landslides that occurred during the November 1988 storm event. The study revealed that factors controlling landslides include: residual soil from weathered granitic rocks susceptible to landslide, steep gradient over 30 percent, the change of vegetation cover, and the triggering factor was highly rainfall.

Khantaprab (1993) investigated the same November 1988 landslides in southern Thailand and proposed the following factors: (1) slope gradient greater than 12 degrees; (2) deforestation and changing pattern of land use and land cover to para rubber plantations; (3) the areas underlain by granitic residual soils, and (4) high cumulative rainfall intensity as the triggering factor.

Nilaweera (1994) studied the effects of root strength properties and root morphology of para-rubber plantations compared with other kind of forest trees, that produced hard deep penetrating root systems in the area of Khao Luang Mountain Range. The replacement of forest trees could cause instability to the soil slopes. From that event, the slopes, between 10 to 40 degrees were the sites where most of landslides occurred.

Thaijeamaree (2003) studied the landslides in Nam Kor Watershed, Nam Kor subdistrict, Lom Sak district, Phetchabun Province. The studies were done by field survey on landslide area, field tests, and laboratory tests. Finite Element Method was performed for soil slope during heavy rainfall using these test results for infiltration analyses. The relationship of rainfall patterns and the stability of slope gave the critical rainfall that cause landslide. This report showed that when the moisture content of the samples increases, the shear strength of the soils decreases. These relationships establish the critical rainfall envelope when the factor of safety (FS.) is equal to unity. With the various rainfall patterns from 1-14 raining days, the critical rainfall envelope can be established and used as future warning levels for the villagers.

Kunsuwan (2005) studied the landslides in Khlong Krating, Khlong Takhian and Klong Thung Phen, in Chantaburi sub-basin during the heavy rainfalls and floods in 1999 and 2001. The hazard map was created on the basis of the relationships between the rainfall patterns, rainfall duration, return period, the slope stability and the critical rainfall envelope in order to be used for landslides warning. The results showed that the slope failures were the area of 25-35 degree slopes, and the depth of 2.5-3.5 meters, The soil profiles were on the weathered granite with high natural moisture contents. The shear strength of soils decreases with the increase in the degree of saturation. The study of the sediment distribution along the rivers showed that the amount of sediments decreased with increasing distance from the source. The critical factor of safety occurred right after the end of heavy rainfall. The correlation of the slope stability analyses with the historical rainfall data leads to critical rainfall envelope of the factor of safety equals to 1.

2.2 Landslides in weathered granite

Granitic rocks are well known to be very sensitive to weathering and are vulnerable to landsliding (Chigira 2001). The weathering rate of minerals of granitic rocks follows the sequence: plagioclase feldspar, biotite, potassium feldspar, muscovite, and quartz (Wahrhaftig, 1965; Isherwood and Street, 1976).

During 1966-1967, in the granite and gneiss areas of Rio de Janeiro, severe rainstorms resulted in tens of thousands of landslides that caused about 1000 casualties (Durgin, 1977).

Southern Italy has also suffered from landslides in weathered granite (Calcatera et al., 1996).

Oyagi (1968) reported that numerous shallow landslides occurred in areas of slightly weathered granite after a rainstorm in Shimane Prefecture (western Japan) in 1964.

Iida and Okunishi (1979) and later Onda (1992) studied weathering profiles of granite underlying the Obara Village, in Aichi Prefecture, of central Japan, where innumerable disastrous landslides occurred following a heavy rainstorm in 1972.

Tobe et al. (2008) studied the distribution of landslides in granite during the heavy rain of 1972 Nishimikawa disaster, where rainfall reached more than 200 mm over a period of 5 hours.

2.3 Rainfall-triggered landslides

Rainfall is an important triggering mechanism in landslide occurrences. It induces shallow landslides, mostly soil slip and debris flows. The rainfall reduces the shear strength of soils decreasing the positive effect on stability due to negative pore pressure by (Bishop, 1959; Campos et al., 1994; Godt et al., 2009) or due to increasing positive pore pressure (Terzaghi, 1943). The failure surfaces may form within the weathered materials (Lu and Godt, 2008; Hawke and McConchie, 2009), but often correspond to the point of contact between the soil and the less permeable bedrock, where a temporary perched water table could develop (Dietrich et al., 2007; Baum et al., 2010).

Some studies show that the type of rainfall-triggered landslide depends largely upon intensity and duration of rainfall (Campbell, 1975; Caine, 1980; Brand et al., 1984; Wieczorek, 1987; Wilson and Wieczorek, 1995; Crozier, 1999; Guzzetti et al. 2004; Aleotti 2004; Giannecchini 2006). Studies have shown that both deep- and shallow seated landslides can be triggered by rainfall, but deep seated landslides are triggered by rainfall over extended periods with a moderate intensity, while shallow landslides such as soil slips and debris flows are usually triggered by short duration, intense precipitations. Different approaches have been presented to explain the relationship between rainfall and slope failures in terms of rainfall thresholds, hydrological models, and coupled hydrological and stability models (Hungr, 1995; Borga et al., 2002; Rezaur et al., 2002; Rahardjo et al., 2002; Tsaparas et al., 2002; Dhakal and Sidle, 2004; Kim et al., 2004; Dahal et al., 2008; Rahardjo et al., 2005; Tofani et al., 2006). Rainfall and liquefaction of slope materials have also been examined recently (Anderson and Sitar 1995; Montgomery et al. 1997; Sassa 1998; Dai et al. 1999; Lan et al. 2003; Collins and Znidarcic 2004; Cai and Ugai 2004) and it is generally observed that rainfall-triggered landslides in course grained soils are caused by increased pore pressures and seepage forces during periods of intense rainfall. In contrast, fine grained soils with low infiltration rates do not lead to the development of positive pore pressure, and failures occur due to a decrease in the shear strength of soils caused by the loss of matric suction. Likewise, studies have also suggested that shallow failures are usually associated with increased positive pore water pressure, while loss of negative pore water pressure or matric suction is mainly responsible for deep-seated failure.

In Italy, landslides are caused primarily by rainfall. Depending on meteorological and physiographical conditions, individual rainfall events can cause slope failures in areas of limited extent or in large regions. In the period 2–6 November 1994, prolonged rainfall triggered several thousands shallow and deep-seated landslides in an area of thousands of square kilometres in northwestern Italy (Regione Piemonte,1998; Luino, 2005). On 1

October 2009, a high intensity rainstorm in the Messina area, Sicily, triggered more than 500 shallow landslides in an area of less than 60 km^2. Both events caused casualties, and severe economic losses.

In California, a storm in 1982 was responsible for 33 deaths and over 18,000 slides with 440 mm of rainfall in 32 hours (Ellen and Wieczorek, 1988).

Jones (1973) studied shallow landslides in Rio de Janeiro, Brazil. The 586 mm of rainfall in a 48 hour period, triggered tens of thousands of landslides that caused around 1,000 deaths.

On 16 July 2006, over 1200 shallow landslides occurred in Jinbu-Myeon, Pyeongchang-gun, Kangwon Prefecture in the Republic of Korea as a result of typhoon rains (Kim et al., 2015) and the total rainfall was amounted to at 450 mm/day.

Shimizu (1988) records a comparable disaster in the San-In district, Japan where a rainfall intensity of 50 mm/hour lasted for 10 hours, caused 100 deaths and damages estimated at 300 billion Yen. Similar extremes have been recorded. In Hong Kong, for example, rainfall of 525 mm over a 24 hour period in 1966 resulted in 35 deaths from the landslide.

Jacobson et al. (1989) describe a lower intensity but longer duration event, also in the Appalachians in 1985, which resulted in 70 deaths and $1.2 billion of damage. Here the greatest intensity recorded was 38 mm/hour with 2 day storm totals reaching 160 to 240 mm.

2.4 Geotechnical properties of landslide sites

The occurrence of landslide in any area may be attributed to the geotechnical (Yalcin 2007), mineralogical and chemical properties of the soils**.**

Siddle et al. (1985) observed that soil properties such as particle size and pore distribution in the soil matrix influence slope stability. These properties influence the rate of water movement in soils and the capacity of the soil to retain water. Finer soils tend to hold higher volumes of water under unsaturated conditions than their coarse textured equivalents (Sidle 1984). Other soil parameters that contribute to landslide occurrence include the rate at which water infiltrates into the soil at depth (Inganga and Ucakuwun 2001). The geotechnical properties of a soil such as its grain size distribution, plasticity, compressibility, and shear strength can be assessed by proper laboratory testing.

Yalcin (2011) studied landslides in Trabzon province in the Eastern Black Sea region of Turkey. There were small and large landslides following heavy rainfall periods in every year. These landslides regularly result in the loss of lives and property. In his study, an assessment of the geotechnical characteristics of the areas where the landslides occur and the immediate vicinity were compared with the characteristics of non-landslide areas. A total of 50 landslides occurring in different locations were studied. The results of the geotechnical investigations showed that the average of liquid limit values were between 49% and 69%, and the average plasticity index of the units ranged from 9% to 19% in the overlying materials in the landslide areas. Heavy rainfall exceeding boundary saturation of soils plays a critical role in causing landslides.

Rodeano (2010) described the importance of geological engineering inputs to landslide hazard occurrences in the Trusmadi Formation slopes, Sabah, Malaysia. Engineering properties of fifty five soil samples indicated that the failure materials mainly consist of poorly graded materials of silty clay soils and are characterized by low to intermediate plasticity content (12 % to 23 %), containing inactive to normal clay (0.43 to 1.47), very high to medium swelling (7.98 to 9.28), low to high water content (5 % to 25 %), specific gravity from 2.61 to 2.69, low permeability (8.78×10^{-3} to 3.28×10^{-3} cm/s), friction angle from 7.72˚ to 26.65˚ and cohesion from 5.11 KPa to 15.34 KPa. The geological influence had transformed the Trusmadi Formation slopes to be highly unstable and susceptible to landslide occurrences. Six related main parameters were attributed: (1) local and regional geology, (2) hydrological and geohydrological, (3) mineralogical and micro structures, (4) local discontinuities structures, (5) physical and engineering properties of soil and rock, and (6) geomorphological processes which can help in evaluating landslide problems in Trusmadi Formation slopes.

Ranjan et al. (2008) studied the contributing parameters for the rainfall-triggered landslides which occurred during an extreme monsoon rainfall event on 23 July 2002, in the hills of Kathmandu valley, in the Lesser Himalaya, Nepal. Parameters such as bedrock geology, geomorphology, geotechnical properties of soil. The resulted soils in landslide is silty clay of low plasticity (ML), cohesion ranges from 4.6 KPa to 12.6 KPa and friction angle ranges from 27.5˚ to 27.6˚

2.5 Effect of clay mineralogy to landslide

Clay minerals are formed by chemical weathering of rock forming minerals. They are small colloidal size crystal and chemically known as hydrous aluminosilicates Depending on the variation of basic sheet structure, different clay minerals are identified. However, kaolinite, montmorillonite and illite are the most common minerals found in clay soils.

2.5.1 Weathering of rocks

Goldich's series (Figure 2.1) makes thermodynamic sense to the extent that as the minerals therein are in the identical order to those in Bowen's classic reaction series describing the order in which the minerals crystallized out of a magma on cooling (Bowen, 1922). Goldich (1938) explained that the higher the temperature at which a mineral crystallized from magma, the greater the extent to which it was out of equilibrium with the surface temperature of Earth and, therefore, the more susceptible it would be to breakdown by weathering at the Earth's surface.

The stages of weathering are listed in Table 2.1 It is apparent that the composition of weathering solutions is strongly dependent on minerals that are undergoing weathering. First the original minerals dissolve and secondary minerals consequently can form from it. Leaching of elements such as calcium, magnesium, sodium, potassium, and soluble silica supports further transformation processes. The gradual loss of soluble silica results in the formation and disappearance of clays in an ordered sequence, starting with those highest in silica content and ending with those containing no silica, i.e., the hydrous oxides. Over long periods, the clays that form first eventually become unstable, decompose and are replaced by other secondary clay minerals which are more stable. First 2 : 1 clay minerals are formed. Iron oxides may also appear early and they seem to persist almost infinitely in the weathering environment, which attests to their great stability under most conditions. As weathering proceeds kaolinites appear, or even

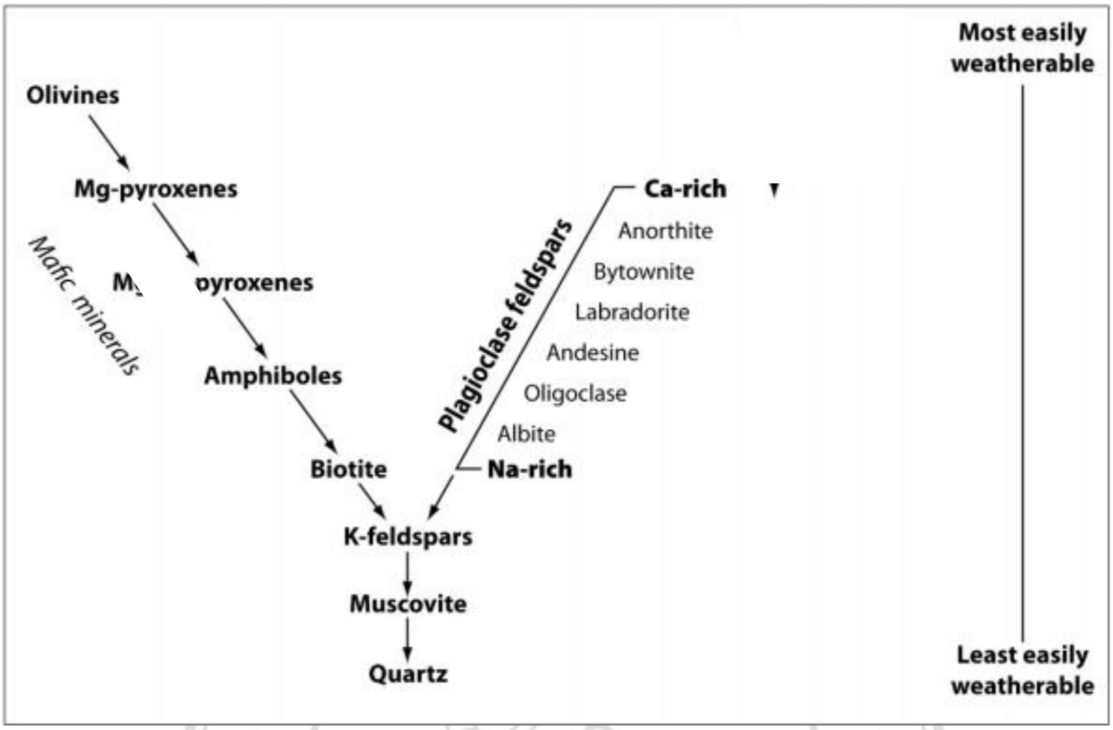

Figure 2.1 Stability series for common primary minerals (Goldich, 1938).

are decomposed, the silica released from it is leached, and the aluminum transforms to a hydrous oxide, usually gibbsite. These minerals tend to persist as the final products of long and intense silicate mineral weathering. The stages of weathering are time related functions, whereas the rate of weathering depends primarily on the climatic factors (temperature, precipitation). Silicate mineral weathering and clay synthesis are limited under either dry or cold conditions, but they proceed rapidly under hot, wet conditions, as in tropical regions.

For igneous rocks the most prevalent minerals are feldspars (60%), pyroxenes and amphiboles (17%), quartz (12%) and mica (4%). Ferro-magnesium minerals (pyroxenes and amphiboles) weather more rapidly than alumino silicate minerals (feldspar, quartz and mica). 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. Thus it could be expected that muscovite may be present in a soil from igneous rocks, whereas the amphiboles, pyroxenes and biotites would be altered completely. The most common primary minerals found in granite rocks consist of feldspar, quartz, mica, and amphibole. In weathered granite soils, primary

Table 2.1 Stages in the weathering of minerals in the < 2 mm fraction of soils (modified table, after White, 1987).

Stage / Type of mineral	**Soil characteristics**
Early weathering stages: Gypsum ($CaSO_4 * 2H_2O$) Calcite ($CaCO_3$) Olivine Pyroxene Hornblende (amphibole) Biotite (mica) Muscovite (mica) Na-Feldspars	These minerals occur in the silt and clay fraction of young soils all over the world, and in soils of arid regions, where lack of water inhibits chemical weathering and leaching. Soils show a very low content of water and organic matter, there is a reducing environment, very limited leaching, and a limited time for weathering.
Intermediate weathering stages: Quartz Hydrous mica (illite) Vermiculite and mixed layer minerals Chlorite Montmorillonite	Soils found mainly in the temperate regions of the world, frequently on parent materials of glacial or periglacial origin; generally fertile, with grass or forest as the natural vegetation. There is ineffective leaching and cations such as Na, K, Ca, Mg, Fe, and silica are retained.
Advanced weathering stages: Kaolinite Aluminium oxides (gibbsite) Iron oxides (goethite, hematite) Titanium oxides (anatase, rutile, ilmenite)	The clay fractions of many highly weathered soils on old land surfaces of humid and hot intertropical regions are dominated by these minerals. The cations Na, K, Ca, Mg, Fe, and silica are removed from the topsoil due to leaching. Secondary minerals are formed in an oxidizing environment with a low pH where acidic compounds are formed and silica is dispersed.

minerals, as residuals of physical and chemical weathering processes, most commonly occur in coarser particles (of sand and silt size). The primary mineral generally leads to one particular type of secondary mineral. Secondary minerals are formed as a result of the alteration of primary minerals or mineraloids by either (1) transformation in the solid state or (2) hydrolysis, dissolution, and recrystallization out of solution. The most common secondary minerals are kaolinite (created by the process of change and chemical weathering of feldspar), chlorite (created by the process of change and chemical weathering of biotite, pyroxene and amphibole), illite (created by the process of change and chemical weathering of mica), and montmorillonite (created by the process of change and chemical weathering of feldspar). During weathering of granitic rocks and rock-forming minerals are partly dissolved by some chemical weathering processes like hydrolysis and hydration. New secondary minerals like illite and montmorillonite are the earliest to be formed, followed by biotite and kaolinite. As leaching intensifies, partial desilicification occurs and many clay minerals can be converted to oxides.

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. Some of the original elements contained in the micas and feldspars are carried away in solution as ions (Na+, Ca+, and K+), and so the clays formed are relatively enriched in aluminium and silicon.

2.5.2 Clay minerals group

The clay minerals can be divided into four major groups. Based on their structures and chemical compositions.

1) The kaolinite group

Kaolinite is formed by weathering or hydrothermal alteration of alumino silicate minerals. It is formed by the alteration of feldspar and muscovite. In order to form, ions like Na, K, Ca, Mg, and Fe must first be leached away by the weathering or alteration process. This leaching is favored by acidic conditions (low pH). Granitic rocks, as they are rich in feldspar, are a common source for kaolinite. Kaolinite is the most common mineral of this group and has a chemical formula $Al_2Si_2O_5(OH)_4$. Kaolinite flakes have no overall charge, but they do have weak positive charges on one surface and weak negative charges on the other. The weak positive and negative charge attract, holding the layers together. Kaolinite do not absorb water and do not expand when it comes in contact with water. However, their overall structure is soft and weak, soaks up water, and thus contributes to landslide. Kaolinite is an important industrial mineral used in many industrial applications. The physical and chemical properties of kaolinite has led to its extensive use as filler, extender, paper coater, ceramic raw material, pigment, and also it is an important raw material for the refractory, catalyst, cement, and fiber glass industries.

2) The smectite group

The most common smectite is montmorillinite, with a general chemical formula $(½Ca,Na)(Al,Mg,Fe)_4(Si,Al)_8O_{20}(OH)_4.nH2O$. The most important aspect of the smectite group is the 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 present. In dry montmorillonites the bonding force is relatively strong. The montmorillonites are expandable clays. Because water has virtually no strength, almost any load will cause layer to slide easily over other layer and prone to landslides when they are wet. Montmorillinite can expand by several times its original volume when it comes in contact with water. This makes it useful as a drilling mud and to plug leaks in soil, rocks, and dams. However, montmorillinite is a dangerous type of clay to encounter if it is found in tunnels or road cuts. Because of its expandable nature, it can lead to serious slope or wall failures. Montmorillinite are used in various forms including a facial powder, filler for paints and rubbers, an electrical, heat and acid resistant porcelain, in drilling muds and as a plasticizer in molding sands and other materials.

3) The illite group

The illite clays have a structure similar to that of muscovite. The general formula for the illites is $K_yAl_4(Si_{8-y},Al_y)O_{20}(OH)_4$ usually with $1 < y < 1.5$, but always with $y < 2$. Because of possible charge imbalance, Ca and Mg can sometimes substitute for K. The K, Ca, or Mg interlayer cations prevent the entrance of H_2O into the structure. Thus, the illite clays are non-expanding clays. Illite type clays are formed from weathering of

K and Al-rich rocks under high pH conditions. Illite occurs as an alteration product of muscovite and feldspar in weathering and hydrothermal environments. Illite is a common constituent in shales and is used as a filler and in some drilling muds and used for the preparation of mixtures for traditional ceramics.

4) The chlorite group

This group is not always considered a part of the clays and is sometimes left alone as a separate group within the phyllosilicates. The chlorite minerals are common components of low-grade greenschist facies metamorphic rocks, and of igneous rocks as hydrothermal alteration products of ferromanganese minerals. The general formula for the chlorite is $(Mg,Fe)_3(Si,Al)_4O_{10}(OH)_2(Mg,Fe)_3(OH)_6$. They are non-expanding. Chlorites are less stable than most of the other clays in acidic environments and are subject to rapid weathering.

The kaolinite, illite, and chlorite are non-expanding minerals and the smectite is expanding minerals. In kaolinite the bonding is strong because of tight H-OH bonding between the layers. The interlayer bonding of illite is mostly by K^+ ions which is relatively strong. Montmorillonite is very weak to weak bonding due to various cations between the sheets, therefore they show a great expansion, especially in wet conditions. In chlorite the bonding is moderate to strong because of the positively charged octahedral layer.

2.5.3 Clay minerals of landslide site

Jaboyedoff et al. (2004) believed that weathering of some minerals, especially clays, may over time reduce the strength of soils and cause landslides. Seasonal changes of stability of slopes may be closely related to the content and type of clay in the slope, especially to the content of montmorillonite, the acidity of rain water in addition to the traditional factor of pore water pressure. Alteration of other clays into montmorillonite is a common stimulus to reduce the strength of slip surface (Shuzui, 2002; Egashira and Gibo, 1988).

Zhao (2009) investigated two landslides in the Three Gorges area in China. The objective is to identify mineralogical composition. The slip surface soil consists of quartz, feldspar, illite, smectite, mica, kaolinite, chlorite, limonite and magnetite.

Hirotomo (2007) determined the cause of the landslide in Guinsaugon, southern Leyte Island Philippines. The most important factor detected was the occurrence of smectite, a kind of clay mineral. The smectite is considered as one of the factors that causes a landslide, because smectite has the properties of expanding or swelling in wet conditions. Apparently, smectite was formed at the late stage of volcanic activity in the area. The second factor was the fault system of the Philippine Fault Zone. Another factor acting as a trigger is the heavy rainfall; over 700 mm for two weeks prior to the landslide.

Ali (2007) were investigated landslides of completely weathered dacitic rock in Kanlica, Turkey. The results showed that the illite and montmorillonite clay minerals have lower shear strengths and higher swelling potentials and are more prone to landslide problems than those composed of kaolinite and chlorite clay minerals.

Jeong et.al (2009) investigated landslides in the three areas that are composed of different types of geology by comparing landslide with soil compositions: Precambrian gneiss (Jangheung area), Jurassic granite (Sangju area), and Tertiary shale and mudstone (Pohang area) in Korea. Main clay minerals contained in soils of the sites where landslides took place are illite, chlorite, kaolinite, and montmorillonite. The character of fine particles is crucial for determining landslide types and the possibility of their occurrence because fine particles such as clays have great specific surface area and expandability that can absorb water within their structural layering, which can change the shear strength and cohesive strength of the soils or regoliths developed on the country rocks.

Dahal (2011) studied landslide in residual soils of andesitic terrain of western Japan. The results of the x-ray diffraction tests are quartz, feldspar, metahalloysite, smectite, and illite. The clay mineralogy of slope materials was also a major contributing factor for rainfall induced landslides in the andesitic terrain.

Clay minerals in general and smectite in particular are quite resistant in dry conditions, but rapidly lose their strength in wet conditions. Thus, softened smectite-rich clay layers with high water contents can have the properties of a lubricant, which, in turn, can be critical for slope stability. In addition to their high plasticity, these smectite have a high swelling potential, which can induce significant vertical overpressure, reducing even more the strength properties. The smectite have structure that can lead to landslide.

2.6 Slope stability analysis

Landslides are a local phenomenon, and slope stability varies from area to area. Many complex interrelated factors contribute to the generation of landslides. Engineering geologists may spend months preparing analyses of soil and rock strength parameters (Early and Skempton, 1972), location of preexisting faults and fracture (Warn, 1966), slope geometry, the orientation of the bedding planes in relation to slopes (Radbruch and Weiler, 1963; Briggs, 1974), and other factors to determine the causes of individual landslide. The four most important factors that cause slope failures, and to which many other factors are related either directly or indirectly, are (1) the nature of the underlying bedrock or unconsolidated deposits, (2) the angle of slope, (3) rainfall, and (4) the presence of older landslide deposits, which can commonly become reactivated or continue to move intermittently over long periods of time.

The Combined Hydrology And Slope Stability Model (CHASM) is a generally applicable model for shallow and deep-seated slope failures that are governed by changing pore water pressures. The model simulates dynamic stability conditions, allowing identification of the factor of safety, the characteristics of the failure and the time of occurrence for any particular initial slope condition and rainfall event.

Anderson and Lloyd (1991) developed CHASM to incorporate vegetative and soil suction effects on slope stability. CHASM initially utilized a two-dimensional finite difference hillslope hydrology model to predict the transient pore water pressures. The model outputs pore water pressures for each specified time step throughout the duration of the model. Pore pressure data (positive or negative) were then incorporated into the two-dimensional slope stability model. The stability model searches various failure surfaces for the lowest factor of safety for a given time step to determine slope safety.

Wilkinson et al. (2002) extended CHASM's modeling capabilities by incorporating hydrological controls such as hillslope soil-water convergence and vegetation cover that have direct impacts on pore water pressures into a three-dimensional model. CHASM's hydrology model is a forward explicit finite difference scheme. Figure

2.3 shows the general schematic of the three-dimensional hydrology model. The model has the capability of simulating detention storage, infiltration, evaporation, and unsaturated and saturated flow. Rainfall is allowed to infiltrate at the top of the cells after any rainfall interception and evaporation rates have been deducted at a rate governed by the infiltration capacity. Unsaturated flow is only assumed to take place in the vertical direction by Marshall and Holmes (1979). Saturated flow between columns is modeled using Darcy’s (1856) equation for saturated flow. At each time step of the simulation, the hydrology model results are directly input into a limit equilibrium model for slope stability. Pore pressures, positive and negative, are incorporated directly into the effective stress determination of the Mohr-Coulomb equation for soil shear strength. These effects were taken into consideration in Bishop’s limit equilibrium equations to determine the factor of safety for each time step in the analysis.

A combined model named CHASM (Combined Hydrology and Stability Model) was presented by Wilkinson et al. (2000). In this method, a 2-D finite slope stability method is used. This model was developed as commercial software (Wilkinson et al., 2002a). This model has been used for various environmental conditions in different countries, for example, in Hong Kong (Wilkinson et al. 2002b), Malaysia (Wilkinson et al. 2000; Wilkinson et al. 2002a; Lateh et al. 2008), Greece (Ferentinou et al. 2006; Sakellariou et al. 2006).

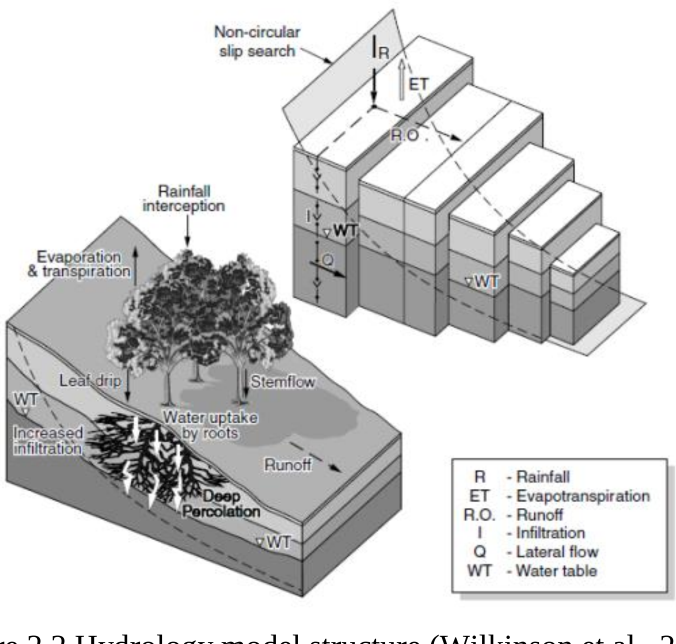

Figure 2.2 Hydrology model structure (Wilkinson et al., 2002).