WEATHERING RATES OF ROCK AND SOIL MASSES IN YEN BAI CITY, VIETNAM

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March, 2011

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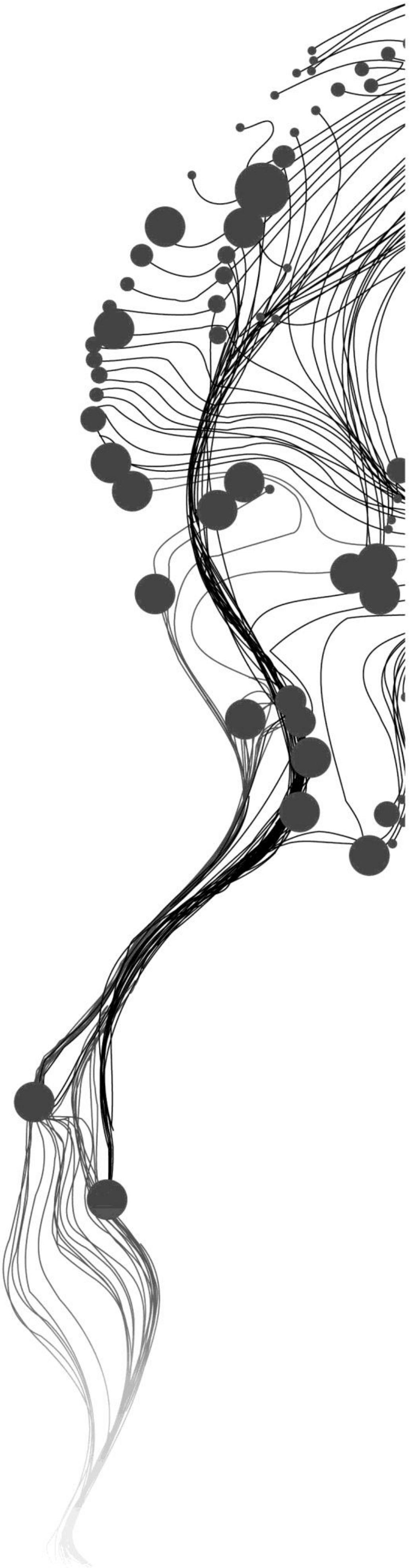

WEATHERING RATES OF ROCK AND SOIL MASSES IN YEN BAI CITY, VIETNAM

ADETORO ADEYEMI EZEKIEL
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Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
Specialization: Applied Earth Sciences (Geo and Environmental Engineering)

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ABSTRACT

Weathering of rock masses, which start from the moment of exposure of a rock mass (e.g. through cutting of slopes) has a large influence on the geotechnical properties of a rock mass within the engineering timescales and is one of the main causes of slope failure, which is occurring presently in Yen Bai City in Vietnam. This called for the need to determine the rate of weathering of the mainly already deeply weathered tropical rock and soil masses of Yen Bai city area, which would allow better design of slopes. Fifteen cut slopes are selected out of inspected thirty – five cut slopes of AR?nc1 and AR?nc2 geological formations of the area and analyzed using Slope Stability Probability Classification (SSPC) and Colman's formula based methods. The SSPC method is used in acquiring the basic geotechnical parameters of the selected cut slopes and in analyzing them to determine their slope stability and other derived geotechnical parameters like cohesion and friction of the rock mass unit (i.e. SCOH and SFRI). The analyses using the two methods are carried out under two perspectives – rock mechanics and spatial analyses. Results show that SCOH and SFRI reduces as exposure time of cut slope increases, and the higher the SCOH and SFRI, the better the slope stability. There is also change in degree of weathering over some years of exposure of rock mass though might not be visible until after 20 years. It also shows that some materials are susceptible to weathering than others within the rock mass materials and between two geological formations. Generally, a comparison of weathering rate of rock mass between Yen Bai tropical and Mediterranean region (where SSPC was developed) shows that weathering rates are much higher in tropical than in the Mediterranean region as expected. A slope in the Yen Bai area is generally made at the maximum angle and slope height that can be sustained in the material at the time of exposure for the top soil layers. In the deeper layers, i.e. in slightly or moderately weathered material, the angle and slope height are not at the maximum at time of exposure, but progressive weathering due to exposure will weather these materials to highly or completely weathered in about 30 years. The slope angle and height cannot be sustained by highly or completely weathered material and the slope will fail.

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Above it all, I acknowledge Almighty God, all glory and thanks go to HIM, the author and finisher of my fate. "Every battle of a warrior is full of confused noise and the garment rolled in blood, but I shall end the battle like a gold refined, by His special Grace..."

DEDICATION

“I shall make it by trust not in my own understanding, but by trust in the Lord God Almighty” – Proverbs 3: 5 – 6.

This thesis is dedicated,

Above all, to GOD ALMIGHTY;
To my lovely wife, DASOLA;
To my lovely children, EMMANUEL and JOSHUA.

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LIST OF SYMBOLS AND ABBREVIATION

φ_{disc}	Angle of internal friction of discontinuity (ies) in a rock mass (unit of measure: degree)
φ_{mass}	Angle of internal friction of a rock mass (unit of measure: degree)
φ_{RRM}	Angle of internal friction of reference rock mass (unit of measure: degree)
φ_{SRM}	Angle of internal friction of slope rock mass (unit of measure: degree)
δ	Difference between dip directions of slope and discontinuity (unit of measure: degree)
AP	Apparent angle of dip of a discontinuity in the direction of the slope dip (unit of measure: degree)
CD	Parameter for the weighted overall condition of a number of discontinuity sets in a rock mass (no unit)
COH_{disc}	Cohesion of discontinuity (ies) of rock mass (unit of measure: Pa or KPa)
COH_{mass}	Cohesion of rock mass (unit of measure: Pa or KPa)
COH_{RRM}	Cohesion of reference rock mass (unit of measure: Pa or KPa)
COH_{SRM}	Cohesion of slope rock mass (unit of measure: Pa or KPa)
CON_{mass}	Parameter for the overall condition of a number of discontinuity sets in a rock mass
CW	Completely weathered of a rock mass (no unit)
DEM	Digital elevation method
DS	Characteristic spacing between the discontinuities in one discontinuity sets in a rock mass (unit of measure: metres)
e	Natural base of logarithms (constant)
ERM	Exposure rock mass
H_{max}	Maximum possible height of a slope if SFRI is lower than the slope dips (unit of measure: metres)
H_{slope}	Height of a slope (unit of measure: metres)
HW	Highly weathered of a rock mass
lm	Parameter for discontinuity infill material in an exposure rock mass unit
IRS	Intact rock strength of an exposure rock mass unit (unit of measure: MPa)
Ka	Parameter for karst along a discontinuity in an exposure rock mass unit
ME	Parameter for the method of excavation used for an exposure rock mass
MW	Moderately weathered of a rock mass
OIS	Orientation independent stability of a slope of rock mass (unit of measure: %)
$R_{app(WE)}(COH)$	Weathering rate in term of cohesion of rock mass
$R_{app(WE)}(FRI)$	Weathering rate in term of friction of rock mass
$R_{app(WE)}$	Weathering rate in term of degree of weathering of rock mass
RCD	Parameter for the weighted overall condition of a number of discontinuity sets in a reference rock mass unit
∇RCOH	Change in cohesion of a reference rock mass (unit of measure: Pa or KPa)
RCOH	Cohesion of a reference rock mass unit (unit of measure: Pa or KPa)
$RCOH_{init}$	Cohesion of a reference rock mass at time of excavation (unit of measure: Pa or KPa)
RCOH (t)	Cohesion of a reference rock mass after time t (unit of measure: Pa or KPa)
RS	Residual soil of a rock mass
∇RFRI	Change in angle of internal friction of a reference rock mass (unit of measure: degree)
RFRI	Angle of internal friction of a reference rock mass unit (unit of measure: degree)
$RFRI_{init}$	Angle of internal friction of a reference rock mass at time of excavation (unit of measure: degree)
RFRI (t)	Angle of internal friction of a reference rock mass after time t (unit of measure: degree)
RIRS	Intact rock strength of a reference rock mass unit (unit of measure: MPa)
Rl	Parameter for the large scale roughness of a discontinuity in an exposure rock mass unit

RRM	Reference rock mass
Rs	Parameter for the small scale roughness of a discontinuity in an exposure rock mass unit
RSPA	Parameter for the overall spacing of a number of discontinuity sets in a reference rock mass unit
RTC	Parameter for the condition of a discontinuity (set) in a reference rock mass unit
SCD	Parameter for the weighted overall condition of a number of discontinuity sets in a slope rock mass unit
∇SCOH	Change in cohesion of a slope rock mass (unit of measure: Pa or KPa)
SCOH	Cohesion of a slope rock mass unit (unit of measure: Pa or KPa)
$SCOH_{init}$	Cohesion of a slope rock mass at time of excavation (unit of measure: Pa or KPa)
SCOH (t)	Cohesion of a slope rock mass after time t (unit of measure: Pa or KPa)
SD	Slope dip (unit of measure: degree)
SDD	Slope dip direction (unit of measure: degree)
SD_{disc}	Dip of discontinuity (unit of measure: degree)
SDD_{disc}	Dip direction of discontinuity (unit of measure: degree)
∇SFRI	Change in angle of internal friction of a slope rock mass (unit of measure: degree)
SFRI	Angle of internal friction of a slope rock mass unit (unit of measure: degree)
$SFRI_{init}$	Angle of internal friction of a slope rock mass at time of excavation (unit of measure: degree)
SFRI (t)	Angle of internal friction of a slope rock mass after time t (unit of measure: degree)
SIRS	Intact rock strength of a slope rock mass unit (unit of measure: MPa)
SME	Parameter for the method of excavation used for a new slope
SPA	Parameter for the overall spacing of a number of discontinuity sets in an exposure rock mass unit
SPA_{mass}	Parameter for the overall spacing of a number of discontinuity sets in a rock mass
SRM	Slope rock mass
SSPA	Parameter for the overall spacing of a number of discontinuity sets in a slope rock mass unit
SSPC	Slope stability probability classification system
STC	Parameter for the condition of discontinuity (set) in a slope rock mass unit
Std error	Standard error or deviation
SWE	Parameter for the degree of weathering of a slope rock mass unit at the end of the engineering lifetime of a slope
SW	Slightly weathered of a rock mass
t	Exposure time of slope (unit of measure: years)
TC	Parameter for the condition of a discontinuity (set) in an exposure rock mass unit
TOPP	Toppling due to discontinuity in a slope of a rock mass
WE	Parameter for the degree of weathering of an exposure rock mass unit
∇WE	Parameter for the change in degree of weathering of an exposure rock mass
WE_{mass}	Weathering parameter for a rock mass unit
VES	Visually estimated stability of a slope of rock mass.

1. INTRODUCTION

1.1. Research backgound

Rock mass is simply defined by ISO (2003) as "the rock together with its discontinuities and weathering profile". The rock mass was broadly defined by Hack (1998) as "collection of rock blocks with discontinuities, with or without inhomogeneity and with anisotropy" (i.e. different properties in different directions). Exposure of rock mass through slope's excavation will trigger action of rock mass degradation agents (weathering, erosion and other surface processes) and therefore makes the question of that slope's stability a matter of time (Huisman, 2006). Slope instability of a rock mass can also be as a result of change in geometry (Kekeba, 2008).

Slope stability is a concept which shows the ability of a slope to repel failure due to mass movement under various factors and human influences (Kuruwita, 1992). The significance of understanding and analyzing rock and soil weathering with time in slope processes will help in designing stable slopes along infrastructures , also affects urban developments, human safety in settlements and reduction of future hazards (Huisman, 2006). The major geotechnical properties that governed the rock and soil slope stability are the strength characteristics of the rock, the geometrical and strength characteristics of the discontinuities (e.g. roughness, strength of wall, infill materials and persistence) and the effects of weathering on the intact rock and discontinuities. There is always need for recurrent assessment of strength and deformability of rock mass in geotechnical studies. However, the assessments is demanding or challenging if the rock mass in question is affected by weathering (Gupta & Rao, 2001).

There are different definitions of weathering in use, for a part depending on the purpose for which the definition is made. A description of weathering is "the breakdown and alteration of rocks and minerals in Earth's surface layer and the product is "regolith" (Pidwirny, 2006). Scott and Pain (2008) defined regolith as "the whole loosened or consequentially re-compacted cover that is on top of existing bedrock and which is created by weathering, erosion, transport or deposition of older material. It includes fractured and weathered basement rocks, saprolites, soils, organic accumulations etc. It could simply be defined as the whole thing from unweathered rock to fresh air".

Other definition of weathering are as follows: Rock weathering causes physical disintegration, chemical decomposition and weakening of rock mass structure which successfully helped the breakdown processes(Bell, 2000). Price (1995) described weathering as "One of the greatest sources of potential difficulties in geotechnical engineering". Moreover, Huisman (2006) stressed that it greatly alters material and mass engineering properties that are usually difficult to forecast. He explained further that a definite reaction is usually demonstrated by a rock and soil mass to weathering-controlling factors at its exposure location. Hack (1998) defined the degree and rate of this reaction as the "susceptibility of a rock mass to further weathering in the future". This notion is regarded as "the weathering rate of rock mass". Weathering could also be defined as the chemical and physical change in time of intact rock and rock mass material under the influence of the atmosphere and hydrosphere". This has to do with a decrease in block size, increase in frequency of discontinuities and permeability, and decrease in shear strength along discontinuities. The outcome of physical weathering is the "breakdown of rock materials into progressively smaller fragment", while the outcome of chemical weathering is "decomposition of minerals" (Hack, 1998).

Weathering ultimately converts rock to a soil mass and the weathering profile was described in terms of three basic units: rock, rock – and – soil, soil. This was subdivided into scale of six different weathering stages of rock mass - fresh, slightly, moderately, highly, completely weathered and residual soil with grade

I to VI respectively. The intact rock are blocks of rock with tensile strength and do not contain mechanical discontinuities. Weathering of intact rock causes material discolouration and intact rock strength reduction. Continuous weathering of rock mineral and cement will result in disintegration of intact rock (and eventually in a residual soil). The degree or state of weathering is the state of weathering of a specific rock mass or geotechnical unit at a particular instant (moment) and susceptibility of weathering is the exposure of rock mass to further weathering in the future (BS5930, 1981/1999; Hack, 1998; ISO, 2003).

Soil is an unconsolidated collection of solid particles in which there are voids that contains water or air or both. It is derived from the breakdown of rock material by weathering and/or erosion (Bell, 2000). McKenzie et al. (2005) defined it as "organically affected upper part of the regolith formed by the interactions between the mineral material of the regolith and organic matter derived largely from vegetation growing in the regolith. Rock debris of all kinds, including weathered rock in place, alluvium, colluvium, aeolian deposits, volcanic ash, and glacial till". It is the final part of product of weathering.

1.2. Research problem

The stability of slope is highly significant because its failure will threaten the safety of people. Slopes failures occur throughout the world, causes economic problem and loss of lives. Weathering is one of the obvious factors that usually causes slope failure by weakening (through chemical or physical processes) of a rock mass in terms of geotechnical applications (Huisman, 2006). A city like Yen Bai has rock masses that are greatly influenced by chemical weathering, which reduced them to loose, crinkle and crumble tropical soils. The fault system and soils make the city prone to development of landslide (Doan, 2004). The needs for more suitable land around the city for construction of infrastructure like roads and building due to rapid urbanization resulted in cutting and exposure of the rock and soil masses in the area (fig. 1.1). Weathering process will start acting on the newly cut and exposed slope materials due to stress released among others, after excavation. The exposure of the cut slopes to weathering and future weathering after construction is / will be the main causes of their failure during their engineering lifetime if there are no geometry change (Hack, et al., 2003; Huisman, 2006).

Figure 1.1: Exposed rock and soil masses through cutting of slopes in the research area

From observation (fig. 1.1 and appendix 1), since there are many cut and exposed slopes in Yen Bai city and the area is also in the tropical region where the effect of climate is very high which resulted in extreme chemical weathering, there is high possibility of slope failure. This could cause great hazards and loss of lives and properties; hence, there is need to carry out thorough study in order to understand and analyze the slope stability, degree and rate of weathering of the rock or soil masses for estimation of future stability, increase human safety, forecast future degree of weathering and reduction of future hazards.

1.3. Research objective

The thesis work will address the following general and specific objectives.

1.3.1. General objective

The general objective of this thesis is to determine the rate of weathering of the deeply weathered tropical rock and soil masses' slopes that have been recently exposed in Yen Bai city of Vietnam. This will help in knowing the weathering influence and deriving a standardized method in determining the degree and rates of weathering for the area; hence in predicting the present weathering rate, future degree of weathering with time for the slope and to forestall slope instability that could result in hazard for the area.

1.3.2. Specific objective

- To establish the relationship between degree of weathering of the slope and its exposure time using one or two of the existing method(s) in deeply weathered tropical rock and soil masses of Yen Bai city.
- To analyze if exposure of rock and soil masses over period up a few dozen years can cause difference in degree of weathering in the area.
- To assess the slope stability of the selected rock and soil masses' slopes.
- To investigate if susceptibility to weathering between two geological formations and within the materials of the selected slopes, can be determined from field observations.

1.4. Research questions

- Which of the existing methods will be used to establish the relationship between degree of weathering of slope and its exposure time in the above stated deeply weathered tropical rock and soil masses?
    - Which parameters will be adopted in order to use the method (s) in analyzing different degree of weathering in the tropical rock and soil masses?
    - Is there provision for these changed parameters or how will these parameters be changed?
- Does the time of exposure of a slope over periods up a few dozen years cause a difference in degree and rate of weathering of a rock mass in the tropical region?
    - How does the weathering profile of selected slopes look like? Does it look like that of Mediterranean region where SSPC was propounded or how is it different?
    - What are the engineering characteristics / properties of rock and soil mass slopes of tropical region?
    - What are the general effects of environmental conditions on the selected slopes?
    - What are the relationship among the properties of the rock and soil mass and the effect of weathering on them?
    - What is the rate of weathering for the tropical region selected slopes? (to be determined)
- How stable are the slopes of the rock and soil masses?
- Whether the difference in susceptibility to weathering between two geological formations and within the materials of the selected slopes can be determined from field observations?

1.5. Research hypotheses

- **For research question 1:** The existing method to be used is SSPC. Then followed by Huisman (2006) formula (derived from Colman (1981) formula). SSPC makes use of stipulated values for rock material weathering condition, spacing (SPA) and condition (CD) of discontinuities, and weathering depth in classifying different degree of weathering and expressed as values in accordance with BS5930 (1981/1999) . These weathering classification and method of excavation values / parameters are derived using Monte Carlo simulation and used to improve / offset the effects of local weathering and method of excavation on IRS, SPA and CD. Factors for SPA and CD parameters were also derived using Monte Carlo simulation.

In general, in SSPC method, the basic parameters used are IRS, SPA and CD, method of excavation and degree of weathering. For the soil part of the deeply weathered tropical regolith, which has no joint, the discontinuity spacing will be the thickness of bedding, fissures or shear plane of the soil while the condition of discontinuities will be the soil's surface texture.

- **For research question 2:** The time of exposure of a slope over period up a few dozen years will cause difference in the degree of weathering in tropical region because the effect of climate i.e. water (moisture content) and temperature are high. This makes chemical weathering (i.e. ion dissolution, hydrolysis and oxidation) to be extreme and rate of weathering becomes high. Hence, change in degree of weathering. The regolith will be rapidly developed and depletion of minerals will happen. There usually will be very thick regolith in this region. Parameters like degree of weathering, spacing and condition of discontinuities increases with depth while IRS reduces with depth upward from fresh rock.

  Since the regolith will be very thick in the tropical region, the degree of weathering could be reclassified to accommodate difference in the regolith layers and the weathering profile as whole. The reclassification will be done using change in colour and texture to identify each layer. The other materials and mass characteristics of the soil will then be taken to notice the difference (Mckenzie, et al., 2005).
- **For research question 4:** A rock mass with lot of discontinuities will weather more rapidly than the one without discontinuities. Susceptibility to weathering depends on clay content, IRS, grain size, rock mineral composition and discontinuities. The higher the rock strength, the less the clay content and susceptibility to weathering. The smaller the grain size, the greater the chemical bonding and the less the susceptibility to weathering (Bell, 2000; Huisman, 2006; Selby, 1993).

1.6. Data sources

The data for this work are gathered from the fieldwork, previous and present relevant available data and literature works.

1.7. Study area

1.7.1. Location and Topography

Yen Bai province has an area of approximately 6,890 km^2 and is situated in the eastern part of Hoang Lien Mountains of North Vietnam at the highlands and midlands' changeover. Yen Bai city, where the research work is carried out, has an area of approximately 56 km^2 and is a distinctive mountainous municipality of Yen Bai province in North Vietnam. It is between latitudes 21^{0}40' to 21^{0}46' north and longitudes 104^{0}50'08" to 104^{0}58'15" East (fig.1.2) (Vinh & Hoanh, 2004).

Yen Bai topography has an average height of 600 m above sea level. The major rivers in the province are Chay, Da, and Red river (the biggest river in North Vietnam. The city is situated on the alluvial plain of the Red River and extends into the hills, north of the river. The hilly topography, upon which the northern part of the town is situated, is in northwest – southeast direction with average elevation above 60 m above sea level and comprises of several hills and mountains. The valley topography spreads among the hilly topography and stretch along the stream valleys with average elevation between 28 and 35m (above sea level). While the alluvial plain lies at the bottom of the hill and mountain along both sides of the Red river with average height of 28 – 50m above sea level (fig.1.3) (Vinh & Hoanh, 2004).

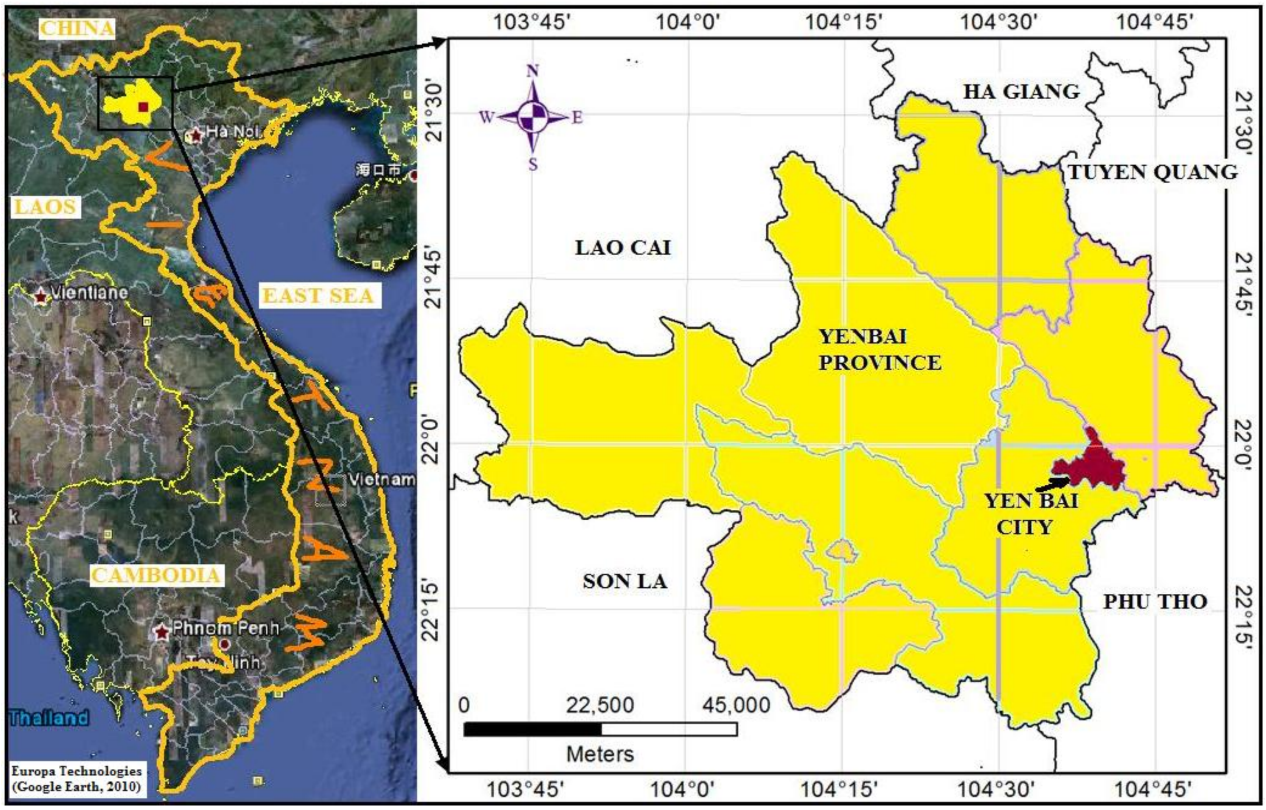

Figure 1.2: Location of the research area - Yen Bai City (left after Europa Technologies, 2010; right after Vinh & Hoanh, 2004)

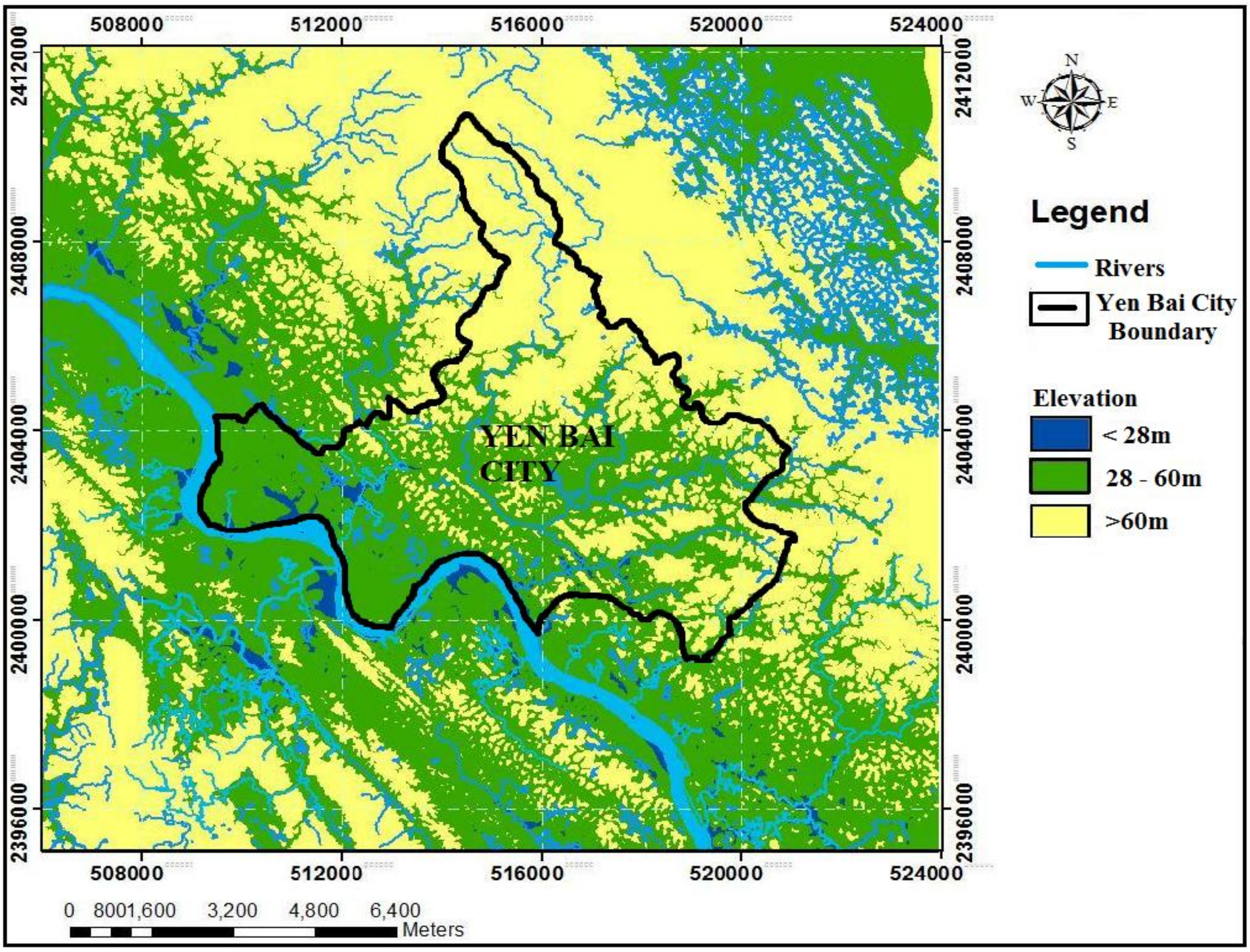

Figure 1.3: The topography of the research area – Yen Bai City (after Vinh & Hoanh, 2004)

1.7.2. Climate

The climate in the Yen Bai province is tropical monsoon and is divided into two seasons - cold and hot seasons. The cold season is between November and March, while the hot season is between April and October. However, there is usually slight change in the climate due to effects of mountainous topography, which resulted in humid summer and less cold winter. The annual rainfall varies from 1,462 to 2057mm with average monthly rainfall ranges between 28 and 390mm. The highest rainfall period of the year occurs between months of May to October, while the lowest rainfall period occurs between November and March (fig. 1.4). The average annual humidity is from 83 to 87% while the annual average temperature varies from 18^{o}C to 28^{o}C (Viet Nam Travel Blog, 2010).

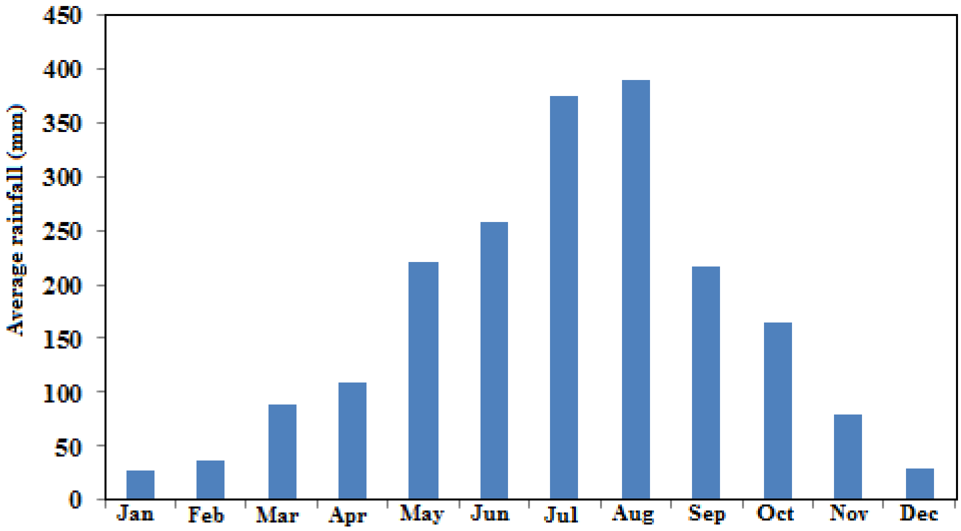

Figure 1.4: Average monthly rainfall for Yen Bai province (1994 - 2004)(after National Center for Hydro-Meteorological Forecasting, Vietnam)

1.7.3. Geology

Vinh & Hoanh (2004) described the geological formations in the Yen Bai Province as follows[1]:

- *Paleo-Proterozoid (AR?nc1, AR?nc2, ARnv1 and ARnv2) formations* – It spreads along the banks of the Red River and follows the direction of the river (northwest - southeast). This formation comprises of *biotite-silimanite-garnet, plagiogneiss, amphibole gneiss, amphibolite, garnet, gneiss diopsite graphite, quartzite and schist-biotite-silimanite-garnet materials.*
- *Paleo-Proterozoid - Meso-Proterozoid (PP-MPnc; $2hg1 and P%2th) formations* – It spreads as tiny portions in the north of the town. This formation comprises of *quartz-biotite-silimanite-garnet schist, biotite-garnet-silimanite schist, amphibolites, quartzite and marble materials.*
- *NeoProterozoid (gaD1Sc and PR3-$1tb1) formations* - It is situated in the northeast of the town around Thac Ba man-made Lake area. This formation comprises of *quartz-phlogopite-biotite schist, quartz two-mica-garnet schist combined with quartzite and muscovite marble materials.*
- *Devon (D1bn and D1sm) formations* – It is situated in the southwest of the town along the bank of the Red River. This formation comprises of *clay shale, quartzite, limestone, and siltstone materials.*
- *Neogen (N13cp, N13pl and N21vy) formations* – It spreads along the sides of the Red River. This formation comprises of *conglomerate, gravel stones, clay shale, coaly shale and coal lenses materials.*
- *Quaternary (N2-Q1, a-apQ1V3, aQIII, aQIV1-2 and aQIV2) formations* – It spreads along the banks of the Red River, around Thac Ba man-made lake and some small stream valleys. This formation comprises of *soft sediments, pebble, granule, clayey sand, and organic materials.*
- *Magma (#2PR1ca, vPR1ca and %1}th) complex* – It consist of some small blocks along the Tan Huong -Thinh Hung fault. The formation comprises of *gabbros, gabbro olivine, biotite granite, porphyritic biotite granite.*

[1] The symbols and question marks in the formation names are according Vinh & Hoanh, 2004, and not a printing error.

- *Faults* – They are easily noticeable along the northwest-southeast zone. The faults are Red River fault, *Thac Ba fault, Tan Huong - Thinh Hung fault, Dao Thinh - Van Lang fault and Quy Mong Au Lau fault*. The Red River fault consists of submerged blocks filled with Neogen residues. It has a number of fracture zones, weathered rock and soil masses and very vulnerable to landslides due to its previous events.

The geological formations present in the Yen Bai City area (fig.3.2) are as follows:

- *Paleo-Proterozoid formations* – which are AR?nc1, AR?nc2 and ARnv2.
- *Paleo-Proterozoid - Meso-Proterozoid formation(s)* - which is P%2th.
- *Neogen formation(s)* – which is N13cp.
- *Quaternary formations* – which are a-apQ1V3, aQIII, aQIV1-2 and aQIV2.
- *Magma complex* – which are vPR1ca and %1}th.
- *Faults* – which are Red River fault, Thac Ba fault, Tan Huong - Thinh Hung fault, Dao Thinh - Van Lang fault and Quy Mong Au Lau fault.
- The area is prone to level eight (six Richter degrees) earthquake in accordance to earthquake zonation mapped by Vietnam Institute of Geosciences and Mineral Resources (VIGMR).

1.8. Thesis layout

The thesis is divided into seven chapters. The first chapter deals with the general introduction of the study. It consists of the research background, research problem, data sources, research objectives, research question and hypotheses, data sources and study area description i.e. location, topography, climate and geology).

Chapter two deals with literature review. This comprises of general concepts and review of related research works on weathering and its effects on slope stability of rock and soil masses.

Chapter three deals with methodology. It consists of description of methods and procedures used in carrying out the study in four main phases namely: pre-fieldwork, fieldwork, post-fieldwork analysis, and interpretation and discussion.

Chapter four deals with fieldwork. It describes all the field data acquired on the cut slopes during fieldwork.

Chapter five deals with rock mechanics analysis and interpretation of the data acquired from fieldwork for slope stability and rate of weathering assessment purpose. It is the first part of post fieldwork phase.

Chapter six also deals with assessment of slope stability and rate of weathering using spatial analysis. It is the second and last phase of post fieldwork phase. It also deals with interpretation and discussion of the derived results.

Chapter seven of the thesis deals with the conclusions drawn and recommendation for further study or research works based on the results of the findings.

2. LITERATURE REVIEW

2.1. Rock masses degradation in cut slopes

"A slope is usually made up of rock materials with different geological origin and lithological complex. The outcome of formation and consequent events on various rock materials and their alteration products is the variation of its weakness and strength. Weak bond between rock mineral components usually results in weak (er) rock and vice versa. This shows that the rock materials strength depends on mineral component and the nature of the bond between the mineral made of the rock unit (Kekeba, 2008). Slope stability becomes questionable after few days the slope is made (cut) due to the effect of degradation agents/processes on the slope and the rock mass as a whole right from that day.

Rock mass is usually exposed to different degradation agents / processes (which are very difficult in nature due to the factors (table 2.1) controlling them) as a result of natural and artificial (man-made) slope (s) on it. Huisman (2006) implied that waning of the rock mass is the beginning of rock mass degradation while breakdown and complete deterioration (decay) is its end. The processes of the degradation based on the engineering timescales are in three phases namely:

- Relaxation or redistribution of stress and strain, which resulted in structural reliability failure;
- Weathering of the slope materials and
- Successive erosion of the slope material – this will not be discussed in this thesis (Huisman, 2006).

2.1.1. Relaxation or redistribution

This process unequivocally happens progressively after excavation of the rock mass from days to months. There is accessibility to water in the rock due to slight opening of discontinuities. It also resulted in decrease in friction resistance and normal stress on discontinuity planes. This process is of two types – primary and secondary relaxation.

2.1.1.1. Primary relaxation

This process occurs immediately after slope's excavation and is due to excavation itself. It always has effect on weathering and erosion throughout all the processes. Huisman (2006) expressed many researchers' view on this relaxation as rebound (Ollier, 1975); flexible relaxation and extensive recuperation when overload stress in the fundamental strata is decreased due to rock masses' excavation (Wetzel & Einsele, 1991). This stress distribution (decrease in overload and restraint horizontal stresses of original rock mass of the slope) due to slope excavation is likely to become anisotropic.

Some concurrent consequences happen which usually affect each other. These are increase in volume, porosity and permeability of the rock material (increase in porosity and permeability is because of micro cracks' development in cemented material), change in running water flow paths and decrease in normal stress in discontinuity planes which resulted in their aperture increment. Other effects include non-fitting and breaking of asperities due to shear displacement along discontinuities, blocks' rotation, shear stress introduction due to unbalanced elastic expansion of intact blocks and subsequent fracturing of intact rock (Huisman, 2006). Many significant changes happen in the rock mass characteristics due to above-mentioned consequences, which are:

- Permanent or irrevocable distortion of rock mass due to combination of decrease in effective friction angle and cohesion of the rock mass discontinuities as results of non-suitability of discontinuities and asperities' shearing, destabilisation of the rock mass due to decrease in normal stress on discontinuity planes; and steepening of existing topography by excavation.
- More accessibility of weathering agents (i.e. possibilities of chemical weathering e.g. solution, and physical weathering e.g. wetting and drying) into the rock mass due to expanding aperture and shear displacement along discontinuities which causes increase in hydraulic conductivity of discontinuities and

fostering of water circulation and penetration. Influence of the presence of water and subsequent actions during rock mass' wetness also extends further into the rock mass (Huisman, 2006).

Table 2.1: Factors controlling rock masses' degradation (after Huisman, 2006)

	PARAMETER	INFLUENCE
Internal	Material composition	The influences and significance of chemical weathering processes is largely determined by the type of materials present in association with the site-specific conditions. Minerals composing rock masses are differently affected by weathering.e.g. some minerals are unstable under surface conditions with low stress levels or the influence of water or temperature when exposed. The presence of (even small) amounts of swelling clays greatly increases the weathering susceptibility.
	Material fabric	The material fabric also determines the means of access for the weathering agents.e.g. void space in the material that is accessible for water increases weathering susceptibility. In weak materials, the material fabric also directly influences erodibility.
	Influences of water	The specific influences of water greatly depend on the material composition.For example, in the presence of soluble components (e.g. gypsum), prolonged availability of water and water retention enhance degradation; in the presence of slaking components (e.g. swelling clays), periodic changes in water content enhance degradation. The availability of reactants for chemical reaction depends partially on the composition of the water phase (reactants may also be derived from the solid materials in the rock, or from gas phases).
	Permeability	Permeability influences the penetration depth of inflowing atmospheric water as well as the rate of groundwater flow. In general, an increase in permeability is associated with an increase in degradation rates.
	Discontinuities (aperture, orientation, persistence, permeability)	The discontinuities determine rock mass strength, as well as the permeability and other hydrologic properties of the rock mass. In combination with the slope orientation and angle, their orientation determines the inflow conditions for infiltration of overland flow.
External	Climate	Climate conditions (temperature, precipitation) are for a large part responsible for determining degradation conditions in specific sites. In the past, average climatic condition were thought to be determining but present insights show that micro-conditions on a slope are of far more influence than originally thought.
	Morphology	The local topograpghy and in a more general sense the site morphology influence stress levels in slope, overland flow discharge, inflow conditions, groundwater flow etc. The morphology directly above the slope will furthermore influence weathering penetration rate.
	Hydrology	In combination with the internal parameters listed above, hydrological conditions influence both type and rate of prevalent degradation processes, both in terms of weathering and erosion.
	Chemistry of rain and ground water (acidity and alkalinity , redox potential, oxidizing or reducing	The chemical properties of rain and ground water determine for a large part the available resources for chemical reactions and hence the prevalent chemical weathering processes. They are influenced by air pollution (e.g. Winkler, 1997), proximity to the sea (Neil, 1989; Inkpen and Jackson,2000), and local factors such as vegetation cover on the slope itself and the above hillside.
	Biochemical influences	The influence of biochemical factors such as lichens is complex and is described in the main text in more detail
	Geological history	The development of weathering profiles in the geological past influences the slope development in present time. This is true both in terms of observed degree of weathering and mechanical development, since historical weathering and associated weakening reduce slope stability. It has to be noted that the weathering environment in the geological past may have been very different from today.
Geotechnical	Slope orientation, geometry and height	These parameters determine the intersection of the slope with the local morphology and geology, thereby influence the boundary conditions for degradation processes. Furthermore, the slope aspect determines the exposure to the prevalent wind directions as well as to solar radiation; type and amount of vegetation cover is in its turn a derivative of this.
	Excavation damage	Opening of existing discontinuities, cracks and discontinuities formed during excavation, determine internal parameters such as aperture or "openess" of discontinuities, permeabiltiy etc.
	Remedial measures	Any remedial measures incorporated in the slope design determine degradation processes, their rates, intensity and effects.
	Land use	Agricutural land use influences weathering processes as shown by Semhi et al. (2000). For example,the use of fertilizers may very well influence natural weathering-erosion processes.

2.1.1.2. **Secondary relaxation**

This process contains considerable outcomes as the above-described primary relaxation and is caused by weathering and erosion influences as a result of continuing changes in material strength, density and volume, slope angle and morphology, stress-strain distribution (It is even a continuous process after the initial influences of main stress release during excavation have degenerated). Hence influences the degree and rate of weathering and erosion processes (and balance between the two), which happen in a cut slope. Its time scale operation is also similar to that of weathering and erosion, and more extent than that of primary relaxation. A general result of secondary relaxation is creep, which is very complicated in quantification (Huisman, 2006).

2.1.2. Weathering

Weathering usually takes place on the exposed surfaces i.e. road cuts, excavation and discontinuities' walls (slope surfaces). This has to do with block sizes' reduction and rate of occurrence of discontinuities' become high. Existence of discontinuities is usually the channels or means used by the weathering agents to penetrate into the rock masses and the initial influences of weathering are usually seen along discontinuities surfaces or the surrounded wall surface region. Weathering then progresses deeply into the rock masses to develop marked heterogeneity of comparative unweathered materials within highly weathered materials and eventually this can make the whole rock mass to reduce to residual soil. Weathering mainly result in reduction of density and strength, and distortion increment. The early set in of weathering usually causes regular increment in mass permeability because of cracks' occurrence and permeability reduction when clay minerals are produced (Bell, 2000; Kekeba, 2008).

Consequently, there is usually reduction in intact rock strength, shear and tensile strength along the discontinuities. The effects of weathering on rock mass will also be felt on its stability as it become unstable with time (Huisman, 2006). Generally, this comprises of different processes with hydrosphere and atmosphere effects, though, the processes may take time (hundred to thousand years) (McSweeney & Grunwald, 1999). Price (1995) expressed the influences of weathering as "the irreversible response of soil and rock materials and masses to their natural or artificial exposure to the near-surface geomorphological or engineering environment". This is attained by weathering processes, which are determined by the type of new environment of the geological materials.

2.1.2.1. The processes of weathering

There are three types of weathering processes namely:
- ✓ Mechanical (physical) weathering,
- ✓ Chemical weathering and
- ✓ Biological weathering

1. Mechanical (physical) weathering

Mechanical weathering can be defined as the process whereby rock materials or minerals are totally disintegrated by mechanical means which could be interior influence (stress) within or exterior influence (stress) exerted on the rock materials/minerals. Either of these stresses usually results in tension and cracks / fissure of the rock mass (Pidwirny, 2006). Different factors (which are grouped into cyclic and static processes) like water uptake and successive expansion, change in temperature or thermal expansion and salt crystal development in the rock pores could cause the process. The mechanical weathering cyclic processes are wetting and drying, heating and cooling, freezing and thawing; while mechanical weathering cyclic processes are crystallization, abrasion and pressure release/spalling (Bell, 2000; Kekeba, 2008; Pidwirny, 2006).

- **Wetting and drying**

Recurrence wetting and drying of rocks (can also be called "slaking") due to expansive force of water which happened when continuous layers of water molecules are build up between the mineral grains of rock can be a disruptive effect, most especially in weak rocks. The rock mass usually falls apart with vast tensional stress due to the increasing water depth (Pidwirny, 2006). Kekeba (2008) expressed some rock properties that are more affected by wetting and drying cycle as:
- presence of clay minerals which foster water adsorption;
- structural weaknesses e.g. discontinuities;
- Pore size distribution.

- **Heating and cooling**

Heating and cooling illustrate situation in which change in rock mass is caused by expansion and contraction due to daily variation in temperature. This is called "Insolation weathering"- due to weak or bad conduction of heat's nature of rock (Pidwirny, 2006). Distinctive cyclic expansion and contraction in favour of the exterior layers of rocks usually result in crack or splitting up of the rock (the term is called "exfoliation"- breaking of fragment away from the parent rock material). This is more intense and can lead to granular breakdown in hot semi-arid than every other regions (Bell, 2000).

The distinctive cyclic expansion and contraction can also be because of disparity in the colours of rock mineral grains, which is mainly based on the inner temperature of the rock. The darker the colour of the grains, the more the expansion (due to the absorptive nature of the colour). This usually causes different rates of cracks at different boundary in a rock mass with many various coloured grains (Kekeba, 2008; Pidwirny, 2006).

- **Freezing and thawing**

Cyclic freezing –thawing process is usually part of the basis for widening of rupture, joints and fissures (i.e. discontinuities), pore spaces and other openings which in turn breakdown the rock masses. Volume expansion (increase in volume up to 9%) usually occurs when water becomes ice, hence resulted in pores pressure increment. Number of freeze-thaw cycles as well as rock grains is of immense significant for weathering process. Coarse-grained tolerate freezing than fine-grained rocks, which in turn means weathering is very high in fine-grained than coarse-grained rocks during this process. The temperature usually fluctuate around -22^{0}C for effective cyclic freeze-thaw process (Bell, 2000).

- **Abrasion**

Abrasion is as a result of contact between two rock surfaces (due to some influences) causing mechanical crushing /wearing / tearing on the surfaces during transportation of rock materials by wind, water or ice (weathering agents) (Pidwirny, 2006). The consequence is glaring and high along discontinuities if there is distortion in the entire rock mass and the measure is minute during erosional transportation (Kekeba, 2008).

- **Crystallization**

Crystallization (static) process is related to freezing (cyclic) process and can also cause stresses required for cracks and widening of openings in rocks and minerals due to alteration of compounds or elements with temperature's variation. The breakdown of rock mass, which is caused by exertion of extra pressure and crystals' development, is as a result of the above-mentioned process (Kekeba, 2008; Pidwirny, 2006). The crystallization process is not only governed by temperature variation, but also the relative humidity, rock or mineral surface and the degree of super saturation of the solution formed by the compounds or elements (Bell, 2000). The crystals' development (whether ice or salt) display change in volume which could be from 1 to 5% during crystallization depending on the above-mentioned factors. This process is conversant with hot arid regions, though it could also happen in cold climates (Pidwirny, 2006).

- **Pressure release/spalling**

This process is caused by unloading of overlaying materials and less subjection to pressure (because of erosion) of exposed rock masses that are formed under high pressure at high depth. There is stress-strain distribution and change in volume throughout the rock masses due to the unloading. The result is of two views. The first view is the horizontal rupture which increase as the rock mass is becoming exposed to the earth surface while the second view is the vertical growth of ruptures which happen due to bending stresses of the unloaded strata of rock mass from corner to corner of a three dimensional plane. The latter is called "spalling" (Kekeba, 2008; Pidwirny, 2006).

2. Chemical weathering

Kekeba (2008) defined chemical weathering as "disintegration or decomposition of minerals by chemical reaction with water, with other chemicals dissolved in water, or with gases in air". He stressed further that the degree of chemical weathering is governed by vulnerability of rock mass to chemical weathering, which is a role of the properties of rock material i.e. texture, porosity, mineralogical composition, and existence of discontinuities. Selby (1993) expressed that chemical weathering is a difficult process because it involves

- Rock and soil minerals which are contaminated and have negligible constituents of different chemical reactivity;
- Compositions variations during reactions, which resulted from uniform simple reactions that happen in phases.
- Compulsory elimination/ejection of weathering products for reactions' continuity.
- The need for varying heat and water for all chemical reactions.
- Variability of minerals in their solubility and reactiveness, which encourage supremacy of the most stable minerals.

The difference between physical and chemical weathering is that there is change in rock minerals' constituents in the latter one and water is its main driving force. A large surface area will have better chemical weathering (McSweeney & Grunwald, 1999). Chemical weathering, which usually result in change in mineral and solution of rocks (Bell, 2000) has some kind of reactions that happen and cause changes in rocks' structure and composition. They are hydrolysis, oxidation, reduction, hydration, carbonation and solution (Pidwirny, 2006). The consequences of change in mineral are hydrolysis, hydration, oxidation and carbonation while acidified or alkalised waters cause that of solution of rocks (Bell, 2000).

- **Solution**

The chemical weathering process, which brought about the dissolution of primary or original rock solid materials in water after breaking down into its constituents (Kekeba, 2008). Selby (1993) described this process as initial phase of chemical weathering and the amount of solution is determined by:

- The quantity of water on the rock particle's surface;
- The solubility of the solids being dissolved and
- The hydrogen ions available, defined by pH (i.e. the negative logarithm of the hydrogen ion concentration).

However, the amount of solution produced from rock reaction with water mainly depends on the climatic conditions, as solution is likely to be very high in humid and hot climates areas (Pidwirny, 2006). Kekeba (2008) expressed a typical example for solubility of a solute in solvent for calcium sulphate in equation (i)

$$CaSO_4\ (s) \Leftrightarrow Ca^{2+}\ (aq) + SO_4^{2-}\ (aq) \text{ --- } (i)$$

- **Oxidation and reduction**

Oxidation is a chemical process that occur due to exposure of rock minerals that are formed under anoxic (oxygen deficient) conditions to the atmosphere (Kekeba, 2008). It can simply be expressed as the reaction between compounds and oxygen. While reduction is the opposite of oxidation. During oxidation, element or compound loses one or more electrons (increase in valence) which will cause its structure to be flexible and more unstable. This is very conversant in tropical regions with high temperatures and precipitation where the usual oxides (i.e. iron and aluminium) show their respective red and yellow staining of soils (Pidwirny, 2006). The degree of oxidation in rock mass is accelerated by water; though it could get involved in the reaction, but it is mainly catalyst (Bell, 2000). Kekeba (2008) expressed a typical oxidation/reduction reaction as:

$$Fe^{3+} + e^{-} \Leftrightarrow Fe^{2+} \text{ --- } (ii)$$

- **Hydration**

Hydration is a chemical weathering process whereby water is added to rock mineral and adsorb into the crystal lattice. The rock mineral becomes more weathered because of further porosity of the rock mineral lattice due to its adsorption (Selby, 1993). Hydration comprises of firm bond of H^+ and OH^- ions to the reacted compound and also gives room to quickening of the other decomposition reactions through crystal lattice's expansion. This allows for additional surface area for the reaction. On several circumstances, the ions are usually structural part of the rock mineral's crystal lattice (Pidwirny, 2006). A typical example of hydration after Selby (1993) is:

$$\underset{\text{Hematite}}{2Fe_2O_3} + 3H_2O \Leftrightarrow \underset{\text{Limonite}}{2Fe_2O_3 \,.\, 3H_2O} \text{ --- (iii)}$$

Because hydration reaction consist of substantial change in volume due to its repeated reversible nature, it is significant in physical weathering (Selby, 1993).

- **Hydrolysis**

Hydrolysis can be defined as chemical / weathering reaction between rock mineral and water i.e. the reaction occur between water ions (H^+ and OH^-) and rock mineral ions (water acts as a reactant and not solvent in this reaction) (Selby, 1993). The consequence is the disintegration of the rock by producing new compounds and by expanding the solution's pH when hydroxide ions are released. Hydrolysis is particularly active (e.g. in usual silicate and alumino-silicate minerals) in weathering due to its electrically charged crystal surfaces (Pidwirny, 2006). The difference between hydration and hydrolysis processes is that the latter one has one broken O-H bond of the water molecule (Kekeba, 2008). He expressed a typical weathering process of silicon through hydrolysis as:

$$Si^{4+} + 4H_2O \Leftrightarrow Si\,(OH)_4 + 4H^+ \text{ -- (iv)}$$

- **Carbonation**

Carbonation involves the reaction between carbonate or bicarbonate ions and water. Carbonates are products of precipitation and skeletons of animals (i.e. products that are rich in carbon dioxide). Presence of carbonic acid (i.e. carbon dioxide and water) is significant for carbonates' production and breakdown of mineral surfaces due to its acidic nature (Pidwirny, 2006). Nevertheless, as some rocks like limestone and dolostone are susceptible to chemical attack, they help in putting carbonates into water e.g. limestone mainly consist of calcium carbonate; when dissolves in water, it produces carbonate ions. However, this may give room to formation of karst and the kind of solution attributes is governed by the rock materials' nature – showing the changes in countenance of solution weathering which usually happen between chalk and limestone (Bell, 2000).

3. Biological weathering

Biological weathering is a process of breaking down of rock and mineral as a result of chemical and physical agents of organisms. These organisms range from bacteria to plants to animals (Pidwirny, 2006). Because biological weathering process is combination of both chemical and physical weathering processes, some researchers did not treat it separately as topic. The weathering process involves but not limited to the following:

- Disintegration of rock particles by animals' burrowing and pressure of growing plants' roots;
- Mingling and transfer of rock and soil materials/particles from one location to another by organisms which foster different weathering processes at some location in rock mass weathering profile;
- Improvement of clear chemical processes like solution of rock materials through organisms' respiration;
- Chelation process which brought about the complicated chemical influences (chelation is a biological process whereby organic- mineral substances (chelates) that can cause decaying of rock and its minerals through elimination of metallic cations are produced);
- Presence or accessibility of water, which is essential element in many physical and chemical processes, can be increased in the rock and soil masses by actions of organisms (i.e. aerial leaves and stems' shade, root masses' presence and humus) and consequently boost weathering;
- The pH of the rock and soil solution can be affected by the respiration of plant roots and cation exchange reaction of plants (Pidwirny, 2006; Selby, 1993).

Generally, the consequences of processes of weathering on rock masses are:

- ✓ The total loss of specific atoms or compounds from cut slopes or weathered surface;
- ✓ Accumulation of particular atoms or compounds to the cut slopes or weathered surface;

- ✓ Complete disintegration of rock masses;
- ✓ Instability of rock masses (with or without cut slopes).

The remains or deposit of weathering (which can be dissolved or transfer by water, discharge to atmosphere as gas or used by plants) comprises of chemically changeable and unchangeable materials. The very usual unchangeable deposit is quartz while the chemically changeable deposits are very easy little compounds or ions. While the less resistant minerals (i.e. alumino-silicate minerals) will change to clay particles, the changed ones will be put together through sedimentary and / or metamorphic processes to become fresh rock and minerals (Pidwirny, 2006). Table 2.2 shows the weathering processes, its influencing factors and the response of the rock materials to each process.

Table 2.2: Processes of weathering, its influencing factors and rock materials' response (after Kekeba, 2008)

MAIN CONTROLS	WEATHERING PROCESSES	RESPONSE OF THE MATERIAL
PHYSICAL ENVIRONMENT Weathering environment Climate Atmosphere Hydrosphere Local factors (e.g. topography, water table)	PHYSICAL WEATHERING Crystallization processes Wetting and drying Colloid processes Organic processes (sheeting, unloading and spalling) Insolation	PHYSICAL REPSONSE Disintegration Volume change Grain size change Surface area change Consolidation
CHEMICAL ENVIRONMENT Lithosphere Lithology Parent rock Structure Climate Atmosphere Hydrosphere Crystal structure	CHEMICAL WEATHERING Hydration Hydrolysis Solution Oxidation Reduction Carbonation Chelation Fixation	CHEMICAL RESPONSE Decomposition, recombination and cation exchange reaction. Unaffected minerals due to lack of time or weak agents. Leaching Dissolved ions.

2.1.2.2. **Weathering rate**

Huisman (2006) expressed that any description of weathering rate should depict it as "the ratio of the change in the state of weathering and a function of time required for that change". The change in weathering is the initial degree of weathering and the degree of weathering at the time of fieldwork measurement while total exposure time is the difference between excavation and present fieldwork date. Generally," the rates of weathering decreases as residual soil is produced and the product reaches physical equilibrium as the rates of formation which decreases as the layer thickens equals its rates of destruction" (Colman, 1981). Weathering rates of rock and soil masses depend upon the durability of the rock mass, which is controlled by mineralogical composition, texture, porosity, strength and discontinuity (Bell, 2000).

Based on the above definition, weathering rate is examined from two aspects:

- ✓ Degree of weathering and
- ✓ Penetration of weathering.

These aspects helped in estimating the weathering processes in cut slope's rock mass and successive transformation in stability of the slope within the engineering lifetime of the slope (Huisman, 2006).

1. Degree of weathering

Degree of weathering is the quantity of change (s) demonstrated by rock mass from its original state due to several degradation/breakdown processes (Kekeba, 2008). It is significantly defined as "degree of decomposition at one particular moment in time (Huisman, 2006). Kekeba (2008) and Huisman (2006) grouped elements governing degree of weathering into two classes: internal and external.

The internal elements are:

- Rock and soil materials' physical properties (parent material's properties) which control the accessibility of weathering fluids i.e. texture, porosity, permeability and discontinuities.
- Rock mineralogical composition, which shows that different rock minerals have different reaction towards weathering processes.

The external elements are elements that have to do with the weathering environment (though their actions are not directly on process of weathering) such as:

- Climate
- Vegetation and
- Geomorphology

They are usually substituted by elements that have direct influence on the degree of weathering, which are:

- Temperature: the rate of reaction is governed by change in temperature;
- Chemistry of weathering solutions, which is determined by the weathering solution's pH.

The degree of weathering in stability of cut slopes is governed by:

- Slope aspect / orientation
- Slope angle
- Slope height and
- Method of excavation

Most of the governing elements depend upon time and are likely to have substantial change over the period of time on site, which makes the degree of weathering also to change with time (Huisman, 2006; Kekeba, 2008).

A highly significant factor of the above mentioned, is climate due to effects of rainfall, temperature and seasonal fluctuations on style and rate of weathering. Change in climate (temperature and precipitation) results in soil differences of tropical, temperate, deserts and polar regions. A thin layer of soil and common exposures of fresh, unweathered rock is a feature of deserts. Physical weathering (i.e. abrasion, crystallization, thermal insolation, wetting and drying and pressure release) is very high and chemical weathering (i.e. hydrolysis, oxidation, reduction, hydration, carbonation, and dissolution) is insignificant due to lack of precipitation. Polar regions also have temperatures that are too low for significant chemical weathering but physical weathering is intensive which makes its soil to be thin and unproductive (Bell, 2000; Christiansen & Hamblin, 2009; Pidwirny, 2006).

In temperate regions, temperature ranges from cool to warm and precipitation between humid and arid. The regolith is improved and develops into depth of some meters due to operation of both physical and chemical weathering. Soils thickness increase with nutrients' retention, which are good for agricultural purposes. In tropical climates / regions, rate of weathering were highly influenced by water (moisture content) and temperature that are very high. Chemical weathering is large and very thick soils are rapidly developed. Feldspars are totally converted to clays and leaching of soluble minerals occurs. In addition, insoluble minerals i.e. silica, aluminium and iron are retained in the thick red soil which is not good for agriculture (Bell, 2000; Christiansen & Hamblin, 2009; Pidwirny, 2006).

Tropical weathering rates are three and a half times higher than temperate weathering rates and more intense with greater depths than in the other climates. However, strength decreases and degree of weathering increases with time upward from fresh rock to residual soils (Bell, 2000; Christiansen & Hamblin, 2009; Pidwirny, 2006).

From above, Climate portrayed that "weathering rates for different kind of climate depend on different rock and soil masses moisture contents which are controlled by temperature and average annual rainfall rates". The average lifetime of one millimetre of fresh granitic rock into a kaolinitic saprolite is between 20 and 70 years for tropical weathering rate. Lateritic soils are ultimate developed soils above most types of rocks in tropical region. Kaolinite, illite or smectite clay minerals are expected in acidic environment and free-draining conditions whilst montmorillonite clay mineral is expected in alkaline environment and poorly drained areas. Kaolinitic soils have higher strength and lower compressibility than smectite (Bell, 2000; McSweeney & Grunwald, 1999).

2. Penetration of weathering

Weathering penetration explains quick entry or break through of weathering front into the rock mass (especially the rock mass is exposed through slope cut). Though, verification of rates of weathering penetration from field evidence is an assiduous task generally due to lack of datable occurrences, but it shows that weathering penetration of a rock material at a particular time can be determined at that time (Kekeba, 2008).

Generally, there will be alteration in the degree of weathering with depth and a weathering front penetrating into the basic rock mass of a slope, which buttressed the believe that degree of weathering steadily decrease with depth. The rate of penetration of weathering will take place in a slope based on the weathering susceptibility of the rock mass and degree of erosion that takes place concurrently with weathering (Huisman, 2006). He defined this phenomenon under two categories, which are:

- Reference weathering penetration rate – This is when weathering penetration is based on weathering alone. It is of impression that increase in penetration depth will cause decrease in penetration rate of a weathering front i.e. the weathered materials that is not immediately eroded is a protective cover for the unweathered portion of a rock mass and usually reduces the rates of occurrence of rock degradation processes. The weathering front penetration will continue steadily at a decreasing rate (with respect to a linear time scale).
- Slope weathering penetration rate – This is a responsive condition in which the weathered cover is partly or fully eroded and resulted in balance between weathering and erosion or incline in dominant direction of one of these processes. This consequently makes the penetration rate of a weathering front for any specified depth to be smaller than that of reference weathering penetration rate.

The weathering penetration rate show that after primary relaxation (when rock mass has been excavated i.e. cutting of slope), the rock mass degradation is a process of finding balance between weathering and erosion while undergoing the effects of stress redistribution (secondary relaxation). The degree at which the balance is achieved establishes the result of the degradation process, the consequence of the degradation on the geotechnical properties of the rock mass and eventually the slope stability (Huisman, 2006). This is elaborated under these three key conditions (table 2.3):

- Erosion partiality (i.e. weathering restricted);
- Balance between weathering and erosion;
- Weathering partiality (i.e. erosion restricted).

Therefore, the weathering rate does not only depend on the degree of weathering and time, but also on engineering importance of penetration depth of a specific weathering degree with reference to slope stability (Huisman, 2006).

Table 2.3: Weathering penetration conditions and its effects on degree and rate of weathering (after Huisman, 2006).

CONDITION	PROCESSES	CONDITION AT TIME OF EXCAVATION	WEATHERING PENETRATION DEPTH	WEATHERING DEGREE ON SLOPE SURFACE	WEATHERING RATE
Imbalance favouring erosion	Erosion only, no weathering.	Absence of weathering zone from previous stage	Zero	Constant	Zero
		Old weathering zone from previous stage present	Decreases until the zone is eroded, then zero	Decreases until the zone is eroded, then constant	Negative until the zone is eroded, then tending to zero (or become zero)
	Some weathering, but erosion penetrates faster than weathering.	Absence of weathering zone from previous stage	Zero	Constant	Zero
		Old weathering zone from previous stage present	Decreases until the zone is eroded, then zero	Decreases until the zone is eroded, then constant	Negative until the zone is eroded, then tending to zero (or become zero)
Balance between weathering and erosion	Erosion and weathering penetrate into the rock mass at equal rates.	Absence of weathering zone from previous stage	Zero	Constant	Zero
		Old weathering zone from previous stage present	Constant, larger than zero	Constant (likely)	Zero
Imbalance favouring weathering	Some erosion, but weathering penetrates faster than erosion.	Absence of weathering zone from previous stage	Increases	Increases	Positive
		Old weathering zone from previous stage present	Increases	Increases	Positive
	Weathering only, no erosion.	Absence of weathering zone from previous stage	Increases	Increases	Positive and constant
		Old weathering zone from previous stage present	Increases	Increases	Positive and constant

2.1.2.3. **Assessment of degree and rate of weathering**

The issue of weathering rates assessment is mainly determined by the manner the degree of weathering at a particular instant of time can really be assessed. The change in this degree per unit of time is strictly the meaning of weathering rate. As a result of this, it is better to define the weathering rate's parameter in a manner that it is lonely governed by the present set of weathering parameters. This kind of variable can be used to measure the rate of degradation process in a slope at a specific time and the future can be inferred from the present time condition. Therefore, forecasting the slope stability in a rock or soil mass within the ideal engineering lifetime of a slope (Huisman, 2006).

Huisman (2006) stipulated that measurement of degree of weathering could be carried through the following means:

- Standardized classification and rating system – this is often referred to as "verbally descriptive approach". It uses ideas of reduction values for geotechnical parameters and slope stability assessment depending on an expected degree of weathering at the end of the engineering lifetime. e.g. British Standard classification (BS5930, 1981/1999), Slope Stability Probability Classification – SSPC (Hack, 1998; Hack, et al., 2003), Mining Rock Mass Rating classification - MRMR (Laubscher, 1990) and the Q-system (Barton, et al., 1974).
- Mechanical index properties method – this is use of testing that can be through the strength estimate (i.e. use of hands, pocket-knives, geological hammer, Schmidt hammer); slake durability test and rock properties tests (i.e. moisture content (Matsukura & Takahashi, 1999), porosity (Nicholson, 2000) and degree of fracture (Fookes, et al., 1971) in determining the degree of weathering.
- Chemical indices methods – This could be comparison between
  - ✓ Weathered material and unweathered parent rock material
  - ✓ Ratio of resistant minerals (e.g. quartz) and non-resistant minerals present in the parent rock mineral removed by weathering processes (e.g. (Guan, et al., 2001; Gupta & Rao, 2001; Irfan, et al., 1978; Kim & Park, 2003).

And generally, weathering rates could be assessed from

- ✓ Geological materials

- ✓ In-situ observation
- ✓ Mass-balance for catchment areas
- ✓ Laboratory tests (the results are doubtful from quantitative view) (Huisman, 2006).

The measurement could be carried out using either chemical properties like pH, Cation Exchange Capacities (CEC) and Sum of exchangeable bases or through physical/mechanical properties like strength, thickness and other mass characteristics of the rock and soil masses.

The research work of Hudson (1969), Kononov (2000), Russell et al. (2001), Hong et al. (2002), Kekeba (2008), Megerssa (2010) and others proposed remote sensing imaging as another good means of measuring degree and rate of weathering from rock weathered slope. The remote sensing imaging method has many merits of being objective, decisive, cheaper, accurate and avoidance of physical contact (Kekeba, 2008).

2.2. Conclusion

The task of analyzing the degree of weathering and weathering rates on rock and soil mass slopes has been carried out in many research works using different means or methods. Irfan et al. (1978) and Gupta and Rao (2001) used petrographical analysis for weathered crystalline rocks (e.g. granite and gneiss), which show predomination of chemical weathering over mechanical weathering. Though the method is very good for the same parent material, it will not give best result in a climatic region where physical weathering is very high with little or no chemical weathering. Weathering analysis of decay of rock and soil materials using large set of parameters upon which Ruxton (1968) and Colman (1981) research works are based on resulted in the limitation of their works, but the method has importance of using weathering features as age indicators. Bennett (1993) and Wakatsuki and Rasydin (1992) used geochemical mass balances equation for rates of weathering and soil formation in tropical regions (i.e. Hong Kong, Japan and USA) which gives defined different rates of weathering and soil formation both globally and regionally.

In this thesis, effort will be made to see to application of SSPC method and method based on Colman (1981) formula propounded by Huisman (2006) using friction and cohesion for analyzing the degree and rates of weathering of rock and soil masses in Yen Bai city, Vietnam. Combination of these methods solves the problem of the above-mentioned research works and methods. Classes of weathering coupled with other geotechnical parameters are used in their measurements. These ideas / methods have not been applied to tropical regions like Vietnam (i.e. Yen Bai city). The SSPC system (Hack, et al., 2003) and Huisman (2006) idea was established and adopted for analysis of degree and rate of weathering on rock mass in a Mediterranean climate region like Falset area in Spain. It has not been used for tropical regions where the regolith is very thick and rate of weathering is very high (i.e. chemical weathering rate).

The probabilistic approach of classification-based weathering measurement (of rock mass slope) followed in this study is probably the most promising, as it helps in interpretation of the statistics variation of the datasets (Huisman, 2006).

3. METHODOLOGY

3.1. Introduction

This thesis work comprises of four main phases fieldwork preparation (pre - fieldwork), fieldwork and post fieldwork analysis phases (fig. 3.1).

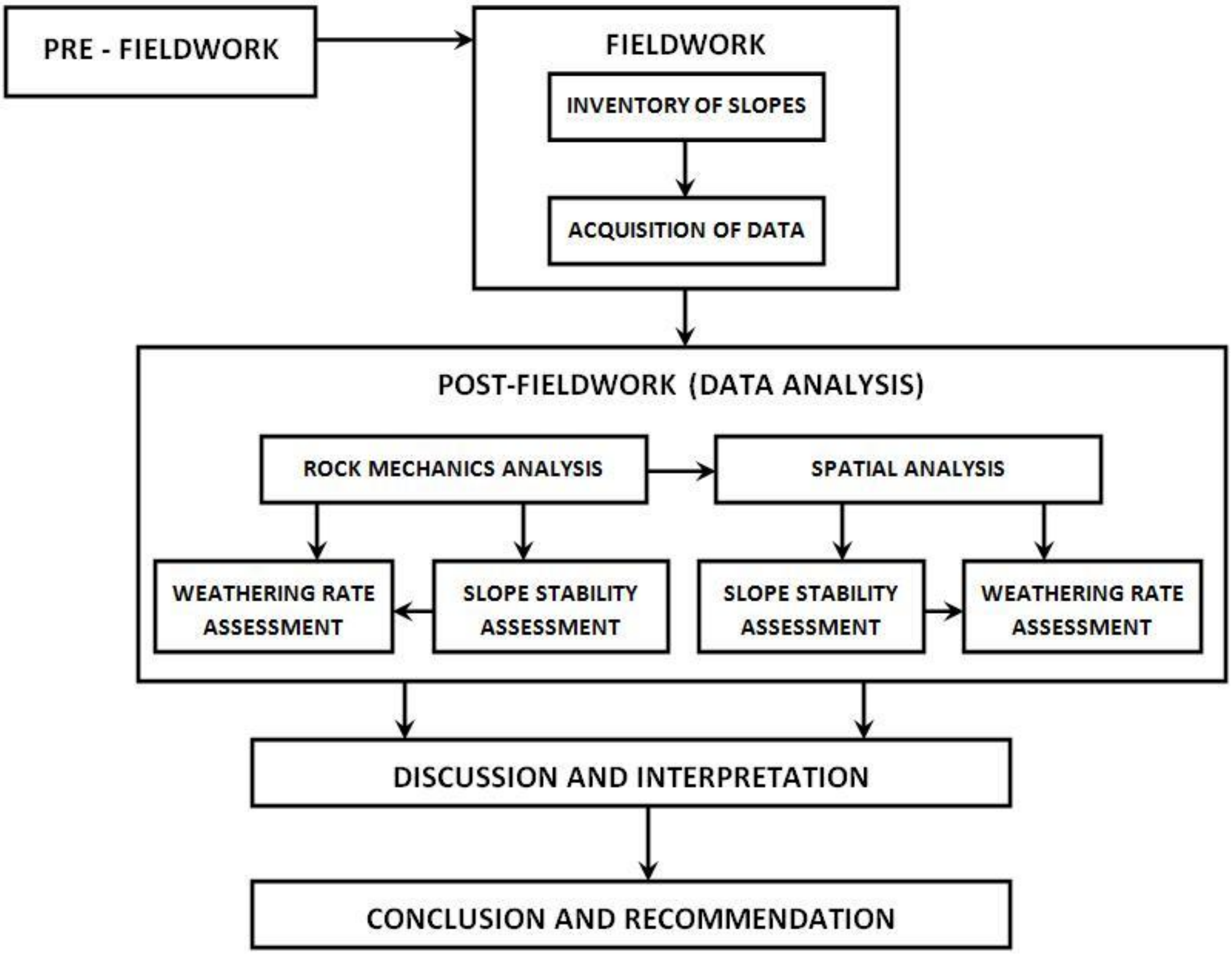

Figure 3.1: Methodology flow chart for the thesis

3.2. Pre-fieldwork phase

This comprises of literature review for acquisition of relevant information related to the past and present works and help on how to go about the study. It also entails general preparation for fieldwork. All the necessary tools and documents including maps related to general information, materials and mass characteristics for the study area and slopes were gathered.

3.3. Fieldwork phase

The fieldwork phase deals with the measurement and acquisition of all the basic geotechnical parameters and any other necessary information of the present or existing exposed conditions of rock and soil masses through cut slopes (i.e. ERM) using SSPC method. This phase is divided into two namely:

- ✓ Inventory of slopes
- ✓ Acquisition of data

3.3.1. Inventory of slopes

Inventory of slopes deals with exploration of the available cut slopes in the study area and selection of the best ones out of them for the study purpose based on the accessibility and presence of the following criteria:

- Two or more cut slope faces with different dates of excavation, i.e. recent and old cut slope faces made at different times. The recent cut slopes are from 0 to 7 years while the old cut slopes are from 20 to 33 years.
- In the same parent materials.

In order to select the man-made study slopes, a reconnaissance (exploratory) survey was done around Yen Bai City. 35 cut slopes were located and inspected. The survey commenced on September 22, 2010 and continued during fieldwork until October 7, 2010. The 35 cut slopes are within the paleo – proterozoid geological formations, of which 20 slopes are in the AR?nc1 paleo-proterozoid geological formation while the remaining 15 slopes are within the AR?nc2 paleo-proterozoid geological formation. From the inspected 35 slopes (fig.3.2), the best 15 slopes are selected for the purpose of this study. 6 slopes are within the AR?nc2 paleo-proterozoid geological formation (i.e. Y1, Y6, Y14, Y18, Y20 and Y21), while the remaining 9 slopes are within the AR?nc1 paleo-proterozoid geological formation (Y2, Y4, Y11, Y12, Y13, Y24, Y27, Y28 and Y33).

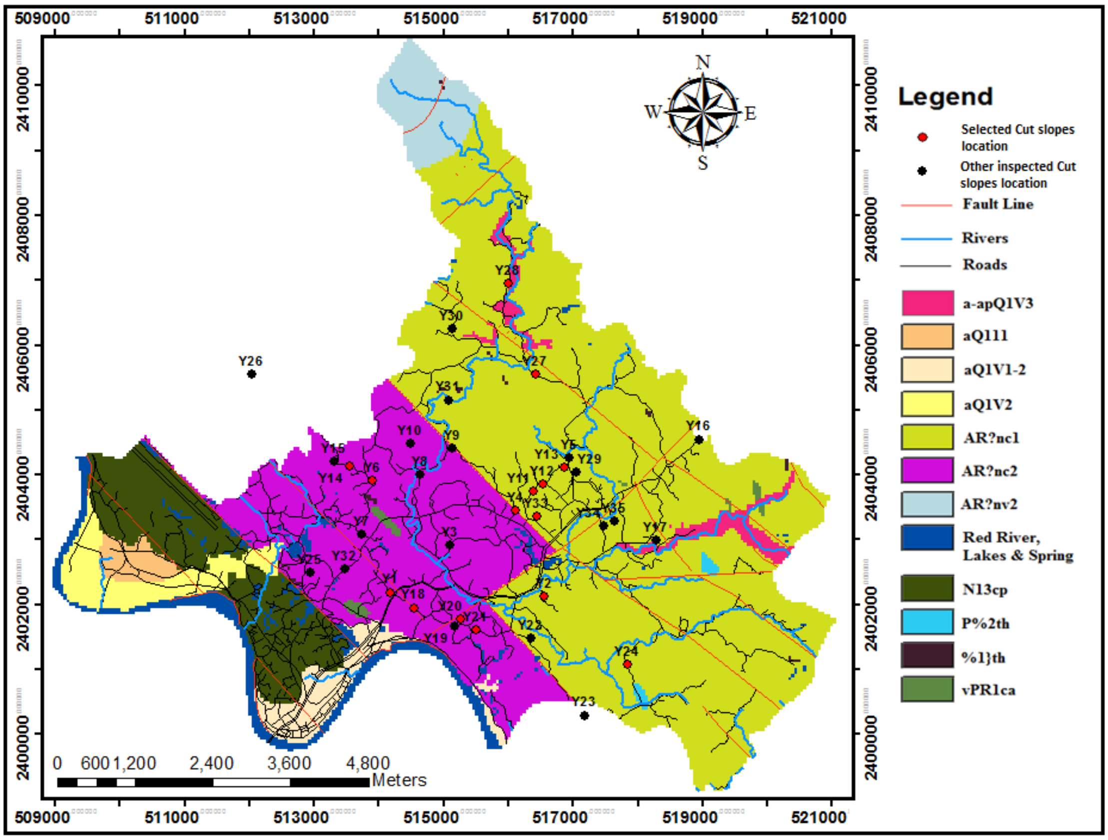

Figure 3.2: The Geology and cut slopes location of the research area - Yen Bai City (after Vinh & Hoanh, 2004)

3.3.2. Acquisition of data (fieldwork data collection)

The fieldwork data collection was conducted from September 22, 2010 to October 9, 2010. During the time of the data collection, the weather conditions were rainy and cloudy for a couple of days, while the other days were bright and dry (as indicated on the field form in fig. 0.68; appendix 4). The mass and material characteristics and general information are collected for each geotechnical unit of the selected cut slopes. The description is made and samples are taken from the face of the slope as existing at the time of the investigation. At some locations, superficial surface material was removed if this was different from the underlying mass. This surface layer was generally not more than a couple of milli- to centimetres thick. Care was taken that descriptions and samples were representative for the outer layers of the slope with a couple of metres thickness. Because no additional excavations could be made, this was ascertained by inspecting niches in the slopes and the sides of the slopes. The descriptions and samples are therefore deemed representative for the layers directly below the slope face. For most slopes, these layers determine the stability of the slope. Deeper under the surface of the face it may be expected that the weathering degree reduces and that geotechnical properties improve. Failure in these layers is not expected which is also confirmed by visual inspection of the failed slopes. For very large slopes with benches, failure may be through less weathered material but such slopes have not been included in this study.

3.3.2.1. Material characteristics

The material characteristics deal with strength, state and nature of rock and soil masses. These comprise of Intact Rock Strength (IRS), colour, structure, accessibility, texture, particle and grain size, and rock / soil name. Almost all of them changed when there is effect of weathering on them. The IRS of the cut slopes are acquired using hand and hammer (and pocket penetrometer for the residual soils), colours are acquired using colour chart, texture are acquired using hand lens, particle and grain size are acquired through the use of sand ruler, while visual inspection is applicable to all of them. Then classified in accordance to British standard (BS5930, 1981/1999) as used in SSPC method (fig. 0.68; appendix 4) (Hack, 1998; Hack, et al., 2003).

3.3.2.2. Mass characteristics

The mass characteristics deals with geometrical and strength characteristics of discontinuities and weathering of rock and soil masses. These comprise of orientation (i.e. SD_{disc} and SDD_{disc}), spacing (SPA) and condition (CD) of discontinuities, state of weathering (WE) and slope geometry (orientation and height i.e. SD, SDD and H_{slope}). The WE of the cut slopes were acquired using hand, hammer and visual inspection, the orientation and spacing of discontinuities, and slope geometry are acquired with inclinometer, compass, and measuring tape while the conditions of discontinuities characteristics (i.e. Rl and Rs scales, Im and Ka) are acquired through visual and tactile inspection. Then classified in accordance to British standard (BS5930, 1981/1999) as used in SSPC method (fig. 0.68; appendix 4) (Hack, 1998; Hack, et al., 2003).

3.3.2.3. General information

The general information here deals with other information or features of the cut slopes other than the material and mass characteristics. These comprise of geological information, date and method of excavation (ME) and any other necessary information. These are acquired through visual inspection, enquiries with the local population and available data from old maps and literature works.
Rock and soil samples are also collected. 120 rock and soil samples have been taken that are considered to be representative for the unit. In weaker masses samples could be obtained by hand while in stronger a hammer was required.

Moreover, from the above contexts, there are two of the rock and soil masses' properties that need to be explained further for better clarification and understanding namely:

- Method of excavation (ME) and
- Weathering classification.

- **Method of excavation**

Excavations are made using different types of method depending upon the one that fitted the type of soil or rock mass, the time limits of a contract/job, obtainable expert worker and the contract/job's budget. The ME has significant effect on the rock mass state, which makes it to be referred to as an exposure specific property. The ME used on it affect the rock mass properties in the exposure. Since the origin of an exposure has a significant effect on the rock mass value and slope stability, the mechanical discontinuities will be much if high stress levels occurred in the rock mass during usual occurrence or slope's excavation. Generally, there are two major types of excavation methods – mechanical and blasting (table 3.1) (Hack, 1998, 2006).

Mechanical methods have many advantages over the blasting methods and are often used for block size reduction after blasting. Rock mass slope excavation by hand and mechanical excavators cause a little amount of damage, hence fewer enhanced mechanical discontinuities. Whereas, blasting methods are more in use nowadays than mechanical even where mechanical methods supposed to be used. It can cause serious rock mass damage and high stress levels, which resulted in intact rock cracking, conversion of integral into mechanical discontinuities and broadening of present mechanical discontinuities due to shock waves from detonation. Integral discontinuities are discontinuities that are as durable as associated rock material, while mechanical discontinuities are planes of substantial weaknesses with shear strength of associated rock material greater than of the discontinuity. Gasses emitted by the explosion cause related consequences. The roughness of discontinuity planes could also be affected by blasting. However, there is decrease in blasting consequences if special techniques like pre-splitting or smooth wall blasting are used (Hack, 1998, 2006).

Table 3.1: Various method of excavation (after Hack, 2006).

Mechanical	Digging	Man-made / shovel / excavator
	Cutting and grinding	borehole
		road header
		trench cutter
		tunnel boring machine (TBM)
		raise borer
	Hammering	jack hammer
		hydraulic / pneumatic hammer
Blasting		pre-splitting
		smooth wall
		conventional tunnel blasting
		conventional large hole blasting
Specials		wood
		chemical expansion
		water (high pressure breaking or jetting)
		sawing (blade or steel cable)

There are also special methods of using expansion characteristics of wood or chemical, water under high pressure, water jet for rock mass erosion and sawing methods (Hack, 1998, 2006). Hack, (1998) derived values for method of excavation using Monte Carlo simulation (table 3.2).

Table 3.2: Values for different methods of excavation (after Hack, 2006).

METHOD OF EXCAVATION (ME)	
Natural / hand made	1
Pneumatic hammer excavation	0.76
Pre-splitting / smooth wall blasting	0.99
Conventional blasting with result:	
good	0.77
open discontinuities	0.75
dislodged blocks	0.72
fractured intact rock	0.67
crushed intact rock	0.62

The cut slopes in the research area are made using mechanical excavator (fig. 0.1; appendix 1). Very little or no effect of the ME on the IRS or on the CD has been found.

- **Weathering classification**

The degree of weathering in BS and SSPC is quantified using parameter WE and SWE. The values for WE and SWE, which are less than one, represent reduction mass properties caused by weathering. The weathering classification in the SSPC system is in accordance to British standard (BS5930, 1981/1999) as stated in table 3.3 below.

Table 3.3: WE values for different degrees of weathering (after Hack, 1998; Hack et al., 2003).

WE (VALUES)	DEGREE OF WEATHERING	DESCRIPTION
1	Fresh (Unweathered)	Unchanged from original state. No visible sign of rock material weathering
0.95	Slightly weathered	Slight discolouration, slight weakening. Discolouration indicates weathering of rock material and discontinuity surfaces. All the rock material may be discoloured by weathering.
0.9	Moderately weathered	Considerable weakened, penetrative discolouration, large pieces cannot be broken by hand. Less than half of the rock material is decomposed or disintegrated to a soil.
0.62	Highly weathered	Large pieces can be broken by hand; more than half of the rock is decomposed or disintegrated to a soil. Does not readily disintegrate (slake) when dry sample immersed in water.
0.35	Completely weathered	Considerably weakened, disintegrates in water; original texture apparent. All rock material is decomposed or disintegrated to soil.
	Residual soil	Soil derived by insitu weathering, but having lost retaining original texture and fabric. There is large change in volume.

3.4. Post fieldwork phase

From the acquired basic data, the slope stability and weathering rate analyses are carried out under two perspectives – rock mechanics and spatial analyses.

3.4.1. Rock mechanics analysis

The slope stability assessment is carried out using SSPC method while the rate of weathering is carried out using the formula derived from Colman formula. However, the weathering rate is analyzed based on the slope friction and cohesion (SCOH and SFRI) derived from SSPC method and excavation time.

3.4.1.1. Slope stability assessment using Slope Stability Classification method (SSPC)

Slope Stability Probability Classification method (SSPC) very strictly prescribes terminology for description of rock mass properties. It describes the rock mass in exposures and where the slope is to be made which are not present in the existing classification system (Hack, 1998). SSPC has three concepts (fig. 3.3), which are used for the analysis of cut slopes in this study:

(1) Decisive and easy means of field data collection - see fieldwork (chapter 3.3 and 4).
(2) Description of "exposure, reference and slope" rock and soil masses using principle of three- step classification system
(3) Stability assessment using probability determination of different failure methods' occurrence instead of single point value (Hack, 1998).

Standard forms were produced for all the steps involved in SSPC system (fig. 3.3) for easy and decisive calculations (fig. 0.68 – 0.70; appendix 4).

- **Exposure Rock Mass (ERM)**

This is the present or existing rock mass exposure (cut slopes) where all the mass and material parameters including general information about the cut slopes are characterized, collected and the data recorded in standardized SSPC forms (fig. 0.68 – 0.70; appendix 4).

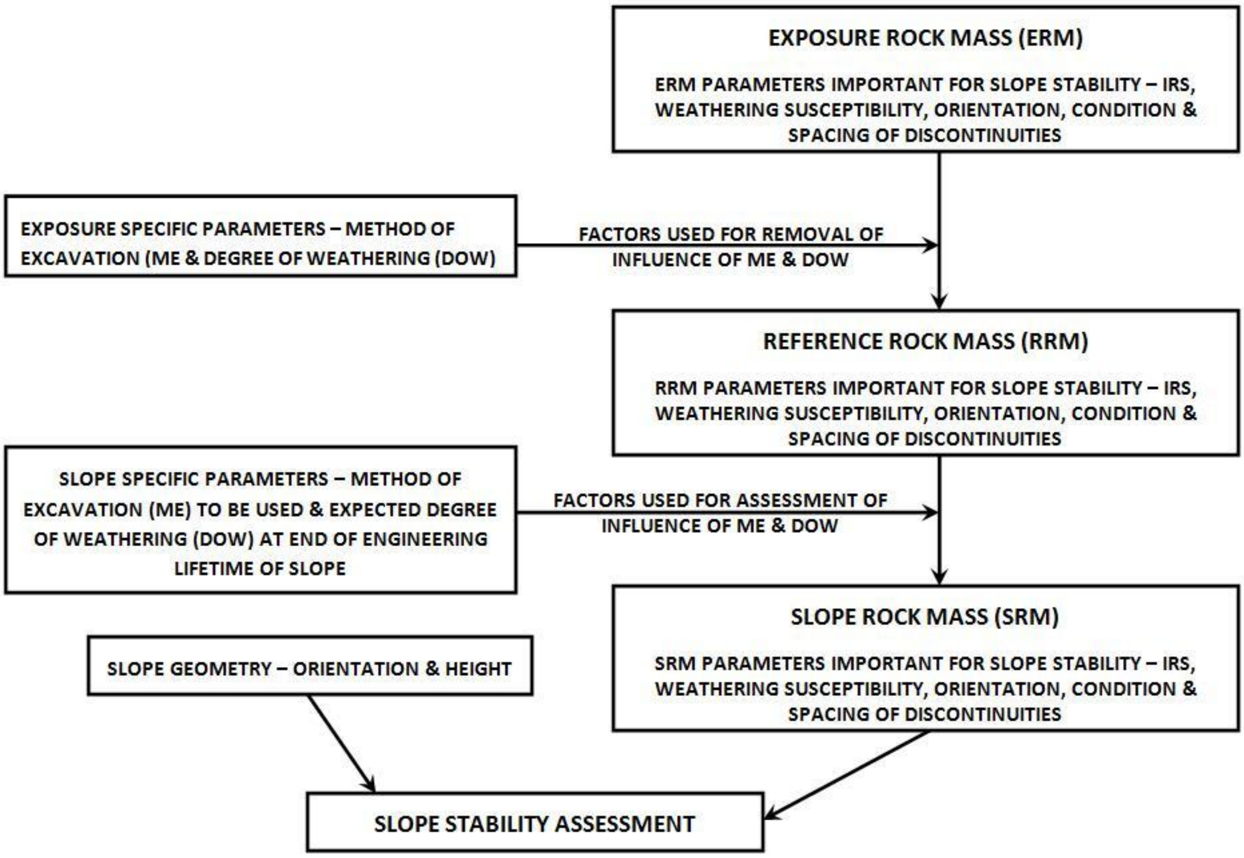

Figure 3.3: Flow diagram of the three-step concept of SSPC system (after Hack, 2003)

- **Reference Rock Mass (RRM) calculation**

This is the assumed or hypothetical unweathered and uninterrupted rock mass that is in existence before excavation. The ERM geotechnical parameters of each measured geotechnical unit of the cut slopes are converted to RRM parameters (i.e. conversion of ERM parameters to those of hypothetical rock mass which presents outside the impact area of weathering and other disturbances) by removing local impacts (*i.e. weathering and disturbance due to excavation method*) on the measured ERM geotechnical parameters. The conversions are carried out using the exposure specific parameters (fig. 3.3). These help make all the geotechnical units' parameters of the cut slopes to show their unique and fundamental geotechnical properties (Hack, et al., 2003). The steps for deriving the RRM geotechnical parameters are as follows:

(i) Derivation of reference rock mass unit's IRS (RIRS) - this is derived by correcting for local impact of weathering on the IRS measured from ERM. The IRS is divided by observed WE value to get RIRS.

RIRS = IRS (MPa) / WE --- (v)

(ii) Derivation of reference rock mass unit's overall spacing of discontinuities (RSPA) – this is derived by correcting for local impact of weathering and method of excavation. The measured SPA (in metres) from ERM is converted to SPA values using factors from a plotted graph. The graph (fig. 0.69; appendix 4) was plotted from the results of broad analyses (Hack, 1998) of SPA in the shear plane model based on Taylor's factors (1980). The product of SPA values are then divided by product of observed WE and ME to get RSPA. The procedures are mathematically expressed as:

SPA = factor 1 * factor 2 * factor 3 --- (vi)

RSPA = SPA / (WE * ME) --- (vii)

(iii) Derivation of reference rock mass unit's weighted overall condition of discontinuities (RCD) – this is derived by correcting for local impact of weathering. The ERM unit's condition of a discontinuity (set) (TC) is initially calculated from the measured shear strength of discontinuities' parameters from ERM (i.e. Rl and Rs scales, lm and Ka) by simply multiplying them together. The calculated TC for discontinuity sets are then weighted by their corresponding spacing values (DS_1, DS_2 and DS_3) to get CD value (Hack, 1998). The CD value is then divided by observed WE value to get RCD. The procedures are mathematically expressed as:

$$TC = Rl * Rs * lm * Ka \text{ ------------------------ (viii)}$$

$$RTC = TC *(1.452 - 1.220 * e^{(-WE)})^{\wedge 0.5} \text{ ------------------------ (ix)}$$

$$CD = \frac{(TC_1/DS_1) + (TC_2/DS_2) + (TC_3/DS_3)}{(1/DS_1) + (1/DS_2) + (1/DS_3)} \text{ ------------------------ (x)}$$

$$RCD = CD / WE \text{ ------------------------ (xi)}$$

(iv) Derivation of reference rock mass unit's friction and cohesion (RFRI and RCOH) – Hack (1998) enhanced the Mohr – Coulomb failure criterion with IRS, SPA and CD to get formula that are used in deriving friction (φ_{mass}) and cohesion (COH_{mass}) values of rock mass in the SSPC method. Hence, RCOH and RFRI are derived based on this formula which are mathematically expressed as :-

$$\varphi_{RRM} = RIRS * 0.2417 + RSPA * 5212 + RCD * 5.779 \text{ ----------------- (xii)}$$

$$COH_{RRM} = RIRS * 94.27 + RSPA * 28629 + RCD * 3593 \text{ ------------ (xiii)}$$

(if RIRS > 132MPa; RIRS =132)

Where

φ_{RRM} = angle of internal friction of the RRM (in degrees)

COH_{RRM} = RRM cohesion (in Pa)

3.4.1.2. Slope stability assessment

The real slope stability assessments for the cut slopes are carried out in the slope rock mass (SRM), which are carried out by modification of RRM parameters with slope specific parameters (fig. 3.3). The results put slope geometry (i.e. SD, SDD and H_{slope}) into consideration to give the probability values of the slope stability. The slopes stability assessments are carried out in two categories - orientation independent stability and orientation dependent stability analyses. Orientation independent stability analysis put into consideration optimization of φ_{SRM} and COH_{SRM}, which depends mainly on SIRS, SSPA and SCD. While Orientation dependent stability put into consideration the sliding and toppling criteria that depend mainly on shear strength of discontinuities (Hack, et al., 2003). The slope details i.e. SME, SWE and geometry are measured from the cut slopes ERM.

➢ **Orientation independent stability assessment**

This is where slope specific parameters (fig. 3.3) are used to assess the effect of ME and future weathering. This involves derivation of SIRS, SSPA and SCD, SCOH and SFRI of the slope rock mass (SRM). All the derived parameters are then used to determine stability probability for the cut slopes.

(i) Derivation of slope rock mass unit's IRS (SIRS) - this is derived by assessing the effect of SWE on reference rock mass (RRM). It is derived by simple multiplication of RIRS and SWE.

$$SIRS = RIRS * SWE \text{ ------------------------ (xiv)}$$

(ii) Derivation of slope rock mass unit's overall spacing of discontinuities (SSPA) – this is derived by assessing the effect of SWE and SME on reference rock mass (RRM). It is derived by multiplication of RSPA, SWE and SME.

$$SSPA = RSPA * SWE * SME \text{ ------------------------ (xv)}$$

(iii) Derivation of slope rock mass unit' weighted overall condition of discontinuities (SCD) – this is also derived by assessing the effect of SWE on reference rock mass (RRM). It is derived by simple multiplication of RCD and SWE.

$$SCD = RCD \text{ (from reference rock mass)} * SWE \text{ -------------------- (xvi)}$$

(iv) Derivation of slope rock mass unit's friction and cohesion (SFRI and SCOH) – Equations (xii) and (xiii) are used but the derived RRM parameters (i.e. RIRS, RSPA and RCD) are replaced by SRM parameters. Thus the equations become :-

$$\varphi_{SRM} = SIRS * 0.2417 + SSPA * 5212 + SCD * 5.779 \text{ ------------------ (xvii)}$$

$$COH_{SRM} = SIRS * 94.27 + SSPA * 28629 + SCD * 3593 \text{ --------------- (xviii)}$$

(If SIRS > 132MPa; SIRS =132)

Where

φ_{SRM} = angle of internal friction of the SRM (in degrees)
COH_{SRM} = SRM cohesion (in Pa)

(v) Calculation of maximum possible height (H_{max}) – this is the maximum possible height that could be attained by the geotechnical parameters of the parent rock materials of the slope using equation (xix).

$$H_{max} = \frac{1.6 * 10\text{-}4 * COH_{SRM} * \sin(SD) * \cos(\varphi_{SRM})}{1 - \cos(SD - \varphi_{SRM})} \text{ --------------- (xix)}$$

Summarily, the influences of weathering and method of excavation are removed from the basic geotechnical parameters (i.e. IRS, SPA and CD) using equations (v) – (xi) to produce the RIRS, RSPA and RCD (of RRM). These derived parameters are substituted into equations (xii) & (xiii) to produce the RCOH and RFRI (COH_{RRM} and φ_{RRM}). The influences of weathering and method of excavation are assessed on the derived RIRS, RSPA and RCD using equations (xiv) – (xvi). The new set of derived parameters is substituted in equations (xvii) & (xviii) to produce the required SCOH and SFRI (i.e. COH_{SRM} and φ_{SRM}). All the calculations in this part are carried out and recorded in SSPC standardized forms (fig. 0.68 – 0.70; appendix 4). From above, ratios of φ_{SRM} to SD and Hmax to Hslope are determined. These ratios are checked out from orientation independent stability 'probability graph (fig. 3.4) to derive the slope stability probability (Hack, 1998; Hack, et al., 2003).

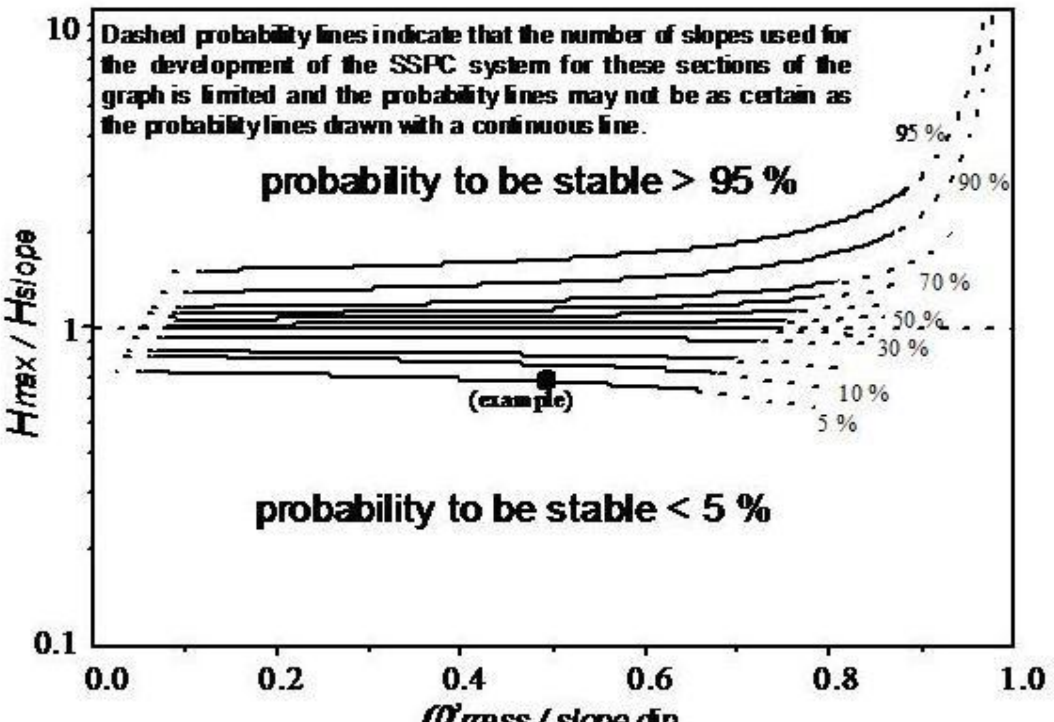

Figure 3.4: Probability graph of orientation independent slope stability; to be used for equation (xvii) and (xix)(see also SSPC form, fig. 0.70(appendix 4) (after Hack, 1998)

➢ **Orientation dependent stability assessment**

This is act of assessing the situation in which the failure on slope depend upon its orientation and that of discontinuities of rock mass which is controlled by shear strength of the discontinuity. The analysis is based on the following:

(i) Planar (sliding) failure – This type of failure (fig. 3.5) is possible where the inclined slope face is greater than the discontinuity plane and at an angle steeper than the frictional angle. It must dip roughly downward in the same direction, but less steeply as the overlying slope face. Kinematically, there must be intersection between the slope face and the plane to enhance movement ("daylight") (Wyllie & Mah, 2004).

(ii) Wedge failure – This type of failure (fig. 3.5) is possible where the slope face is greater than the plunge of the two intersections of two planes (sliding vector) and at an angle greater than the combined friction angle of the planes that form the wedge. The line of intersection must plunge downward and "daylight" out of the slope face. The analysis (fig. 3.5) can be carried in the same way as planar failure. The wedge daylight envelope is the locus of all poles representing lines of intersection whose dip directions lie in the plane of the slope face (Wyllie & Mah, 2004).

(iii) Toppling failure – This type of failure (fig. 3.5) is possible where slant jointing dips into the slope at a steep angle. The planes' dip must be steep enough to foster interlayer slip (Wyllie & Mah, 2004).

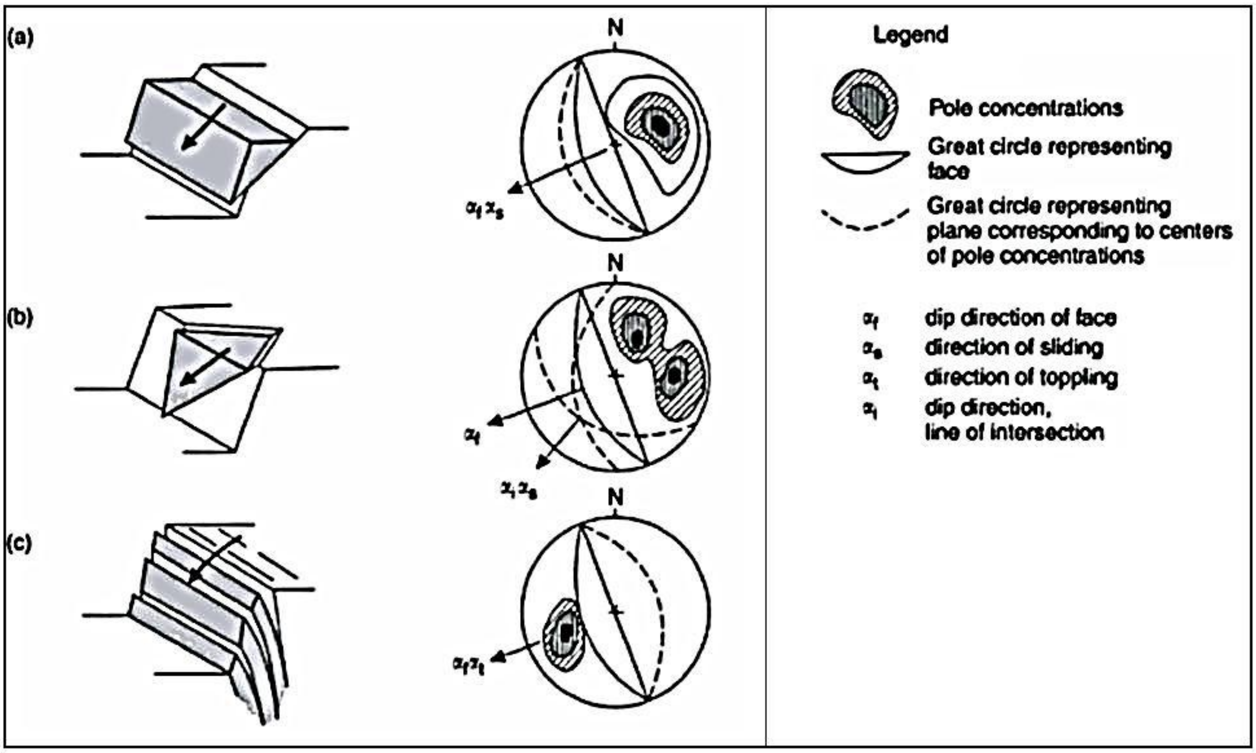

Figure 3.5: Types of block failure in slope (a) Planar (sliding) (b) Wedge (C) Toppling failure (after Wyllie & Mah, 2004)

The orientation dependent stability is taking care of in the SSPC system under two criteria – toppling and sliding criteria. For this study, these are determined using the formula and graphs designed for this purpose under SSPC method. It involves calculating for AP in and opposite direction of slope dip and slope condition of discontinuity (STC). Then the results are checked using various graphs and conditions (fig. 3.6 and table 3.4). AP and STC are mathematically expressed in equation (xx) and (xxi)

$$AP = \arctan(\cos\delta * \tan(SD_{disc})) \text{ -- (xx)}$$

Where

δ = difference between SDD and SDD_{disc}

All the conditional expressions of AP are as indicated in table 3.4 and SSPC standardized form (fig. 0.69; appendix 4).

$$STC = RTC * (1.452 - 1.220 * e^{(-SWE)})^{0.5} \text{ ------------------------------------ (xxi)}$$

Where

e = 2.7182818

All the above-explained calculations on the cut slopes are carried out and recorded in SSPC standardized forms (fig. 0.68 – 0.70; appendix 4) (Hack, 1998; Hack, et al., 2003).

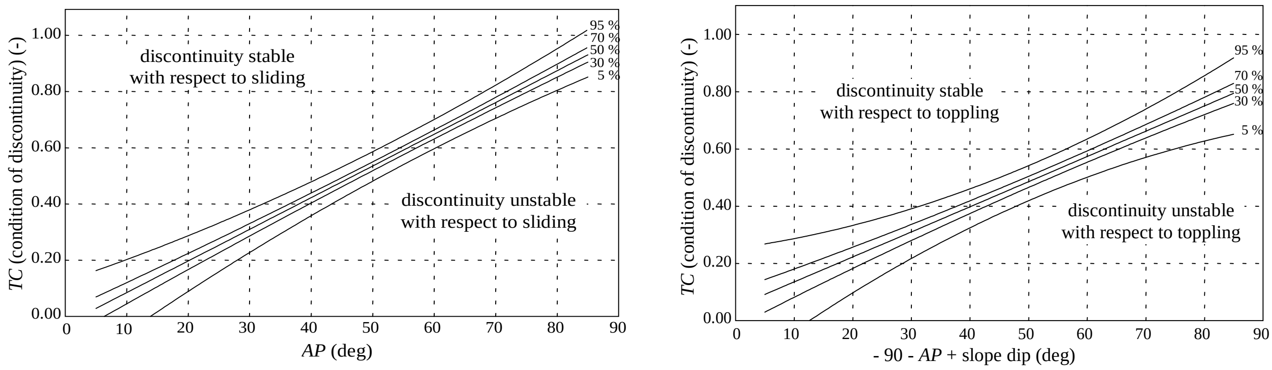

Figure 3.6: Sliding (left) and toppling (right) probability graph for orientation dependent slope stability; to be used for equation (xx) and (xxi) (after Hack, 1998)

Table 3.4: Condition and stability probability for orientation dependent stability assessment; to be used for equation (xx), (xxi) and fig. 3.6 (after Hack, 2003)

CONDITION	DIRECTION	STABILITY	
		SLIDING	TOPPLING
AP > 84° or AP < -84°	VERTICAL (V)	100%	100%
(SD + 5°) < AP < 84°	WITH (W)	100%	100%
(SD - 5°) < AP < (SD + 5°)	EQUAL (E)	100%	100%
0° < AP < (SD - 5°)	WITH (W)	USE GRAPH SLIDING	100%
AP < 0° and (-90° - AP + SD) < 0°	AGAINST(A)	100%	100%
AP < 0° and (-90° - AP + SD) > 0°	AGAINST (A)	100%	USE GRAPH TOPPLING

3.4.1.3. **Sensitivity analysis method of the cut slopes**

Two criteria are used for the sensitivity analysis purpose of the cut slopes, which are:

- Use of high IRS and small SPA - i.e. High strength and small block size of rock. This is process whereby IRS of every geotechnical unit of the cut slopes is increased by one class while its SPA is reduced by stipulated unit of measurement (i.e. 0.1m). However, no SPA values that are at the limit of 0.005m are decreased because it will become zero, which is not realistic.
- Use of low IRS and large SPA - i.e. Low strength and large block size of rock materials. This is process whereby IRS of every geotechnical unit of the cut slopes is decreased by one class while its SPA is increased by stipulated unit of measurement (i.e. 0.1m). However, no IRS values that are at the limit of 1.25MPa are decreased because it will become zero, which is not realistic.

3.4.1.4. **Weathering rates assessment**

Assessment of weathering rate in this study is based on the slope friction and cohesion (SCOH and SFRI) of recent and old cut slopes made at different times. The steps followed in the analysis are:

- Determination of required cut slopes parameters (observed WE, SCOH and SFRI, and t) using SSPC method.
- Determination of weathering rates of the SFRI and SCOH at different times of the cut slopes.
- Probability values.

- **Determination of required cut slopes parameters**

The dataset (table 0.1 and 0.2 (appendix 3)) used for weathering rates assessment purpose of the 15 selected cut slopes are acquired through SSPC method. The measured IRS, observed WE, SPA and CD of the cut slopes are used to calculate SCOH and SFRI values for the present and past dates of excavation using equations (v) to (xviii). The calculated SCOH and SFRI values of recent (0 to 7 years), medium (10 years; in two cut slopes) and old (20 to 33 years) cut slopes are plotted against exposure time (t) and observed WE for each of the 15 selected cut slopes at various exposure times (t). The SFRI and SCOH values are also plotted against exposure time (t) and observed WE for the geological formations (i.e. AR?nc1 and AR?nc2).

- **Determination of weathering rates**

Huisman (2006) used an experimental expression (equation xxii) propounded by Colman (1981) to explain and calculate the weathering rate of particular rock slopes. This expression is also used, but SFRI and SCOH at time of excavation and after time t are used instead of observed WE at time of excavation and after time t in determining the weathering rates of cut slopes in the study area.

$$P / P_O = C_1 + C_2 \log (1 + t) \text{ --- (xxii)}$$

Where:

P = Concentration of glass in volcanic ashes (%) at time t
P_O = Initial concentration of glass in volcanic ashes (%)
C_1 and C_2 = Coefficients (constants)
t = Exposure time (years) (Colman, 1981).

By replacing the terms in equation (xxii) with SFRI and SCOH, the equation becomes

$$SFRI\ (t) = SFRI_{init} - R_{app\ (WE)} \log (1 + t)$$

$$R_{app\ (WE)} = \frac{SFRI\ (t) - SFRI_{init}}{\mathrm{Log}\ (1 + t)} \text{ --- (xxiii)}$$

If SFRI is replaced by SCOH, the equation (xviii) becomes

$$R_{app\ (WE)} = \frac{SCOH\ (t) - SCOH_{init}}{\mathrm{Log}\ (1 + t)} \text{ -- (xxiv)}$$

Where

$\nabla SCOH = SCOH\ (t) - SCOH_{init}$ (in degrees)
$\nabla SFRI = SFRI\ (t) - SFRI_{init}$ (in KPa)

Equations (xxiii) and (xxiv) are used in determining weathering rates (in terms of SFRI and SCOH) for all the cut slopes in the AR?nc1 and AR?nc2 geological formations. The results are used in plotting ∇SCOH and ∇SFRI against logarithmic scale of exposure time (t) as shown in fig. 5.5.

- **Determination of probability values for the geological formations**

The weathering rates values from equations (xxiii) and (xxiv) are substituted into equation (xxv). The derived results are converted to probability values for the weathering rates of each geological formation by checking for their equivalents in Z-score table (appendix 4) (Tuttuh-Adegun, et al., 1997).

$$Pr\ (Z) = (Z - \text{mean})/\text{standard deviation} \text{ ------------------------------------ (xxv)}$$

Where:

Z = required weathering rate value (s) for each geological formation
Mean = mean of all the weathering rate values for each geological formation

3.4.2. Spatial analysis

A spatial weathering analysis is carried out for the Yen Bai city area using the data acquired from field through measurement and calculation (using SSPC method), while the geological and contour maps are acquired from the Ministry of Geology and Mineral Resources, Hanoi, Vietnam (Vinh and Hoanh, 2004). The data used in this analysis are AP, exposure time (t), observed WE, RFRI, RCOH, STC and slope geometry (i.e. SD, SDD and H_{slope}). The exposure time, observed WE and slope geometry are acquired directly from field, while RFRI and RCOH are calculated from IRS, SPA and CD using SSPC method (equations xii & xiii). The RFRI, RCOH and observed WE values are interpolated and combined with the geological map to produce rock maps using ArcGIS software (Arcmap). The maps are prepared based on the average and overall interpolated RFRI and RCOH values for the observed WE layers. The overall RFRI and RCOH maps are used in slope stability analysis, while average interpolated RFRI and RCOH maps are used in weathering rate analysis. Digital Elevation Map (DEM) is produced from contour map (with a cell size of 5m), slope and aspect maps are produced from the DEM map using ArcGIS software (Arcmap). The flow chart for the analysis is shown in fig. 3.7.

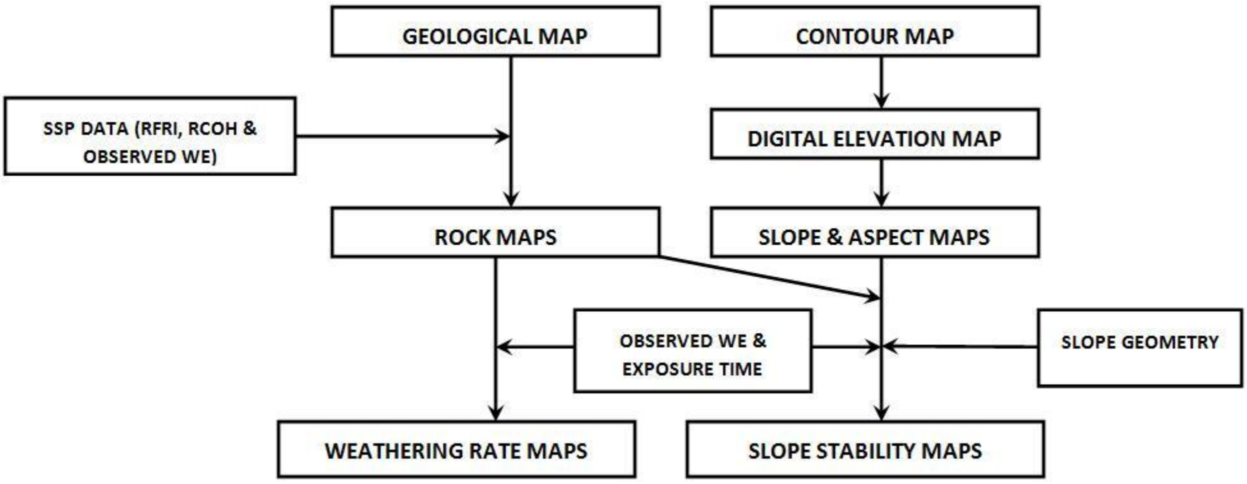

Figure 3.7: Flow diagram for the spatial analysis

- **Slope stability assessment**

The slope stability assessment is also carried out in two ways – orientation independent and dependent stability. The slope stability assessment is carried out in SSPC since it depends on the geotechnical parameters of the rock mass cut slope and could not be analyzed in this study using GIS. However, the interpolated values from the created RFRI, RCOH and observed WE maps used for the weathering rates analysis in GIS with slope geometry parameters of the series of selected cut slopes are used for the assessment. The interpolated RCOH and RFRI values (i.e. COH_{RRM} and φ_{RRM}) are substituted for the SCOH and SFRI (i.e. COH_{SRM} and φ_{SRM}) in equation (xix). The overall stability for the selected slopes are calculated using the overall height (H_{slope}) of each selected slope, while the stability for the observed WE layers are calculated using the defined weathering profile (fig. 5.2).

- **Creation of weathering rate maps**

The weathering rate maps are created by applying equations (xxiii) and (xxiv) using raster calculator in ArcGIS. The ∇SCOH and ∇SFRI in the equations are replaced by interpolated ∇RCOH and ∇RFRI values for each weathering layer (fig. 5.2). The analysis is in two steps:

- Creation of weathering rate map for each weathering layer.
- Creation of overall weathering rates maps for each geological formation and the whole study area.

The probability values for the weathering rates spatial analysis are then derived by applying equation (xxv) using raster calculator.

4. FIELD DATA

4.1. Introduction

During fieldwork, from the inspected 35 cut slopes (fig. 3.2), the best 15 cut slopes are selected for the purpose of this study. 6 slopes are within the AR?nc2 paleo-proterozoid geological formation (i.e. Y1, Y6, Y14, Y18, Y20 and Y21), while the remaining 9 slopes are within the AR?nc1 paleo-proterozoid geological formation (Y2, Y4, Y11, Y12, Y13, Y24, Y27, Y28 and Y33). However, field data of 6 cut slopes (i.e. Y1, Y2, Y4, Y6, Y24 and Y27) are expressed under this chapter, while the remaining 9 cut slopes are expressed under appendix 1. Though the summary of all the 15 cut slopes are expressed in table 4.1 and 4.2 at the end of this chapter.

4.2. Description and acquired data of the studied slopes

The acquired field data of the 6 cut slopes are as follows:

4.2.1. Cut slope Y1

The Cut slope Y1[2] is located at Group 15, Yen Ninh commune, beside Cao Thang street, Yen Bai city (Easting: 514171; Northing: 2402194) (fig 4.1, appendix 1 (fig. 0.5–0.7)). The rock mass length and height are approximately 100m by 17m. The slope was excavated (using a mechanical excavator (fig.0.1 (appendix 1); no visible excavation damage) for building construction purpose, which makes only 25m of its length to be easily accessible while the remaining length is not easily accessible because they are directly behind existing buildings. The rock mass is in the AR?nc2 paleo-proterozoid geological formation and consists of porphyritic granite (feldspar) & crystalline schist (intercalated with different rock minerals like amphibolites and chlorites) with medium grain size and well-developed undulose foliation. The granite has off-white with yellow stain colour while the schist with different rock minerals have colours varying from reddish black to light brown. The different lithologies are shown in fig. 4.1.

The rock mass of slope Y1 has three cut slopes excavated at different times; denoted recent, medium and an old cut. The recent cut slope is two months old; the medium cut slope is ten years old while the old cut slope is thirty years old.

4.2.1.1. Recent cut slope

The recent cut slope (fig.4.1) is easily accessible with total mapped length of 20m; SDD and SD angle of 045^0 and 59^0 respectively. The slope has large problem because the top part is unstable as shown by the slit (indicated at the right hand top side in fig 4.1). The direction of view of the slope is 225^0 and the accessible part of this slope (up to 3m) is divided into three geotechnical units – G1, G2, and G3. The geotechnical units are described as follows:

GEOTECHNICAL UNIT G1 – It has approximate length of 7m and is divided into two sub-geotechnical units G11 and G12 (fig. 4.1). G11 is porphyritic granite, which has off-white with yellow stain colour. Its SPA is 0.90m; the SDD_{disc} and SD_{disc} (i.e. joint orientations) are $002^0/50^0$, $075^0/75^0$ and $065^0/65^0$ (fig.0.2; appendix 1); persistent >3m along strike and dip; large-scale roughness (Rl) is slightly wavy, small-scale roughness (Rs) is rough stepped; no infill material (lm) and karst (Ka). The WE for the unit is slightly weathered. While G12 is crystalline amphibolitic-schist, which has its colour varying from reddish black to light brown. Its SPA is 0.85m; the SDD_{disc} and SD_{disc} (i.e. joint orientations) are $005^0/85^0$, $075^0/75^0$ and $065^0/65^0$ (fig.0.3; appendix 1); persistent >3m along strike and dip; large-scale roughness (Rl) is slightly wavy, small-scale roughness (Rs) is rough stepped; infill material (lm) is clay and no karst (Ka). The WE for the unit is moderately weathered. GEOTECHNICAL UNIT G2 – It has approximate length of 7.8m and is divided into two sub-geotechnical units G21 and G22 (fig.4.1). G21 is porphyritic granite, which has off-white with yellow stain colour. Its SPA is 0.90m; the SDD_{disc} and SD_{disc} (i.e. joint orientations) are $002^0/50^0$, $075^0/75^0$ and $065^0/65^0$ (fig. 0.2; appendix 1);

[2] The state of weathering for the geotechnical units of Cut slope Y1 – recent and medium were erroneously assessed due to early inexperience and indecision of the observer during fieldwork. Nevertheless, corrected on 25/11/2010 (after the fieldwork).

persistent >3m along strike and dip; large-scale roughness (Rl) is slightly wavy, small-scale roughness (Rs) is rough stepped; no infill material (lm) and karst (Ka). The WE for the unit is slightly weathered. While G22 is crystalline amphibolitic-schist, which has its colour varying from reddish black to light brown. Its SPA, SDD_{disc} and SD_{disc} are the same with sub-unit G21; persistent >3m along strike and dip; large-scale (Rl) roughness is slightly wavy, small-scale roughness (Rs) is rough stepped; infill material (lm) is clay and no karst (Ka). The WE for the unit is moderately weathered.

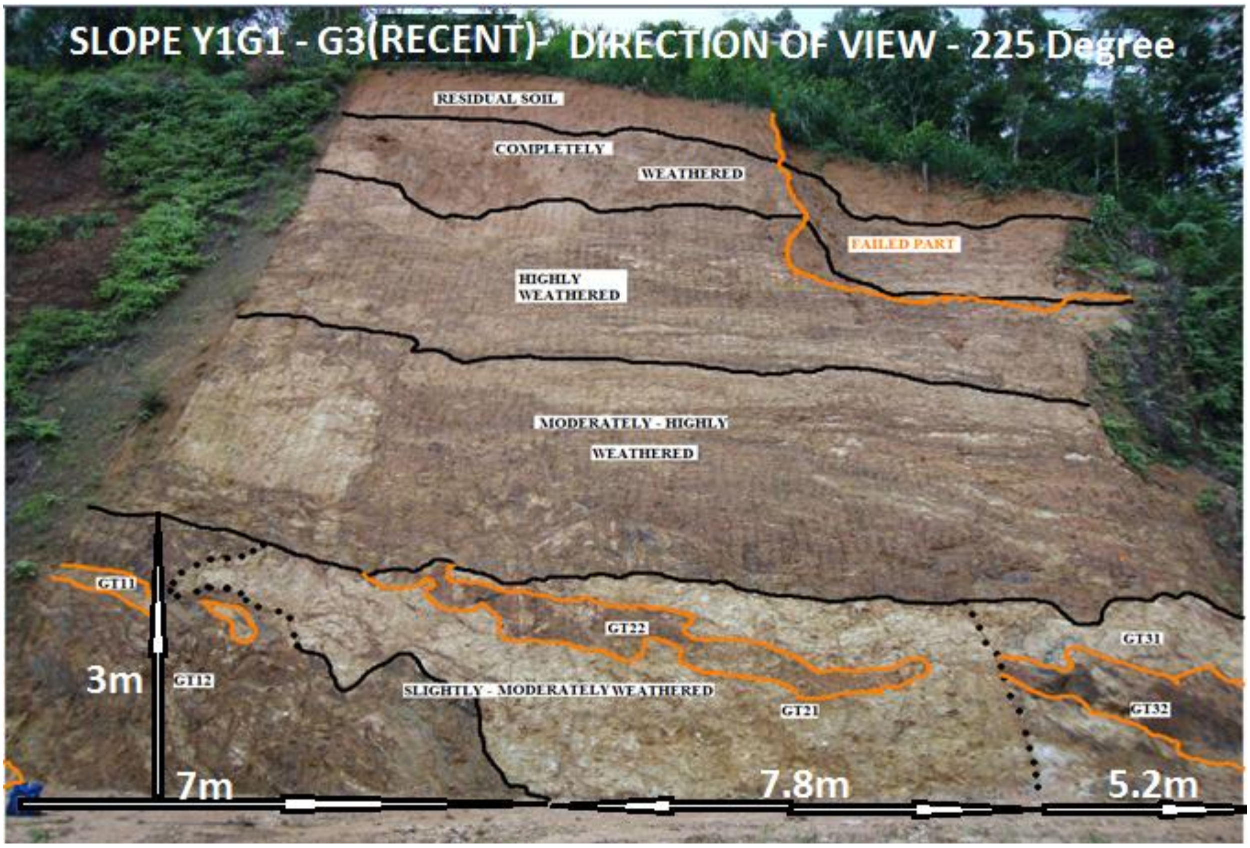

Figure 4.1: The different lithologies and degrees of weathering (see table 3.3) for the recent cut of Slope Y1 (Direction of view - 225^{O})

GEOTECHNICAL UNIT G3 – It has total length of 5.2m and is divided into two sub-geotechnical units G31 and G32 (fig.4.1). G31 is porphyritic granite, which has off-white with yellow stain colour. Its SPA is 0.90m; the SDD_{disc} and SD_{disc} (i.e. joint orientations) are $004^0/70^0$, $032^0/55^0$ and $040^0/50^0$ (fig. 0.4; appendix 1); persistent >3m along strike and dip; large-scale roughness (Rl) is slightly wavy, small-scale roughness (Rs) is rough stepped, no infill material (lm) and karst (Ka). The WE for the unit is slightly weathered. While G32 is crystalline chlorite –schist, which has its colour varying from dark to light green. Its SPA is 0.85m; the SDD_{disc} and SD_{disc} (i.e. joint orientations) are $016^0/70^0$, $032^0/55^0$ and $040^0/50^0$ (fig. 0.4; appendix 1); persistent >3m along strike and dip; large-scale roughness (Rl) is slightly wavy, small-scale roughness (Rs) is rough stepped; infill material (lm) is clay and no karst (Ka). The WE for the unit is moderately weathered.

4.2.1.2. **Medium cut slope**

The accessibility of the medium cut slope is fair with mapped length of 5m; SDD and SD angle of 0450 and 750 respectively(fig. 0.5; appendix 1); hence, cannot be easily reached since it is behind and very close to a building. It has the same type of parent formation materials as the recent slope of Y1. The H_{slope} is the same as the recent slope. The slope is unstable as shown by the slits on every parts of the slope. It has only one geotechnical unit – G4 and is divided into two sub-geotechnical units G41 and G42. G41 is porphyritic granite, which has off-white with yellow stain colour and kaolinite clay patches. While G42 is crystalline amphibolite-schist, which has its colour varying from reddish black to light brown. The slope face is covered with algae and ferns, which makes the characterization of the discontinuities impossible. It is assumed that the SDD_{disc}, SD_{disc}, SPA and CD are the same as the G3 geotechnical unit of the recent slope. The WE for the unit is moderately weathered.

4.2.1.3. Old cut slope

The old cut slope is not easily accessible because it is directly behind existing buildings. It has total length of approximately 75m. The parent formation materials, H_{slope} and SD angle are assumed the same as the recent slope. The slope has large problem because the top part is unstable as shown by the slit (indicated at the centre and left hand top side in fig. 0.6 (appendix 1). Some parts lower in the slope contain kaolinite clay, very wet and covered by ferns, alga and bushes (fig.0.7; appendix 1).

An accessible part of 7m length was mapped out of the old slope total length (fig.0.7; appendix 1) and considered as one geotechnical unit – G5, which is divided into two sub-geotechnical units G51 and G52. G51 is porphyritic granite with large quantity of crypto – crystalline and soapy kaolinite clay, which has white colour. While G52 is weathered schist, which has its colour varying from dark brown to light brown. The slope face is covered with algae and ferns, which makes the characterization of the discontinuities impossible. For the unit, it is assumed that the SDD_{disc} and SD_{disc} are the same as the G1 geotechnical unit of the recent slope. While SPA is 0.005m (fig. 0.8; appendix 1)[3]; large-scale roughness (Rl) is slightly wavy, small-scale roughness (Rs) is rough undulating; infill material (lm) is clay, no karst (Ka) and the WE is highly weathered (for both sub-geotechnical units G51 and G52).

4.2.2. Cut slope Y2

The Cut slope Y2 is located at Group 34, Dong Tam commune, behind Yen Bai Newspaper office nearby Hoa Lam hotel, Yen Bai city (Easting: 516543; Northing: 2402132)(fig. 0.9 & 0.10; appendix 1). The rock mass length and height are approximately 100m by 23m respectively. The slope was excavated (using mechanical excavator; no visible excavation damage) for building construction purpose, which makes only 50m of its length to be easily accessible while the remaining length is not easily accessible because they are directly behind existing buildings. The rock mass is in AR?nc1 paleo-proterozoid geological formation and consists of porphyritic granite (feldspar) & crystalline schist (intercalated with different rock minerals like mica and garnet) with medium grain size and well-developed undulose foliation. The granite has ash/gray with brown stain colour while the schist with different rock minerals have colours varying from reddish black to brown. The different lithologies are shown in fig. 4.2, 0.9 & 0.10 (appendix 1). The rock mass of slope Y2 has two cut slopes excavated at different times; denoted recent and an old cut. The recent cut slope is three years old while the old cut slope is thirty years old.

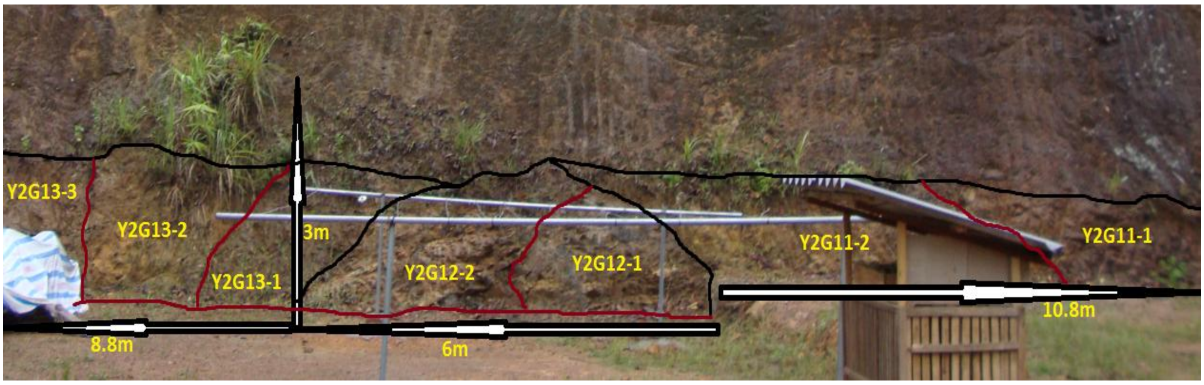

Figure 4.2: The different geotechnical units for the recent cut of Slope Y2

4.2.2.1. Recent cut slope

The recent cut slope (fig. 0.9 & 0.10; appendix 1) is easily accessible with total mapped length of 38m; SDD and SD angle of 280^0 and 64^0 respectively. The slope was cut into steps along its height to enhance its stability. The height and SD angle of the first step (bench) is approximately 8m and 45^0 respectively. The direction of view of the slope is 100^0 and the accessible part of this slope (up to 3m) is divided into five geotechnical units – G11, G12, G13, G14, and G15a. The geotechnical units are described as follows:

[3] Small block size (i.e. spacing of 0.005m) with large IRS is considered for geotechnical unit G5 due to inaccessibility and impossibility of characterization of discontinuities.

GEOTECHNICAL UNIT G11 – It has approximate length of 11m and is divided into two sub-geotechnical units G11-1 and G11-2 (fig.4.2). G11-1 is crystalline garnet-schist, which has its colour varying from reddish black to brown. Its SPA are 0.06m, 0.07m and 0.1m; the SDD_{disc} and SD_{disc} (i.e. joint orientations) are $275^0/85^0$, $330^0/70^0$ and $240^0/85^0$; persistent >10m along strike and >3m along dip; large-scale roughness (Rl) is wavy, small-scale roughness (Rs) is rough stepped; infill material (lm) is clay and no karst (Ka). The WE for the unit is moderately weathered. While G11-2 is also crystalline garnet-schist, which has ash with black/brown stain colour. Its SPA are 0.05m, 0.07m and 0.1m; the SDD_{disc} and SD_{disc} (i.e. joint orientations) are $280^0/80^0$, $330^0/75^0$ and $220^0/85^0$; persistent >10m along strike and >3m along dip; large-scale roughness (Rl) is wavy, small-scale roughness (Rs) is rough stepped; infill material (lm) is non-sheared material and no karst (Ka). The WE for the unit is moderately weathered.
GEOTECHNICAL UNIT G12 – It has approximate length of 6m and is divided into two sub-geotechnical units G12-1 and G12-2 (fig.4.2). G12-1 is crystalline garnet-schist, which has its colour varying from reddish black to brown. Its SPA are 0.05m, 0.06m and 0.08m; the SDD_{disc} and SD_{disc} (i.e. joint orientations) are $300^0/85^0$, $240^0/65^0$, $010^0/70^0$, $210^0/85^0$ and $270^0/60^0$ (fig.0.11; appendix 1); persistent >3m along strike and <3m along dip; large-scale roughness (Rl) is wavy, small-scale roughness (Rs) is rough stepped; no infill material (lm) and karst (Ka). The WE for the unit is slightly weathered. While G12-2 is also crystalline garnet-schist, which has its colour varying from reddish black to brown. Its SPA are 0.05m, 0.06m and 0.1m; the SDD_{disc} and SD_{disc} (i.e. joint orientations) are $280^0/80^0$, $320^0/70^0$, $235^0/70^0$, $005^0/80^0$and $250^0/40^0$ (fig. 0.12; appendix 1); persistent >3m along strike and <3m along dip; large-scale roughness (Rl) is wavy, small-scale roughness (Rs) is rough stepped; infill material (lm) is non-sheared material and no karst (Ka). The WE for the unit is moderately weathered.
GEOTECHNICAL UNIT G13 – It has approximate length of 9m and is divided into three sub-geotechnical units G13-1, G13-2, and G13-3 (fig. 4.2). G13-1 is crystalline mica-schist, which has reddish black colour. Its SPA are 0.06m, 0.06m and 0.1m; the SDD_{disc} and SD_{disc} (i.e. joint orientations) are $320^0/70^0$, $235^0/70^0$, and $005^0/80^0$ (fig. 0.12; appendix 1); persistent >3m along strike and <3m along dip; large-scale roughness (Rl) is wavy, small-scale roughness (Rs) is rough stepped; infill material (lm) is non-sheared material and no karst (Ka). The WE for the unit is moderately weathered. G13-2 is porphyritic granite, which has gray with brown stain colour. It is assumed that the SDD_{disc}, SD_{disc} and CD are the same as the G13-1sub-geotechnical unit. Its SPA is 0.005m (fig. 0.8; appendix 1). The WE for the unit is slightly weathered. Non-accessibility makes the characterization of the discontinuities for sub-geotechnical unit G13-3 impossible. A visual inspection from far showed that the parent material is the same as that of G13-1; hence, it is assumed that the mass characteristics are the same as the G13-1 sub-geotechnical unit.
GEOTECHNICAL UNIT G14 – It has approximate length of 9m and one geotechnical unit. It has degree of weathering which is higher than the other part of recent cut slope (fig. 0.9 & 0.10; appendix 1) because of human influence over its surface. It is being used for transportation of log of woods from ground level to the top of the slope (mountain). This quicken up its degree of weathering with time due to its surface opening to weathering agent / process and disturbance through this influence. It is crystalline mica-schist, which has its colour varying from reddish black to brown. It is assumed that the SDD_{disc}, SD_{disc} and SPA are the same as the G13 geotechnical unit (persistent >10m along strike); large-scale roughness (Rl) is slightly wavy, small-scale roughness (Rs) is rough stepped; infill material (lm) is clay and no karst (Ka). The WE for the unit is highly weathered.
GEOTECHNICAL UNIT G15a – It has approximate length of 3m and one geotechnical unit (fig.0.10; appendix 1). It is crystalline mica-schist, which has its colour varying from reddish black to brown. Its SPA are 0.06m, 0.07m and 0.1m; the SDD_{disc} and SD_{disc} (i.e. joint orientations) are $200^0/85^0$, $285^0/70^0$ and $310^0/70^0$; persistent >3m along strike and dip; large-scale roughness (Rl) is wavy, small-scale roughness (Rs) is rough stepped; infill material (lm) is clay and no karst (Ka). The WE for the unit is moderately weathered.

4.2.2.2. **Old cut slope**

The old cut slope is accessible (though it is directly behind agricultural plantation) with mapped length of 12m and SD angle of 71^0 (SDD is the same as the recent cut). The slope has large problem because the top part is unstable as shown by the slit (fig. 0.10; appendix 1). The accessible part of this slope (up to 3m) has one geotechnical unit (G15b) of weathered schist with its colours varying from reddish black to light brown. It is assumed that the SDD_{disc} and SD_{disc} are the same as the G15a geotechnical unit; Its SPA is 0.005m; large-scale roughness (Rl) is wavy, small-scale roughness (Rs) is smooth undulating; infill material (lm) is clay and no karst (Ka). The WE for the unit is completely weathered.

4.2.3. Cut slope Y4

The Cut slope Y4[4] is located at Group 22, Dong Tam street nearby Stadium / Hieu street, Yen Bai city (Easting: 516106; Northing: 2403452) (fig. 4.3 & 0.13 (appendix 1)). The rock mass length and height is approximately 60m by 17m respectively. The slope was excavated (using mechanical excavator; no visible excavation damage) for building construction purpose, which makes only 24m of its length to be easily accessible while the remaining length is not easily accessible because they are directly behind existing buildings. The rock mass materials is in the AR?nc1 paleo-proterozoid geological formation and consists of porphyritic granite (cryptocrystalline quartz and feldspar) & crystalline mica-schist with fine to medium grain size and well-developed undulose foliation. The granite has white colour while the mica-schist has its colour varying from reddish black to light brown. The different lithologies are shown in (fig. 4.3 & 0.13 (appendix 1)). The rock mass of slope Y4 has three cut slopes excavated at different times; denoted recent, medium and an old cut. The recent cut slope is one week old; the medium cut slope is five years old while the old cut slope is thirty years old.

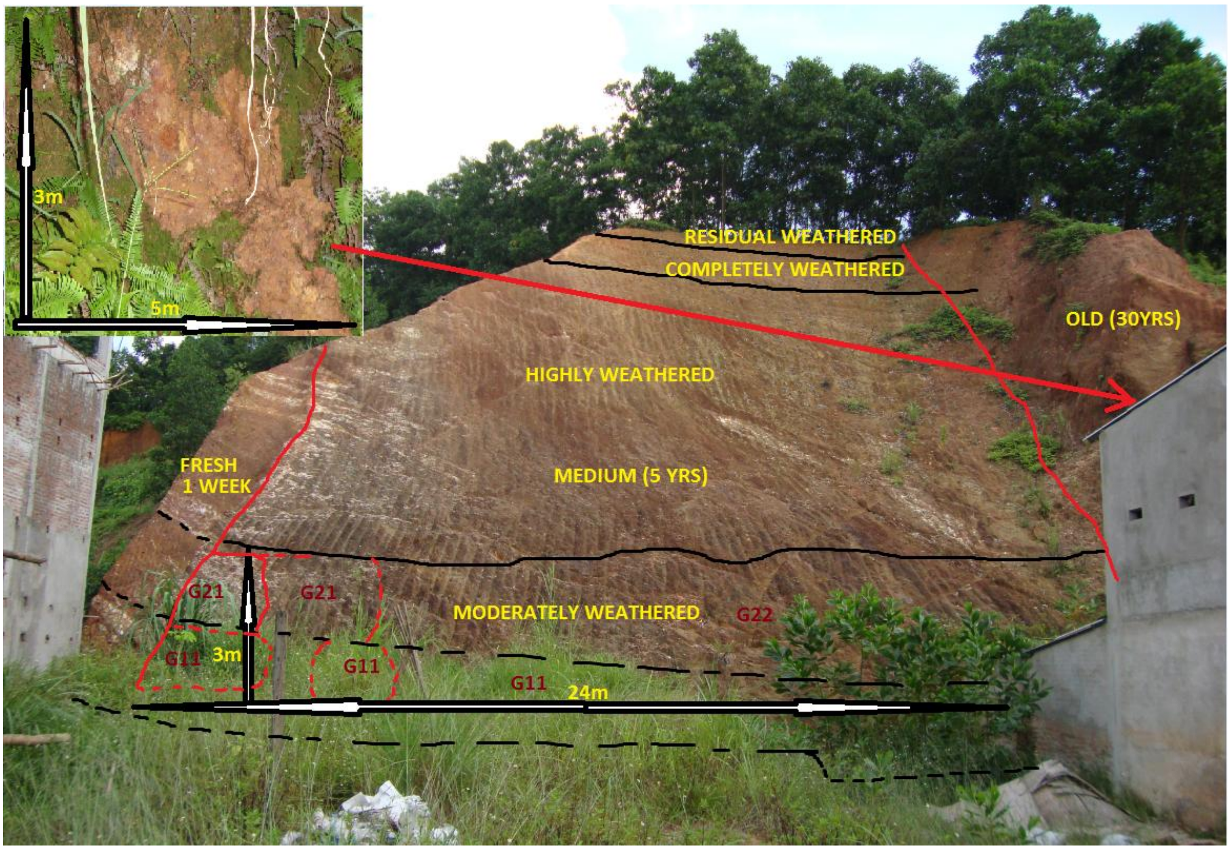

Figure 4.3: The different lithologies and degrees of weathering (see table 3.3) for the medium cut of Slope Y4 (Direction of view - 145^{O})

4.2.3.1. Recent cut slope

The recent cut slope (fig. 0.13; appendix 1) is easily accessible with total mapped length of 14m; SDD and SD angle of 005^{0} and 77^{0} respectively. The slope is not easily accessible (not easily accessible because it is directly behind ongoing constructed building), stable and very steep. The direction of view of the slope is 185^{0} and the

[4] The name of the geotechnical units of Cut slope Y4 (i.e. G11, G21, G31 and G41) were assessed during the fieldwork using the rock minerals names alone. Nevertheless, corrected using the rock name on 25/11/2010 (after the fieldwork) during the write-up.

accessible part of this slope (up to 3m) is divided into two geotechnical units – G3 and G4. The geotechnical units are described as follows:

GEOTECHNICAL UNIT G3 – It has approximate length of 14m and is divided into two sub-geotechnical units G31 and G32 (fig.0.12; appendix 1). G31 is porphyritic granite, which has white colour. Its spacing of discontinuity sets are 0.005m, 0.008m and 0.01m; the SDD_{disc} and SD_{disc} (i.e. joint orientations) are $019^0/60^0$, $025^0/55^0$, $045^0/70^0$, $050^0/80^0$ and $330^0/85^0$ (fig. 0.14; appendix 1); persistent >3m along strike and dip; large-scale roughness (Rl) is slightly wavy, small-scale roughness (Rs) is rough stepped; infill material (lm) is fine clay and no karst (Ka). The WE for the unit is highly weathered. While G32 is crystalline mica-schist, which has its colour varying from reddish black to brown. Its SPA are 0.06m, 0.1m and 0.1m; the SDD_{disc} and SD_{disc} (i.e. joint orientations) are $045^0/70^0$, $290^0/30^0$ and $330^0/85^0$ (fig. 0.14; appendix 1); persistent >3m along strike and dip; large-scale roughness (Rl) is wavy, small-scale roughness (Rs) is rough stepped; infill material (lm) is fine non-sheared material and no karst (Ka). The WE for the unit is slightly weathered.

GEOTECHNICAL UNIT G4 – It also has approximate length of 14m and is divided into two sub-geotechnical units G41 and G42 (fig. 0.13; appendix 1). G4 has the same parent formation materials and units as G3 geotechnical unit (recent cut slope Y4). Hence, it is assumed that the SDD_{disc}, SD_{disc}, SPA and CD (except infill material (lm) of G42, which is fine clay) are the same as the G3. The WE for the sub-geotechnical units G41 and G42 are highly and moderately weathered respectively.

4.2.3.2. **Medium cut slope**

The medium cut slope is easily accessible with total mapped length of 24m and SDD of 325^0 ((fig. 4.3). The cut slope has two SD angles – the bottom SD angle is 37^0 (from the ground level to height of approximately 10m) and the top SD angle is 64^0 (from the remaining height of approximately 7m). The direction of view of the slope is 145^0 and the accessible part of this slope (up to 3m) is divided into two geotechnical units – G1 and G2. The geotechnical units are described as follows:

GEOTECHNICAL UNIT G1 – It has approximate length of 24m and is divided into two sub-geotechnical units G11 and G12 (fig. 4.3). G11 is porphyritic granite, which has white colour. Its spacing of discontinuity sets are 0.06m, 0.1m, 0.1m and 0.1m; the SDD_{disc} and SD_{disc} (i.e. joint orientations) are $040^0/70^0$, $280^0/30^0$, $310^0/80^0$ and $330^0/90^0$ (fig. 0.15; appendix 1); persistent >3m along strike and dip; large-scale roughness (Rl) is wavy, small-scale roughness (Rs) is rough undulating; infill material (lm) is fine clay and no karst (Ka). The WE for the unit is highly weathered. While G12 is crystalline mica-schist, which has its colour varying from reddish black to light brown. Its SPA are 0.06m, 0.1m and 0.1m; the SDD_{disc} and SD_{disc} (i.e. joint orientations) are $280^0/30^0$, $310^0/80^0$ and $330^0/90^0$ (fig. 0.15; appendix 1); persistent >3m along strike and dip; large-scale roughness (Rl) is wavy, small-scale roughness (Rs) is rough stepped; infill material (lm) is fine clay and no karst (Ka). The WE for the unit is moderately weathered.

GEOTECHNICAL UNIT G2 – It also has approximate length of 24m and is divided into two sub-geotechnical units G21 and G22 (fig. 4.3). G2 has the same parent formation materials and units as G1 geotechnical unit (medium cut slope Y4). Hence, it is assumed that the SDD_{disc}, SD_{disc}, SPA and CD are the same as the G1. The WE for the sub-geotechnical units G21 and G22 are highly and moderately weathered respectively.

4.2.3.3. **Old cut slope**

The old cut slope is not easily accessible because it is directly behind existing buildings. It has total mapped length of 5m and is unstable (fig. 4.3 & 0.16 (appendix 1)). The H_{slope} and SDD are the same as the medium slope, while the SD angle is 63^0 (rough estimation). The direction of view of the slope is 145^0 and the accessible parts (up to 3m) of this slope has one geotechnical unit – G5, which is divided into two sub-geotechnical units G51 and G52. G51 is crypto – crystalline and soapy kaolinite clay, which has white colour. While G52 is soil with mica-schist fragment, which has its colour varying from dark brown to light brown. The slope face is covered with algae and ferns, which makes the characterization of the discontinuities impossible. For the unit, it is assumed that the SDD_{disc} and SD_{disc} are the same as the G1 geotechnical unit of the medium slope. While SPA is 0.005m (fig. 0.8; appendix 1); large-scale roughness (Rl) is wavy, small-scale roughness (Rs) is smooth undulating; infill material (lm) is clay, no karst (Ka) and the WE is completely weathered for both sub-geotechnical units.

4.2.4. Cut slope Y6

The Cut slope Y6 is located at Group 17, Cuong Bac hamlet, Nam Cuong commune, Yen Bai city (Easting: 513893; Northing: 2403913) (fig. 4.4). The rock mass length and height are approximately 100m by 11m. The slope is easily accessible, well drained and excavated (using a mechanical excavator; no visible excavation damage) for building and road construction purpose. The rock mass is in the AR?nc2 paleo-proterozoid geological formation and consists of porphyritic granite (feldspar) & crystalline mica-schist with medium grain size and well-developed undulose foliation. The granite has white with yellow stain colour while the mica-schist has colour varying from reddish black to brown. The different lithologies are shown in fig. 4.4. The rock mass of slope Y6 has two cut slopes excavated at different times; denoted recent and an old cut. The recent cut slope is five years old while the old cut slope is twenty years old.

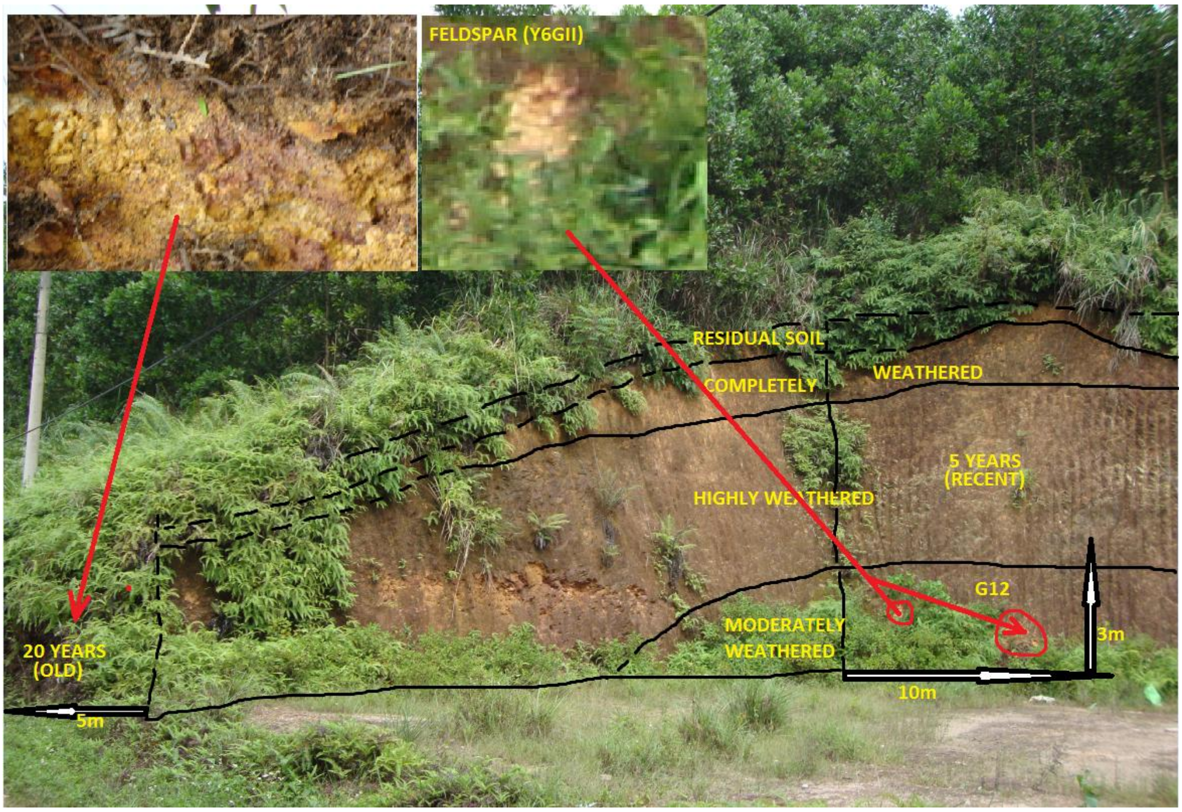

Figure 4.4: The different lithologies and degrees of weathering (see table 3.3) of Slope Y6 (Direction of view - 30^{O})

4.2.4.1. Recent cut slope

The recent cut slope (fig. 4.4) is accessible with total mapped length of 10m; SDD and SD angle of 210^0 and 66^0 respectively. The direction of view of the slope is 030^0 and the accessible (mapped) part of this slope (up to 3m) has one geotechnical unit – G1, which is divided into two sub-geotechnical units G11 and G12. G11 is porphyritic granite, which has white with yellow stain colour. Its SPA is 0.005m. The sub-geotechnical unit's face is covered with bushes, which makes the characterization of the discontinuities impossible. It is assumed that the SDD$_{disc}$, SD$_{disc}$ and CD are the same as the G12 sub-geotechnical unit of the recent slope. The WE for the unit is moderately weathered. While G12 is crystalline mica-schist, which has its colour varying from reddish black to brown. Its SPA are 0.05m, 0.07m and 0.15m; the SDD$_{disc}$ and SD$_{disc}$ (i.e. joint orientations) are 200^0/40^0, 240^0/75^0 and 300^0/70^0 (fig. 0.17; appendix 1); persistent >3m along strike and dip; large-scale roughness (Rl) is wavy, small-scale roughness (Rs) is rough stepped; infill material (lm) is non-sheared material and no karst (Ka). The WE for the unit is moderately weathered.

4.2.4.2. Old cut slope

The old cut slope (fig. 4.4) is accessible with total mapped length of 5m. The parent formation materials, slope dip direction, and dip angle are the same as the recent slope. The accessible (mapped) part of this slope (up to 3m) has one geotechnical unit – G2, which is divided into two sub-geotechnical units G21 and G22. The slope face is covered with algae and ferns, which makes the characterization of the discontinuities impossible. It is assumed that the parent materials, SDD_{disc}, SD_{disc}, SPA and CD (except infill materials (lm), which is fine clay) are the same as the G1 geotechnical unit of the recent slope. The WE is highly weathered for both sub-geotechnical units.

4.2.5. **Cut slope Y24**

The Cut slope Y24 is located at Group 3, Tran Ninh hamlet, Tan Thinh commune, Yen Bai city (Easting: 517839; Northing: 2401074) (fig. 4.5). The rock mass length and height are approximately 31m by 15m. The slope is easily accessible, and excavated (using a mechanical excavator; no visible excavation damage) for building and road construction purpose. The rock mass is in AR?nc1 paleo-proterozoid geological formation and consists of crystalline schist (intercalated with different rock minerals like garnet and mica) with medium grain size and well-developed undulose foliation. The colour varies from reddish black to brown. The different lithologies are shown in fig. 4.5. The rock mass of slope Y24 has two cut slopes excavated at different times; denoted recent and an old cut. The recent cut slope is two years old while the old cut slope is twenty-five years old.

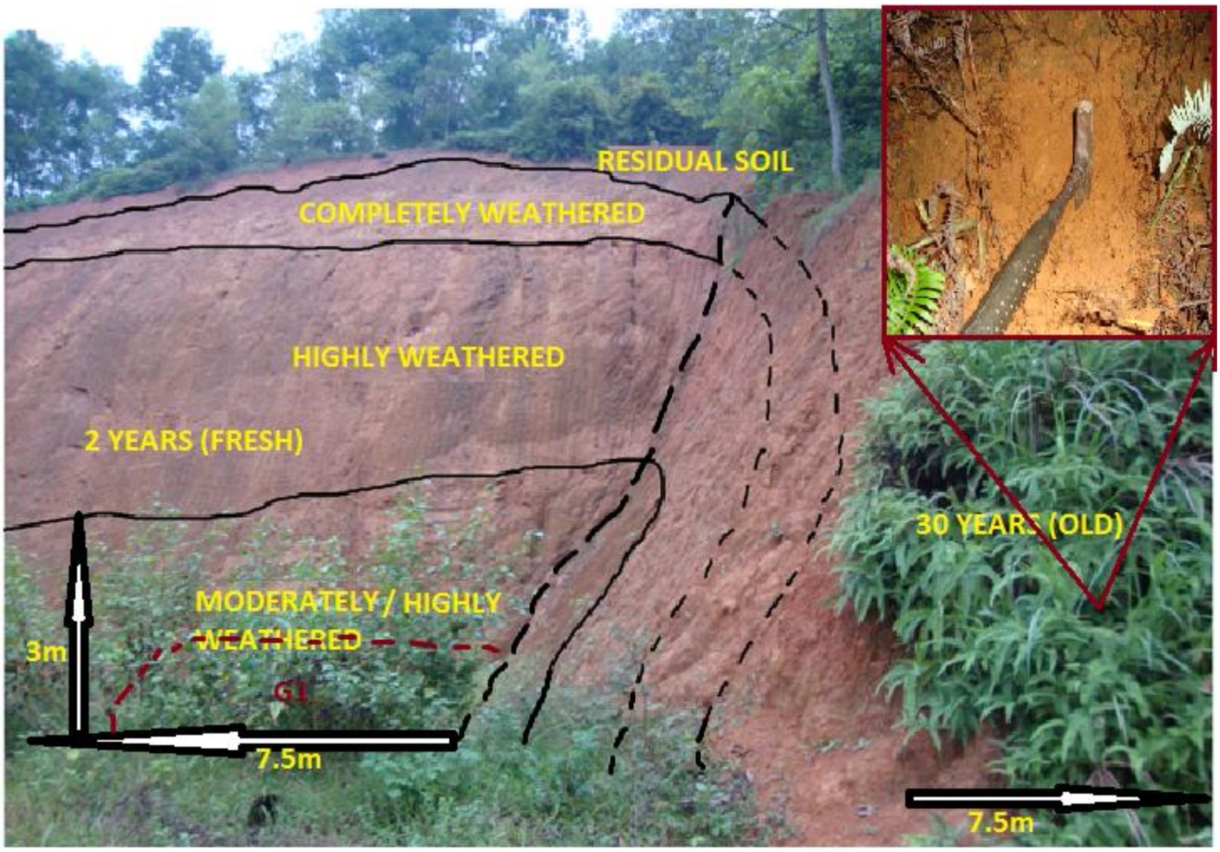

Figure 4.5: The different lithologies and degrees of weathering (see table 3.3) of Slope Y24 (Direction of view - 70^O)

4.2.5.1. **Recent cut slope**

The recent cut slope (fig. 4.5) is accessible with total mapped length of 7.5m; SDD and SD angle of 250^0 and 65^0 respectively. The direction of view of the slope is 070^0 and the accessible (mapped) part of this slope (up to 3m) has one geotechnical unit – G1, which is divided into two sub-geotechnical units G11 and G12. G11 is garnet schist colours varying from reddish black to brown. Its SPA are 0.07m and 0.10m; the SDD_{disc} and SD_{disc} (i.e. joint orientations) are $190^0/70^0$, $240^0/85^0$ and $255^0/55^0$ (fig. 0.28; appendix 1); persistent >3m along strike and dip; large-scale roughness (Rl) is wavy, small-scale roughness (Rs) is rough stepped; infill material (lm) is fine clay and no karst (Ka). The WE for the unit is moderately weathered. While G12 is crystalline garnet-mica-schist, which has its colour varying from reddish black to brown. Its SPA are 0.03m, 0.05m and 0.06m. It is assumed that the SDD_{disc}, SD_{disc} and CD of the unit are the same as the G11 sub-geotechnical unit. The WE for the unit is moderately weathered.

4.2.5.2. Old cut slope

The old cut slope (fig. 4.5) is accessible with total mapped length of 7.5m. The slope dip direction and dip angle are the same as the recent slope. The accessible (mapped) part of this slope (up to 3m) has one geotechnical unit – G21, which is clay soil with light brown colour. Its SPA is 0.002m. The slope face is covered with algae, ferns and bushes, which makes the characterization of the discontinuities impossible. It is assumed that the SDD_{disc}, SD_{disc} and CD of the unit are the same as the G1 geotechnical unit of the recent slope. The WE for the unit is residual soil.

4.2.6. Cut slope Y27

The Cut slope Y27 is located at Group 1, Thanh Niem hamlet, Minh Bao commune, Yen Bai city (Easting: 517839; Northing: 2401074) (fig.4.6 & 0.29 (appendix 1)). The rock mass length and height are approximately 125m by 19m. The slope was excavated (using a mechanical excavator; no visible excavation damage) for building and road construction purpose. The rock mass is in the AR?nc1 paleo-proterozoid geological formation and consists of porphyritic granite (feldspar and quartz) & crystalline mica-schist with medium grain size and well-developed undulose foliation. The granite has white with yellow and light brown stains colour while the mica-schist has colours varying from reddish black to brown. The different lithologies are shown in fig. 4.6.
The rock mass of slope Y27 has two cut slopes excavated at different times; denoted recent and an old cut. The recent cut slope is five years old while the old cut slope is above twenty years old.

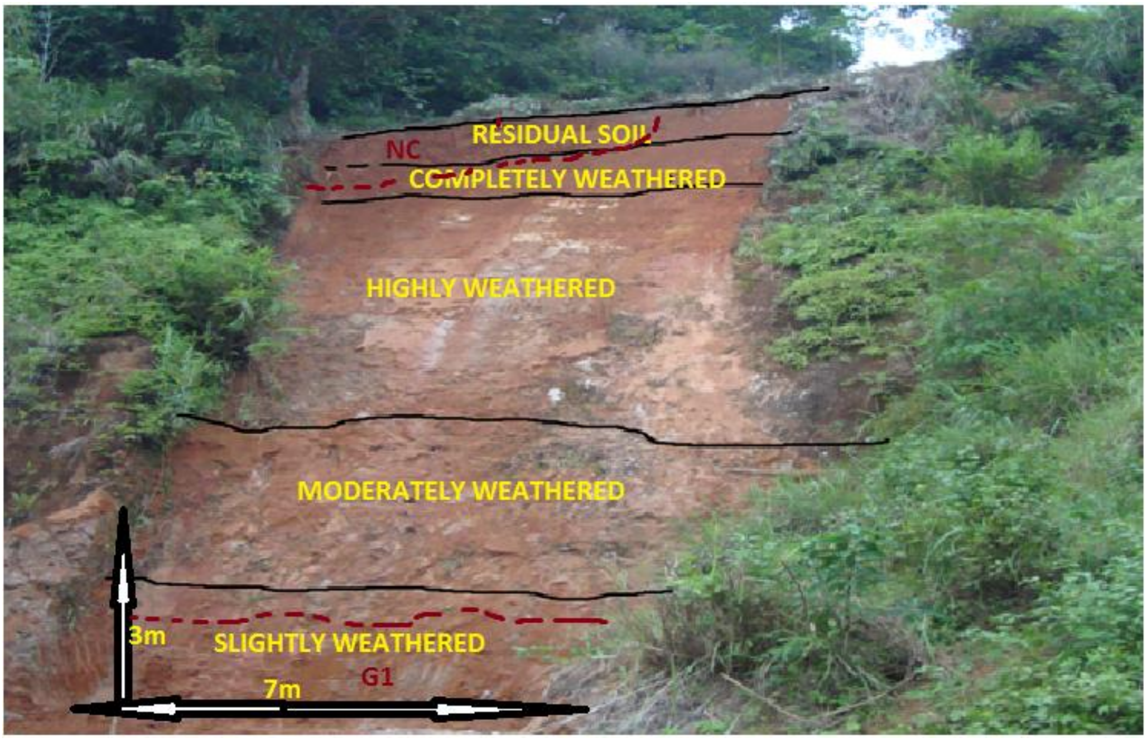

Figure 4.6: The different lithologies and degrees of weathering (see table 3.3) for the recent cut of Slope Y27 (Direction of view - 040^{O})

4.2.6.1. Recent cut slope

The recent cut slope (fig. 4.6) is accessible with total mapped length of 7m; SDD and SD angle of 220^{0} and 65^{0} respectively. The sediment materials from the top cut of the slope (indicated at the left hand top side (NC) in fig 4.6) make the characterization of discontinuities set difficult. The direction of view of the slope is 040^{0} and the accessible (mapped) part of this slope (up to 3m) has one geotechnical unit – G1, which is divided into three sub-geotechnical units G11, G12 and G13. G11 is porphyritic granite (feldspar), which has white with light brown stain colour. Its SPA are 0.03m, 0.06m and 0.12m; the SDD_{disc} and SD_{disc} (i.e. joint orientations) are 160^{0}/75^{0}, 200^{0}/70^{0} and 235^{0}/50^{0}; persistent >3m along strike and dip; large-scale roughness (Rl) is wavy, small-scale roughness (Rs) is rough stepped; infill material (Im) is fine non-sheared material and no karst (Ka). The WE for the unit is slightly weathered. G12 is crystalline mica-schist, which has its colour varying from reddish black to brown. Its SPA are 0.06m, 0.30m and 0.30m. It is assumed that the orientations and condition of discontinuities of the unit are the same as the G11 sub-geotechnical unit. The WE for the unit is slightly weathered. While G13 is porphyritic granite (feldspar and quartz fragment), which has white with yellow stain colour. Its SPA is 0.005m. It is assumed that the SDD_{disc}, SD_{disc} and CD of the unit are the same as the G11 sub-geotechnical unit. The WE for the unit is also slightly weathered.

4.2.6.2. **Old cut slope**

The old cut slope (fig. 0.29; appendix 1) is accessible with total mapped length of 7m. The parent formation materials, SDD, and SD angle are the same as the recent slope. The slope has large problem because it is unstable as shown by the slit (indicated at the left hand side in fig 0.29; appendix 1). The accessible (mapped) part of this slope (up to 3m) has one geotechnical unit – G2, which is divided into two sub-geotechnical units G21 and G22. G21is crystalline mica-schist, which has its colour varying from reddish black to brown, while G22 is porphyritic granite with kaolinite clay, which has white colour. The slope face is covered with algae and ferns, which makes the characterization of the discontinuities impossible. Its SPA is 0.005m. It is assumed that the SDD_{disc}, SD_{disc} and CD (except infill materials (lm), which is fine clay) of the unit are the same as the G1 geotechnical unit of the recent slope. The WE is highly weathered for both sub-geotechnical units.

Generally, the geotechnical unit of recent/medium cut slope that is very close to the old cut slope was considered for the weathering rate study purpose (such that the same rock materials could be found in both cut slopes). Moreover, the SDD_{disc} and SD_{disc} of the old cut slope is assumed the same with that of recent cut slope where it is not accessible. The summary of all the field data acquired for all the selected 15 cut slopes (studied slopes) are shown in table. 4.1 and 4.2.

From the field observation, up to 20 years of exposure, visually the weathering degree seems not to increase. However, visually change in the degree of weathering becomes visible after 20 years of slope's exposure. The medium-grained schist is also more susceptible to weathering than medium/coarse-granite due to presence of mica contents in the schist (Wyllie & Mah, 2004). The high mica contents of the schist materials also resulted in its weak bond, which allows more integral discontinuities to become mechanical.

A slope in the Yen Bai area is seriously liable to failure when its degree of weathering degenerated to highly, completely weathered or residual soil (and the failure could be triggered by weathering agents like human, plant roots, rainfall and erosion). Generally, the slope is made at the maximum angle and slope height that can be sustained in the material at the time of exposure for the top soil layers. In the deeper layers, i.e. in slightly or moderately weathered material, the angle and slope height are not at the maximum at time of exposure, but progressive weathering due to exposure will weather these materials to highly or completely weathered in about 30 years. The slope angle and height cannot be sustained by highly or completely weathered material and the slope will fail (fig. 4.1 – 4.6; fig. 0.2 – fig. 0.32 (appendix 1), table 4.1[5] and 4.2).

[5] Errata: Porphyritic feldspar should be replaced by porphyritic granite (feldspar) and cryptocrystalline quartz by porphyritic granite (quartz)

Table 4.1: Summary of acquired field data for the studied slopes

NAME	GENERAL INFORMATION	MATERIAL CHARACTERISTICS	MASS CHARACTERISTICS
SLOPE Y1	Location: 2402194N / 514171E. Date & method of Excavation: 2mths/10yrs/30yrs (Excavator). Geological formation: AR? nc2 paleo-proterozoid (Granite and metamorphic rock materials).	Accessibility: 3m. Porphyritic feldspar & crystalline schist (amphibolites & chlorite) with medium grain size and well-developed undulose foliation. The colours are of off-white with yellow stain (feldspar) and reddish black to light brown (schist).	Moderately weak, slightly to moderately (recent) and highly (old) weathered. Joints orientation of 002°/50°, 005°/85°, 075°/75°, 065°/65°; spacing 0.005 to 0.90m; persistent >15m along strike and >3m along dip; large-scale roughness is slightly wavy, small-scale roughness is rough stepped, infill materials are fine and coarse, and no karst. Slope dip-direction/dip and height: 045° / 59° (75°) and 17m.
SLOPE Y2	Location: 2402132N / 516543E. Date & method of Excavation: 3 yrs/30yrs (Excavator). Geological formation: AR?nc1 paleo-proterozoid (Granite and metamorphic rock materials).	Accessibility: 3m. Porphyritic feldspar & crystalline schist (garnet & mica) with medium grain size and well-developed undulose foliation. The colours are of ash/gray with brown stain (feldspar) and reddish black to brown (schist).	Moderately strong, slightly to moderately (fresh) and completely (old) weathered. Joints orientation of 240°/85°, 275°/85°, 330°/70°, 210°/85°, 240°/65°, 300°/85°, 010°/70°, 270°/600°, 005°/80°, 235°/70°, 320°/70°, 280°/80°, and 250°/40°, 200°/85°. Spacing 0.005 to >1m; persistent >10m along strike and >3m along dip; large scale roughness is wavy, small scale roughness is rough stepped, infill material is fine and no karst. Slope dip-direction/dip and height: 280° / 45° (75°) and 23m (Old -19m).
SLOPE Y4	Location: 2403452N / 516106E. Date & method of Excavation: 1 week/5yrs/30yrs (Excavator). Geological formation: AR?nc1 paleo-proterozoid (Granite and metamorphic rock materials).	Accessibility: 3m. Porphyritic feldspar, cryptocrystalline quartz & crystalline mica-schist with fine to medium grain size and well-developed undulose foliation. The colours are of off-white (feldspar), transparent white (quartz) and reddish black to light brown (schist).	Weak to moderately strong, slightly to highly (recent) and completely (old) weathered. Joints orientation of 025°/55°, 019°/60°, 050°/80°, 045°/70°, 330°/85°, 310°/80° and 290°/30°; spacing 0.005 to 1m (0.06 to 1m – medium); persistent >3m along strike and >3m along dip; large-scale roughness is slightly wavy, small-scale roughness is rough stepped/rough undulating; infill material is fine and no karst. Slope dip-direction/dip and height: 005° / 37° & 77° (325° /63° - old) and 10m (Old -17m).
SLOPE Y6	Location: 2403913N / 513893E. Date & method of Excavation: 5yrs/20yrs (Excavator). Geological formation: AR?nc2 paleo-proterozoid (Granite and metamorphic rock materials).	Accessibility: 3m. Porphyritic feldspar & crystalline mica-schist with medium grain size and well-developed undulose foliation. The colours are of off-white (feldspar) reddish black to light brown (schist).	Moderately weak, slightly to moderately (recent) and highly (old) weathered. Joints orientation of 002°/50°, 005°/85°, 075°/75°, 065°/65°; spacing 0.005 to 0.90m; persistent >15m along strike and >3m along dip; large-scale roughness is slightly wavy, small-scale roughness is rough stepped, infill materials are fine and coarse, and no karst. Slope dip-direction/dip and height: 045° / 59° (75°) and 17m.
SLOPE Y11	Location: 2403752N / 516377E. Date & method of Excavation: 5yrs/30yrs (Excavator). Geological formation: AR?nc1 paleo-proterozoid (Granite and metamorphic rock materials).	Accessibility: 3m. Porphyritic feldspar & crystalline mica-schist with medium grain size and well-developed undulose foliation (recent); Crypto - crystalline & soapy kaolinite and silty clay soil with fine to medium grain size. The colours are of off-white (feldspar), white (kaolinite) and reddish black to light brown (schist and silty clay).	Weak to moderately strong, Highly (recent) to completely weathered and residual soil (old). Joints orientation 150°/75°, 062°/40°, 230°/80°, 100°/50°, 150°/60° and 130°/70°; spacing 0.002 to 1m; persistent >3m along strike and >3m along dip; large-scale roughness is wavy, small-scale roughness is rough stepped; infill material is fine clay and no karst. Slope dip-direction/dip and height: 150° / 79° and 16m.
SLOPE Y12	Location: 2403860N / 516537E. Date & method of Excavation: 7yrs/30yrs (Excavator). Geological formation: AR?nc1 paleo-proterozoid (Granite and metamorphic rock materials).	Accessibility: 3m. Cryptocrystalline quartz & crystalline mica-schist (amphibolites & mica) and silty clay with fine to medium grain size and well-developed undulose foliation. The colours are of transparent white (quartz) and reddish black to light brown (schist and silty clay).	Moderately weak; Highly (recent) to completely weathered and residual soil (old). Joints orientation 340°/60°, 010°/85°, 235°/65°, 020°/35° and 029°/70°; spacing 0.002 to 1m; persistent >3m along strike and >3m along dip; large-scale roughness is wavy, small-scale roughness is rough undulating; infill material is fine clay and no karst. Slope dip-direction/dip and height: 030° / 76° and 16m.
SLOPE Y13	Location: 2404125N / 516865E. Date & method of Excavation: 1yr/30yrs (Excavator). Geological formation: AR?nc1 paleo-proterozoid (Granite and metamorphic rock materials).	Accessibility: 3m. Porphyritic feldspar & crystalline schist (amphibolites & mica) and silty clay with fine to medium grain size and well-developed undulose foliation. The colours are of ash tainted with black (Feldspar), reddish brown to dark purple (schist) and brown (silty clay).	Moderately weak; Highly (recent) to completely weathered and residual soil (old). Joints orientation 330°/80°, 060°/75°, 003°/65° and 002°/40°; spacing 0.002 to 1m; persistent >3m along strike and >3m along dip; large-scale roughness is wavy/slightly wavy, small-scale roughness is rough stepped / smooth undulating; infill material is fine clay and no karst. Slope dip-direction/dip and height: 005° / 80° (40° – old) and 16m (7.2m).

Table 4.2[6]: Summary of acquired field data for the studied slopes (cont'd).

NAME	GENERAL INFORMATION	MATERIAL CHARACTERISTICS	MASS CHARACTERISTICS
SLOPE Y14	Location: 2404139N / 513542E Date & method of Excavation: 1yr/30yrs (Excavator). Geological formation: AR?nc2 paleo-proterozoid (Granite and metamorphic rock materials).	Accessibility: 3m. Porphyritic feldspar & crystalline amphibolitic-schist with medium grain size and well-developed undulose foliation. The colours are of white (Feldspar) and reddish brown to dark purple (schist).	Moderately strong; Highly (fresh) to completely weathered (old). Joints orientation 065°/80°, 090°/75°, 345°/75° and 050°/60°; spacing 0.005 to 1m; persistent >3m along strike and >3m along dip; large scale roughness is wavy, small scale roughness is rough stepped; infill material is fine clay and no karst. Slope dip-direction/dip and height: 017° / 68° and 10m.
SLOPE Y18	Location: 2401955N / 514539E Date & method of Excavation: 1yr/30yrs (Excavator). Geological formation: AR?nc2 paleo-proterozoid (Granite and metamorphic rock materials).	Accessibility: 3m. Porphyritic feldspar & crypto - crystalline kaolinite with fine to medium grain size. It has ash or white with brown stain colour.	Moderately strong; Highly (recent) to completely weathered (old). Joints orientation 028°/65°, 015°/10°, 290°/60°, 032°/70° and 300°/80°; spacing 0.005 to 0.8m; persistent >3m along strike and >3m along dip; large-scale roughness is wavy, small-scale roughness is smooth stepped; infill material is fine clay and no karst. Slope dip-direction/dip and height: 220° / 60° and 15m.
SLOPE Y20	Location: 2401780N / 515263E Date & method of Excavation: 1yr/30yrs (Excavator). Geological formation: AR?nc2 paleo-proterozoid (Granite and metamorphic rock materials).	Accessibility: 3m. Porphyritic feldspar & crystalline schist (garnet & mica) and clay with fine to medium grain size and well-developed undulose foliation. The colours are of white with brown stain (Feldspar), reddish black to brown (Schist & clay).	Strong; Moderately (recent) to residual soil (old). Joints orientation 260°/45°, 170°/65°, 276°/70° and 330°/85°; spacing 0.002 to >1m; persistent >3m along strike and >3m along dip; large-scale roughness is wavy, small-scale roughness is rough stepped; infill material is fine clay and no karst. Slope dip-direction/dip and height: 200° / 56° and 22m.
SLOPE Y21	Location: 2401611N / 515498E Date & method of Excavation: 8mths/30yrs (Excavator). Geological formation: AR?nc2 paleo-proterozoid (Granite and metamorphic rock materials).	Accessibility: 3m. Porphyritic feldspar, crystalline mica-schist and silty clay soil with fine to medium grain size and well-developed undulose foliation. The colours are of white with yellow stain (feldspar) and reddish black to light brown (schist and silty clay).	Weak; completely (recent) to residual soil (old). Joints orientation 270°/50°, 180°/75° and 295°/55°; spacing 0.002 to 1m; persistent >3m along strike and >3m along dip; large-scale roughness is wavy, small-scale roughness is rough stepped; infill material is fine clay and no karst. Slope dip-direction/dip and height: 200° / 80° and 10m.
SLOPE Y24	Location: 2401074N / 517839E Date & method of Excavation: 2yrs/25yrs (Excavator). Geological formation: AR?nc1 paleo-proterozoid (Granite and metamorphic rock materials).	Accessibility: 3m. Crystalline schist (garnet & mica) and clay with fine to medium grain size and well-developed undulose foliation. The colours are reddish black to brown.	Moderately weak; moderately/highly (recent) to residual soil (old). Joints orientation 190°/70°, 240°/85° and 255°/55°; spacing 0.002 to 1.5m; persistent >3m along strike and >3m along dip; large-scale roughness is wavy, small-scale roughness is rough stepped; infill material is fine clay and no karst. Slope dip-direction/dip and height: 250° / 65° and 15m.
SLOPE Y27	Location: 2405547N / 516423E Date & method of Excavation: 5yrs/20+yrs (Excavator). Geological formation: AR?nc1 paleo-proterozoid (Granite and metamorphic rock materials).	Accessibility: 3m. Porphyritic adamellite and crystalline mica-schist with fine to medium grain size and well-developed undulose foliation. The colours are of white with yellow stain (feldspar) and reddish black to light brown (schist).	Moderately strong; slightly (recent) to highly weathered (old). Joints orientation 235°/50°, 200°/70° and 160°/75°; spacing 0.005 to >1m; persistent >3m along strike and >3m along dip; large-scale roughness is wavy, small-scale roughness is rough stepped; infill material is non-softening & sheared material (recent) and fine clay (old); no karst. Slope dip-direction/dip and height: 220° / 65° and 19m.
SLOPE Y28	Location: 2406958N / 516002E Date & method of Excavation: 2yrs/29yrs (Excavator). Geological formation: AR?nc1 paleo-proterozoid (Granite and metamorphic rock materials). metamorphic rock materials).	Accessibility: 3m. Porphyritic feldspar, crystalline schist and sandy clayey soil with fine to medium grain size and well-developed undulose foliation. The colours are of white with yellow stain (feldspar) and reddish brown to light brown (schist and sandy clayey).	Moderately strong; highly (recent) to residual soil (old). Joints orientation 030°/70°, 125°/45°, 150°/65°, 190°/60° and 010°/70°; spacing 0.002 to >1m; persistent >3m along strike and >3m along dip; large-scale roughness is wavy, small-scale roughness is rough stepped; infill material is fine clay and no karst. Slope dip-direction/dip and height: 105° / 82° and 5.4m. fine clay and no karst. Slope dip-direction/dip and height: 030° / 76° and 16m.
SLOPE Y33	Location: 2403370N / 516436E Date & method of Excavation: 6mths/33yrs (Excavator). Geological formation: AR?nc1 paleo-proterozoid (Granite and metamorphic rock materials).	Accessibility: 3m. Porphyritic feldspar, crystalline mica-schist and sandy clayey soil with fine to medium grain size and well-developed undulose foliation. The colours are of white with yellow stain (feldspar) and reddish black to light brown (schist and sandy clayey).	Strong; slightly/moderately (recent) to residual soil (old). Joints orientation 040°/80°, 285°/85°, 315°/60° and 165°/65°; spacing 0.002 to 1m; persistent >3m along strike and >3m along dip; large-scale roughness is wavy, small-scale roughness is rough stepped; infill material is fine clay and no karst. Slope dip-direction/dip and height: 295° / 74° and 12m.

6 Errata: Porphyritic feldspar should be replaced by porphyritic granite (feldspar) and porphyritic ademallite by porphyritic granite (quartz and feldspar)

5. ROCK MECHANICS ANALYSIS AND INTERPRETATION

5.1. Weathering profile

Weathering profile (fig. 5.1), a schematic typical perpendicular or vertical unit/segment that passes through the weathering zones from the surface of ground to fresh bedrock is developed for Yen Bai City area based on the SSPC method weathering classification (table 3.3) in accordance to BS 5930 (1999).

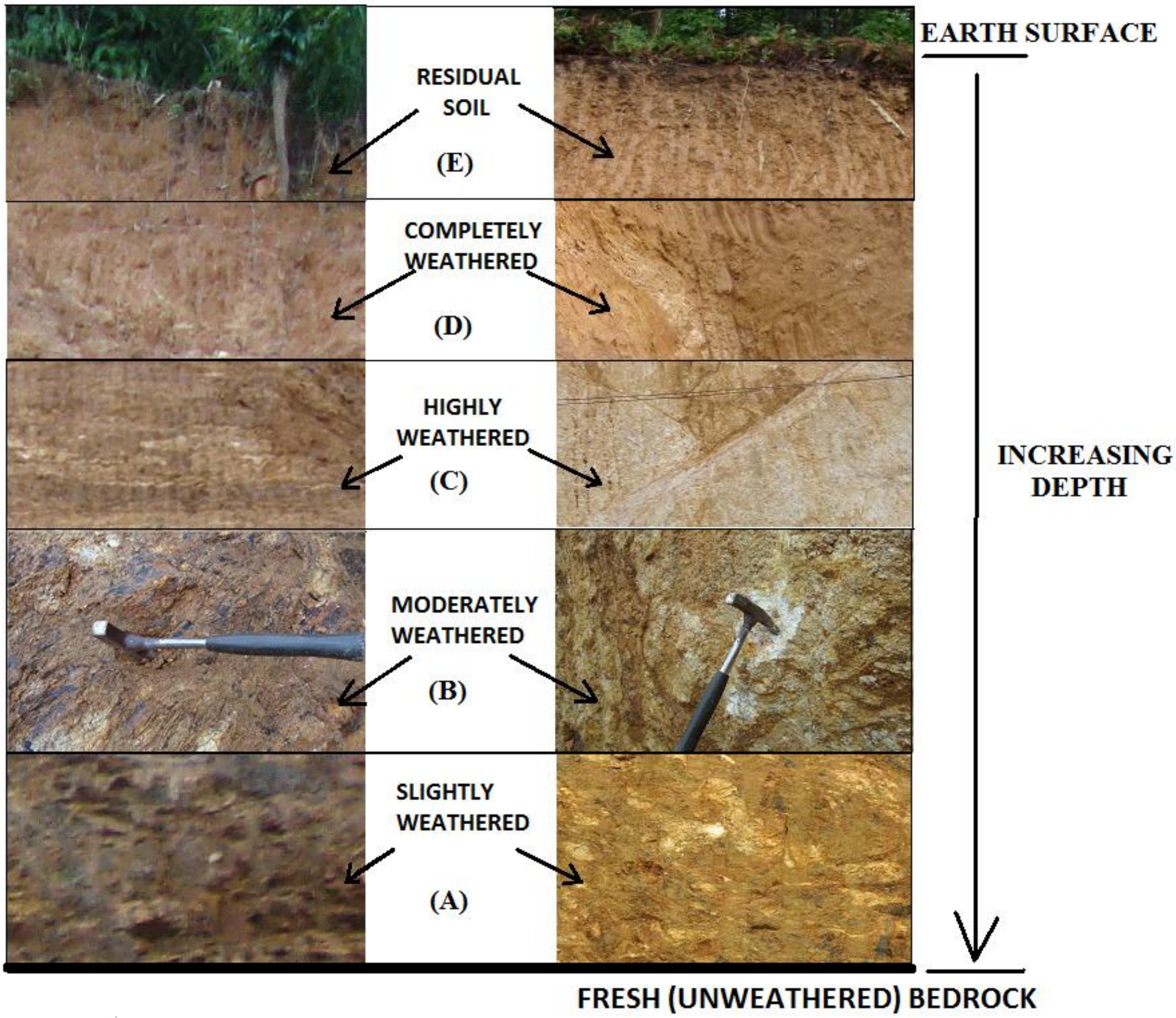

Figure 5.1: Typical weathering profiles of rock and soil masses from the research area (for the description of weathering degrees, see table 3.3.)

In engineering terms, the slightly and moderately weathered rock materials have similar behaviour like fresh rock with early set in of weathering; hence, the layers are called WEATHERED BEDROCK. This is shown in fig. 5.1(A) layer where the rock materials have black and brown stains colours against the original reddish brown and white colours which indicates its weathering (slightly weathered). The sources of this layer's outcrops are shown in fig. 0.53 & 0.54 (appendix 1). While in fig. 5.1B (layer), the black and brown discolourations increased and penetrated more into the rock materials. There is presence of clay materials in the discontinuities, which indicates considerable weakening of the rock materials (moderately weathered). The sources of this layer's outcrops are shown in fig. 0.55 (appendix 1). In the highly and completely weathered rock materials, the structural and textural characteristics of the parent rock materials can still be identified though more than half of the rock materials have disintegrated into soil (as indicated in fig. 5.1 (C & D) layers) (Hack, 1998). The sources of these layer's outcrops are shown in fig. 0.56 & 0.57 (appendix 1).

The upper most layers of rock and soil masses weathering profile is residual soil (fig. 5.1(E) layer) – layer where parent rock materials have lost their structural and textural characteristics. However, it might be insitu, but its origin cannot be traced to a specific parent rock material (Bell, 2000).

A defined weathering profile of rock and soil masses determined from the average thickness of each of the weathered layers of selected cut slopes in Yen Bai City area based on the above fig. 5.1 is created (fig. 5.2) and is used for stability and weathering rate analyses for each of the layer.

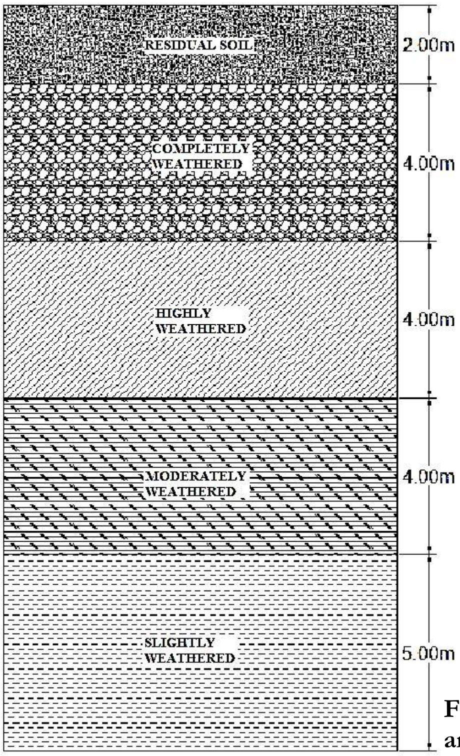

Figure 5.2: A conceptual weathering profile for the area (The depths values are average values found in the area).

5.2. Slope stability analysis

Two types of stability analyses are gradually carried out using SSPC method (chapter 3.4.1.1) – orientation dependent stability and orientation independent stability for the first three cut slopes (i.e. Y1, Y2 and Y4).

- **Orientation independent stability.**

The orientation independent stability analysis is carried out using equations (v) to (xix) and probability graph in fig. 3.4. The results are shown in table 5.1.

In cut slope Y1 (table 5.1 and 0.4 (appendix 3)), all the geotechnical units that have low IRS with high SPA and CD values show high SCOH (i.e. COH_{SRM}), SFRI (i.e. φ_{SRM}) and OIS; so also the geotechnical units that have extreme IRS with low SPA and CD values. In cut slope Y2, all the geotechnical units that have high IRS and low SPA show high SFRI and OIS, but low SCOH. In cut slope Y4, all the geotechnical units that have IRS, average CD and low SPA values show average SFRI, low SCOH and high OIS.

Generally, it could be seen that cut slope Y1 with lowest IRS, highest SPA with CD values ranging from average to highest has the highest SFRI, SCOH and OIS. This is followed by cut slope Y2 with highest IRS, lowest SPA and higher CD values than cut slope Y4.

Table 5.1: Slope parameters (including orientation independent stability (OIS)) for the first three cut slopes derived from SSPC method (using equations (v) to (xix) and fig. 3.4).

SLOPE	EASTING	NORTHING	WE	IRS(MPa)	SPA	CD	SFRI(Deg.)	SCOH(KPa)	OIS (%)
Y1G11	514163	2402181	0.95	1.25	0.493	0.903	30	16	36
Y1G12	514163	2402181	0.90	3.13	0.493	0.587			
Y1G21	514163	2402181	0.95	1.25	0.493	0.903			
Y1G22	514163	2402181	0.90	3.13	0.493	0.587			
Y1G31	514163	2402181	0.95	1.25	0.493	0.903			
Y1G32	514163	2402181	0.90	3.13	0.493	0.587			
Y1G41	514163	2402181	0.90	1.25	0.493	0.496			
Y1G42	514163	2402181	0.90	3.13	0.493	0.496			
Y1G51	514163	2402181	0.62	150.00	0.003	0.418			
Y1G52	514163	2402181	0.62	75.00	0.003	0.587			
Y2G11-1	516543	2402132	0.90	31.25	0.098	0.523	24	11	33
Y2G11-2	516543	2402132	0.90	75.00	0.096	0.855			
Y2G12-1	516543	2402132	0.95	75.00	0.079	0.903			
Y2G12-2	516543	2402132	0.90	31.25	0.101	0.808			
Y2G13-1	516543	2402132	0.90	75.00	0.101	0.808			
Y2G13-2	516543	2402132	0.95	150.00	0.003	0.808			
Y2G14	516543	2402132	0.62	75.00	0.003	0.496			
Y2G15a-1	516543	2402132	0.9	75.00	0.100	0.523			
Y2G15a-2	516543	2402132	0.90	31.25	0.100	0.523			
Y2G15b-1	516543	2402132	0.35	75.00	0.003	0.315			
Y4G11	516120	2403428	0.62	75.00	0.003	0.440	15	7	13
Y4G12	516120	2403428	0.90	3.13	0.114	0.523			
Y4G21	516120	2403428	0.62	75.00	0.003	0.440			
Y4G22	516120	2403428	0.90	8.75	0.111	0.523			
Y4G31	516120	2403428	0.62	75.00	0.003	0.496			
Y4G32	516120	2403428	0.95	8.75	0.113	0.808			
Y4G41	516120	2403428	0.62	75.00	0.011	0.523			
Y4G42	516120	2403428	0.62	75.00	0.114	0.808			
Y4G51	516120	2403428	0.35	31.25	0.003	0.413			
Y4G52	516120	2403428	0.35	3.13	0.003	0.413			

- **Orientation dependent stability.**

The slope orientation dependent stability analysis is carried out for the first three cut slopes (i.e. Y1, Y2 and Y4) using equations (xx) and (xxi), probability graphs in fig. 3.6 and stipulated conditions in table 3.4. The results achieved are shown in table 5.2.

From table 5.2, each of the sub-geotechnical units of all the cut slopes has at least three discontinuities orientation e.g. the discontinuities orientation for sub-geotechnical unit Y1G11 are 002/50, 075/75 and 065/60. This is arranged in the table with all the SDD_{disc} separated by slant line (i.e. 2/75/65), so also the SD_{disc} (i.e. 50/75/60). Their directions (i.e. W/W/E) and AP values (41/73/58) also follow this principle. However, a value is recorded for STC (i.e. 0.90) because all of them have the same value for this parameter. The toppling values ranges between -72 and -114 for all the orientations, which show equivalent of 100% toppling stability probability (fig. 3.6).

The minimum sliding stability probability values for the geotechnical units of the three cut slopes are shown to be <5%, while that of toppling is 100%. The implication is that the cut slopes are likely to fail through sliding (though, might not be the whole slope at once, since some geotechnical units are still 100%), while it shows that the slope is not subjected to toppling failure. However, the sliding failure is likely to happen in the geotechnical units of the rock masses that have fine/medium grained crystals like with higher quantity of mica (lead to low COH_{disc} and φ_{disc})(Wyllie & Mah, 2004) which could be true of the three cut slopes (chapter 4).

Table 5.2: Orientation dependent stability assessment for the first three cut slopes derived from SSPC method (using equations (xx) to (xxi), table 3.4 and fig. 3.6).

ID	SDDidsc.	SDdisc.	DIRECTION	AP	STC	TOPP	STABILITY PROBABILITY	
							SLIDING (%)	TOPPLING (%)
Y1G11	2/75/65	50/75/60	W/W/E	41/73/58	0.90	Minimum = -114 Maximum = -72	Minimum =<5 Maximum = 100	100
Y1G12	5/75/65	85/75/60	W/W/E	83/73/58	0.59			
Y1G21	2/75/65	50/75/60	W/W/E	41/73/58	0.90			
Y1G22	2/75/65	50/75/60	W/W/E	41/73/58	0.59			
Y1G31	4/32/40	70/55/50	E/W/W	64/54/50	0.59			
Y1G32	16/32/40	70/55/50	W/W/W	67/54/50	0.59			
Y1G41	4/32/40	70/55/50	E/W/W	64/54/50	0.50			
Y1G42	16/32/40	70/55/50	W/W/W	67/54/50	0.50			
Y1G51	2/75/65	50/75/60	W/W/E	41/73/58	0.42			
Y1G52	5/75/65	85/75/60	W/W/E	83/73/58	0.59			
Y2G11-1	275/330/240	85/70/85	V/W/W/	85/60/83	0.52	Minimum = -143 Maximum = 37	Minimum = <5 Maximum = 100	100
Y2G11-2	230/330/220	80/75/85	W/W/W	75/67/80	0.86			
Y2G12-1	300/240/210/10/270	85/65/85/70/120	V/W/W/W/A	85/59/76/0/-60	0.90			
Y2G12-2	320/235/280/250/5	70/110/80/140/80	W/A/W/A/W	65/-63/80/-36/26	0.81			
Y2G13-1	320235/5	70/110/80	W/A/W	65/-63/26	0.81			
Y2G13-2	320/235/280/250/5	50/110/80/140/80	E/A/W/A/W	42/-63/80/-36/26	0.81			
Y2G13-2	235/280/250/5	110/80/140/80	A/W/A/W	80/-63/-36/26	0.81			
Y2G14	320/235/280	50/110/80	W/A/W	42/-63/80	0.50			
Y2G15a	200/310/285	85/70/70	E/E/W	63/67/70	0.52			
Y2G15b	200/310/285	85/70/70	W/E/E	63/67/70	0.32			
Y4G11	310/280/330/40	80/30/90/70	W/W/V/E	80/22/90/3	0.44	Minimum = -143 Maximum = -22	Minimum = <5 Maximum = 100	100
Y4G12	310/280/330	80/30/90	W/W/V	80/22/90	0.52			
Y4G21	310/280/330/40	80/30/90/70	W/W/V/E	80/22/90/3	0.44			
Y4G22	310/280/330	80/30/90	W/W/V	80/22/90	0.52			
Y4G31	25/19/50/45/330	55/60/80/70/85	W/W/W/W/W	53/59/76/65/84	0.50			
Y4G32	330/45/290	85/70/30	W/W/W	84/65/8	0.81			
Y4G41	25/19/50/45/330	55/60/80/70/85	W/W/W/W/W	53/59/76/65/84	0.52			
Y4G42	330/45/290	85/70/30	W/W/W	83/65/8	0.81			
Y4G51	310/280/330/40	80/30/90/70	W/W/V/W	80/22/90/3	0.41			
Y4G52	310/280/330	80/30/90	W/W/V	80/22/90	0.41			

5.2.1. **Sensitivity analysis of the cut slopes**

The sensitivity analysis is carried out as explained in chapter 3.4.1.3 and the results shows that all the cut slopes standard errors are below 50% (table 5.3). When the IRS and SPA values are varied (low and high, then vice versa) (table 5.1, 5.3 and 0.4 (appendix 3)), there is general increase in SFRI, SCOH and OIS pertaining to low IRS, high SPA and CD values (cut slope Y1). Thus, it shows that the cut slope has the best stability amidst the three cut slopes.

While high IRS and low SPA favoured cut slope Y2, which could be as a result of very high IRS. However, it is likely that the effects of the IRS will not be felt on the geotechnical units or cut slopes after 132 MPa, which is the set limit in the SSPC formula. This shows that failure in slopes is frequently connected with the shear strength of discontinuities (Hack, 1998). Since the SFRI and SCOH of cut slope Y1 is greater than others, it is likely that its degree of weathering at this present time is lower than that of cut slope Y2 and Y4, since during weathering process, SFRI and SCOH also will be affected (reduced) as SPA and CD values are affected (Huisman, 2006). Another factors worth of mentioning here (but will not be discussed) which could affect the weathering are the slope geometry (i.e. orientation and height) and the effect of water and erosion on the cut slopes.

The VES from table 5.3 show that all the three cut slopes have different types of instability in ascending order (Y4 is most unstable and Y1 is least unstable).

Table 5.3: Summary of slope geotechnical parameters (sensitivity analysis results) including Visual Estimate Stability (VES) for the first three cut slopes

SLOPE		IRS	SPA	OIS	VES
Y1	Maximum	39.75	0.313	24	Large Problem – It slides on top and sides and has potential of failure in nearest future.
	Actual	24.25	0.395	36	
	Minimum	11.63	0.466	40	
	Std error	49.77	0.21		
Y2	Maximum	132.50	0.267	40	Large Problem – It slides on top left side and is stabilized by cutting of steps along its height. It has potential of failure in nearest future.
	Actual	69.38	0.355	33	
	Minimum	29.25	0.433	11	
	Std error	35.04	0.05		
Y4	Maximum	90.50	0.224	21	Though the middle part is stable but the sides are not alright. The right side is unstable while the left side is too steep and possible to fail in the nearest future.
	Actual	43.00	0.316	13	
	Minimum	17.38	0.401	<5	
	Std error	34.62	0.06		

Generally, it could be deduced that some cut slopes have a high IRS, SPA or CD, or their combination and result thus in larger values for SCOH and SFRI and higher calculated SSPC stability probability, and this is different for different cut slopes. Therefore, there are cut slopes that have a better stability due to, in particular a higher IRS and SPA, while others have a better stability due to higher IRS with a high CD. A comparison between the OIS and VES show that instability in the three cut slopes are likely to happen due to sliding and combination of IRS, SPA and CD.

5.3. Analysis of weathering rates of the selected cut slopes

Analysis of weathering rate in this study is carried out in accordance to methodology in chapter 3.4.1.4. The results for the plotting of SCOH and SFRI against exposure time (t) and observed WE are shown in fig. 5.3 (for each of the cut slopes e.g. Y27) and fig. 5.4 for the geological formations (AR?nc1 and AR?nc2). The results for the weathering rates of the geological formations and its equivalent probabilities (using equations (xxiii) to (xxv)) are shown in table 5.4. The graphs of ∇SCOH and ∇SFRI against exposure time are shown in fig. 5.5.

It could be seen that decrease in observed WE resulted in decrease in SCOH and SFRI, and it happen as exposure time increases (fig 5.3 and 5.4). The exponential graphs (fig. 5.4b & d) show the values for the cut slopes to be more correlated with exposure time than that of fig. 5.4a & c, which could be likened to dynamic weathering rate over time series of measurement on which Colman and Ruxton based their weathering rate formula (Colman, 1981; Huisman, 2006). The results from fig. 5.3 also show that the SFRI and SCOH values of granite are higher than schist rock materials. This portray that the schist materials in the area is likely to be weaker and more susceptible to weathering than the granite materials. Generally, AR?nc2 geological formation has higher SFRI and SCOH than AR?nc1 geological formation (fig. 5.4).

It can be deduced from above that the degree of weathering increases (weathering increases from slightly weathered to residual soil) as the SCOH and SFRI decreases when exposed through excavation and this will happen as exposure time increases.

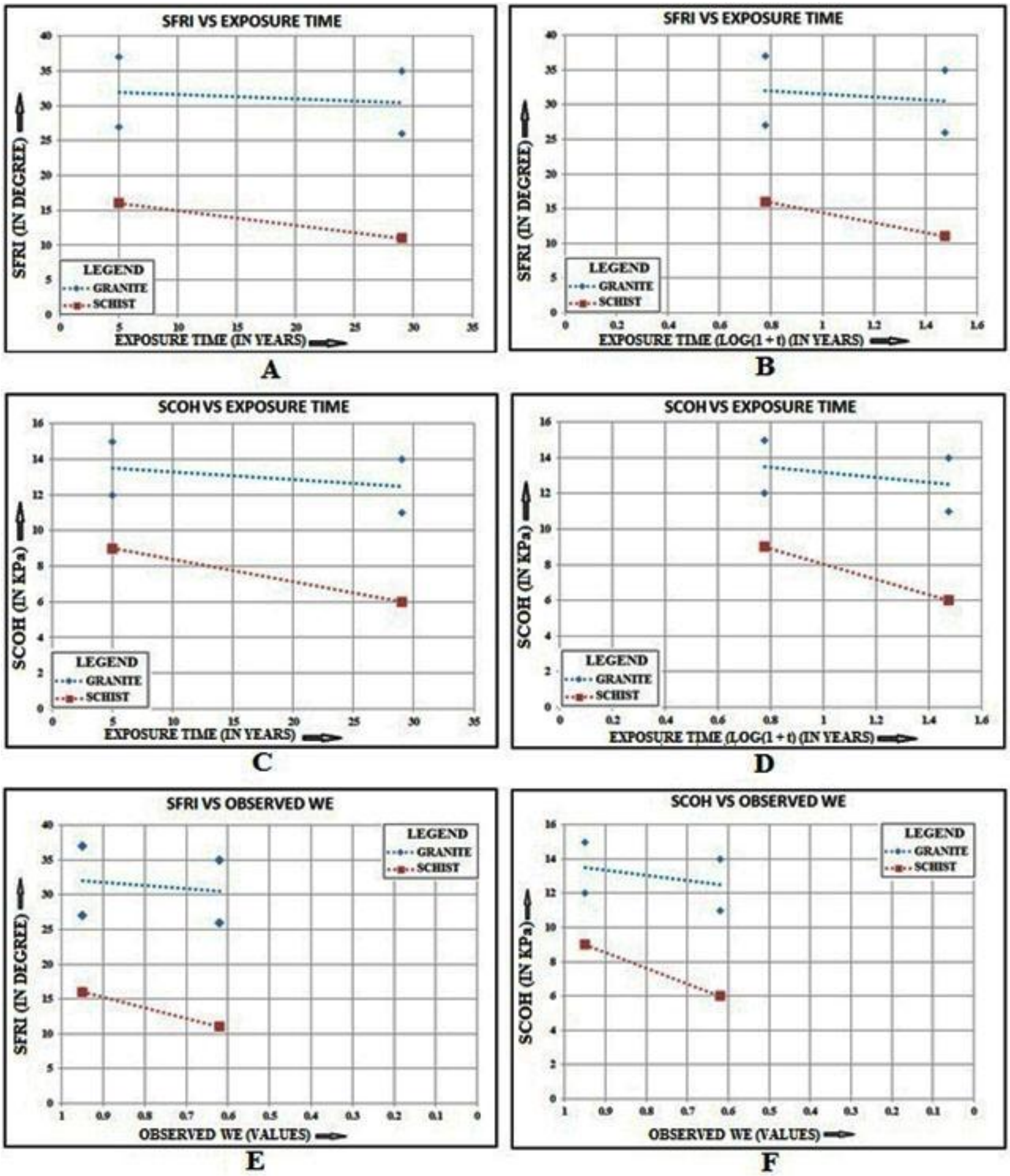

Figure 5.3: Graphs for cut slope Y27: (A & C) SFRI and SCOH versus exposure time; (B & D) SFRI and SCOH versus log (1 + exposure time); (E& F) SFRI and SCOH versus observed WE; (Blue line) plotted graph for granite rock materials; (Red line) plotted graph for schist.

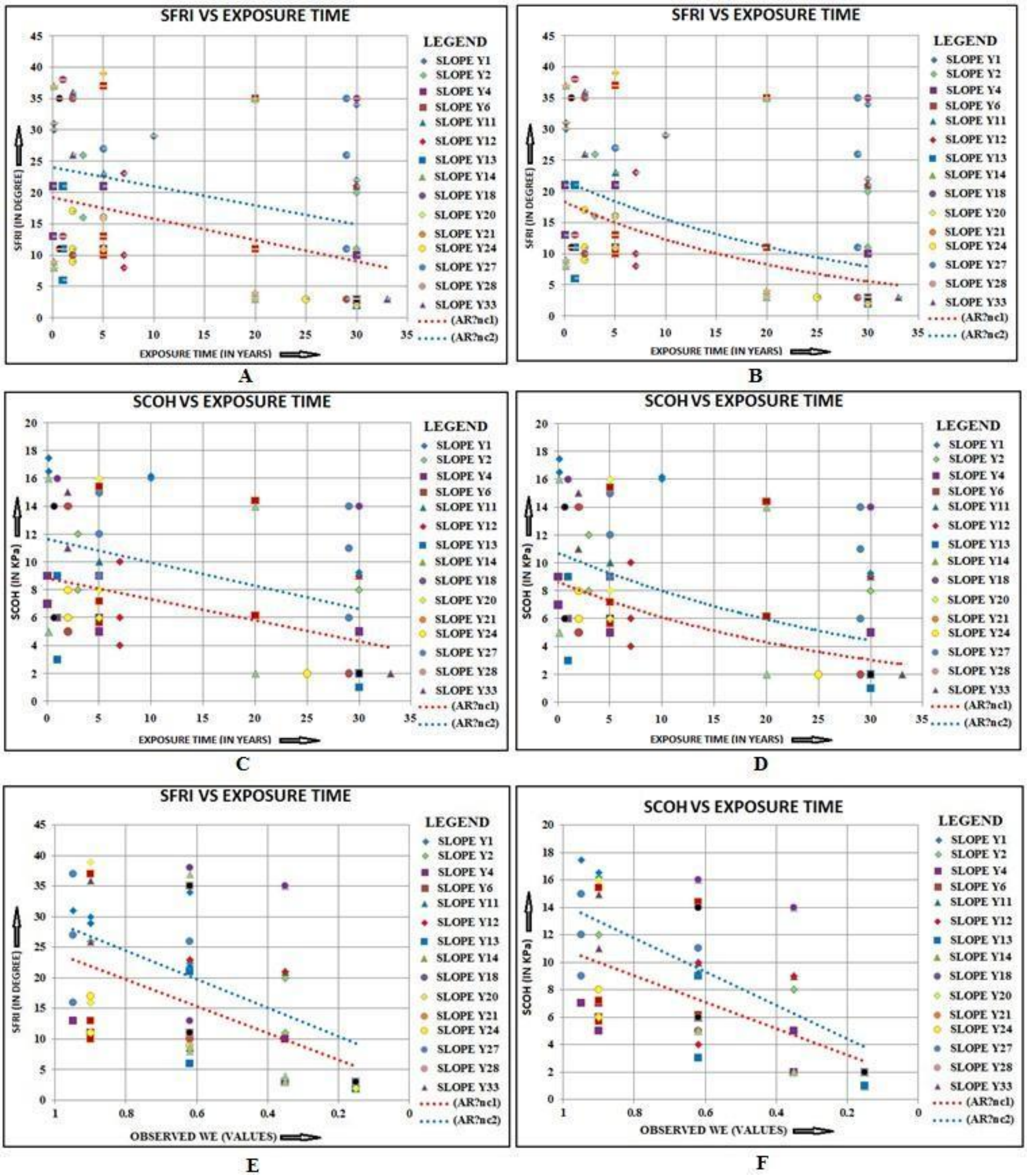

Figure 5.4[7]: Graphs for AR?nc1 and AR?nc2 geological formation: (A & C) linear graph for SFRI and SCOH versus exposure time; (B & D) exponential graph for SFRI and SCOH versus exposure time; (E& F) SFRI and SCOH versus observed WE.

[7] A value of 0.15 is assumed for the residual soil because SSPC has no value for it. The observed WE values from SW to CW are derived for SSPC using Monte Carlo Simulation, which is beyond the scope of this thesis.

Table 5.4: Weathering rate and probability for different geological formation in the research area (equations (xxiii) to (xxv) are used for the calculation)

FORMATION	CUT SLOPES		WE	EXP.TIME	∇SFRI	∇SCOH	$R_{app(WE)}$(SFRI)	$R_{app(WE)}$(SCOH)	Pr(SFRI)	Pr(SCOH)
AR?nc1	Y2, Y4, Y11, Y12, Y13, Y24, Y27, Y28, Y33	Maximum	0.95	27.00	18.56	8.16	12.83	5.64	43	34
		Actual	-	32.98	13.22	6.52	8.63	4.26		
		Minimum	0.00	23.00	9.94	6.93	7.03	4.90	21	18
		Std error			4.23	1.96	2.98	1.39		
AR?nc2	Y1, Y6, Y14, Y18, Y20, Y21	Maximum	0.95	29.30	21.93	10.44	15.50	7.38	44	39
		Actual	-	32.98	14.50	7.03	9.47	4.59		
		Minimum	0.00	15.00	8.61	3.88	5.95	2.68	32	31
		Std error			5.25	2.83	3.86	2.18		

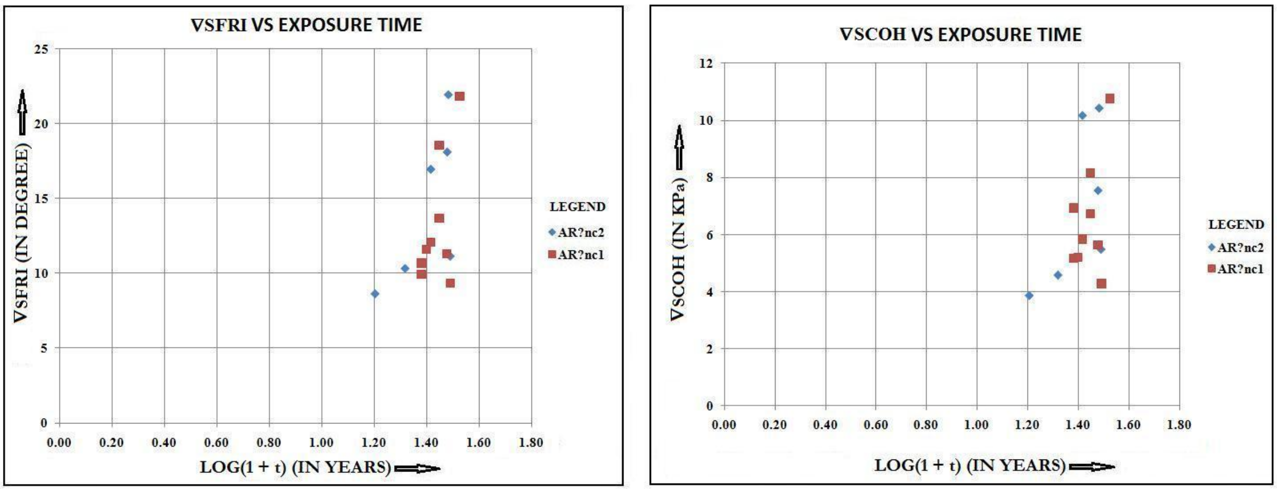

Figure 5.5: Change in cohesion and friction of slope rock mass (∇SCOH and ∇SFRI) against logarithmic scale of exposure time (t) for the geological formations

The graphs (fig. 5.5) is plotted to buttress the above fig. 5.4. The increase in ∇SCOH and ∇SFRI as exposure time increases show the depletion of the cohesion and friction from the cut slopes of rock masses as time goes on. The AR?nc2 geological formation have high ∇SCOH and ∇SFRI, weathering rates ($R_{app(WE)}$(COH) and $R_{app(WE)}$(FRI)), so also high probability values than in the AR?nc1 geological formation (table 5.4). As the ∇SCOH and ∇SFRI increases with exposure time, there is reduction in IRS, shear and tensile strength of rock masses and eventually slope failure (Huisman, 2006). Consequentially, it is expected that the AR?nc2 geological formation will be more liable to slope failure, landslides, creeps and other related disaster than AR?nc1 geological formation.

6. SPATIAL WEATHERING ANALYSIS AND INTERPRETATION

6.1. General maps

The general maps (DEM, slope, aspect and rock maps) are prepared for the analysis based on chapter 3.4.2. The results are shown in fig. 0.63 – 0.67(appendix 3). The slope varies from 0^o to 53^o, which represent the natural slope angles (dip) of the study area. The aspect varies from 0 to 360^o. This is the dip direction of the natural slope. The basic rock maps are RFRI, RCOH and observed WE maps (fig. 0.65 – 0.67 (appendix 3) show the maps for the overall interpolated RFRI and RCOH layers and maximum observed WE value).

6.2. Slope Stability Maps

- **Orientation independent analysis**

The orientation independent stability analyses of three different cut slopes (Y6, Y24 and Y27) are carried out as explained in chapter 3.4.2. The results are shown in table 6.1, 6.2 and 6.3.

Table 6.1: Orientation independent stability (OIS) assessment for the selected cut slopes using interpolated RFRI & RCOH for different geological formations

FORMATION	ID	SDD (deg.)	SD (deg.)	H (m)	RFRI (deg.)	RCOH (KPa)	OIS (%)
AR?nc2	Y6	210	66	11	41	19	>95
AR?nc1	Y24	250	65	15	27	13	<5
AR?nc1	Y27	220	64	19	27	13	<5

The above table 6.1 shows the three cut slopes with their geological formations (i.e. AR?nc1 and AR?nc2). What is of interest here is the cut slope Y6 that has low Hslope with high RCOH and RFRI that resulted in high OIS. While the cut slopes, Y24 and Y27 have high Hslope with low RCOH and RFRI that resulted in low OIS.

Table 6.2: Orientation independent stability (OIS) assessment for the selected cut slopes using overall RFRI & RCOH for all geological formations

ID	SDD (deg.)	SD (deg.)	H_{Slope}	RFRI (deg.)	RCOH (KPa)	OIS (%)
Y6	250	66	11	33	15	55
Y24	220	64	15			10
Y27	220	64	19			<5

The above table 6.2 shows the effect of averaging of RFRI and RCOH between the two geological formations which leads to under estimation of OIS for AR?nc2 (cut slope Y6) and over estimation of OIS for AR?nc2 (cut slope Y24. Hence, it will not be good to use average of the two geological formations' RCOH and RFRI in determining their OIS and other derived parameters like weathering rates.

Table 6.3: Orientation independent stability (OIS) assessment for the selected cut slopes based on the weathering profile (fig.5.2)

FORMATION	ID	RFRI	RCOH	SDD	SD	H_{Slope}	ORIENTATION INDEPENDENT STABILITY				
							SW	MW	HW	CW	RS
AR?nc1	Y6	67.02	27.99	210	66	11	-	>95	>95		
		40.53	18.53					>95	>95	>95	>95
		22.59	11.32					<5	<5	30	>95
AR?nc2	Y24	35.13	15.75	250	65	15	40	50	93	>95	
		27.23	13.05				<5	<5	10	80	>95
		15.14	8.60				<5	<5	<5	<5	>95
AR?nc2	Y27	35.13	15.75	220	65	19	7	50	92	>95	
		27.23	13.05				<5	<5	9	85	>95
		15.14	8.60				<5	<5	<5	>5	>95

Generally in table 6.3, OIS increases as height reduces towards the top of the weathering profile (i.e. RS; fig. 5.2). This is because cut slope height has effect on the stress in the rock mass of the cut slope. High stress levels will result in slope instability due to rock mass failure. It also portrays that the higher the slope, the more the opening of discontinuities and the more the slope is subjected to failure (Hack, 1998). It could also be seen that increase in RCOH and RFRI lead to increase in OIS.

- **Orientation dependent stability**

The results of orientation dependent stability analysis carried out on the three different cut slopes (i.e. Y6, Y24 and Y27) as expressed in chapter 3.4.2 is shown in table 6.4.

Table 6.4: Orientation dependent stability for the selected cut slopes

ID	SDDidsc. (deg.)	Sddisc. (deg.)	DIRECTION	AP	STC	TOPP	STABILITY PROBABILITY	
							SLIDING (%)	TOPPLING (%)
Y6	240	75	WITH	73	0.52	-96.38	>95	>95
Y6	200	40	WITH	40	0.52	-63.14	>95	>95
Y6	300	70	WITH	0	0.52	-23.57	>95	>95
Y24	190	70	WITH	54	052/0.95	-79	>95	>95
Y24	240	85	VERTICAL	85	052/0.95	-110	>95	>95
Y24	255	55	WITH	55	052/0.95	-80	>95	>95
Y27	235	50	WITH	49	0.52/0.95	-75	50	>95
Y27	200	70	EQUAL	69	0.52/0.95	-94	>95	>95
Y27	160	75	EQUAL	62	0.52/0.95	-87	>95	>95

The results show that part of cut slope Y27 is subjected to failure through sliding while the other cut slopes (i.e. Y6 and Y24) are not. This seems true as the photograph of the slope shows the slit (as indicated in fig. 0.29; appendix 1). Generally, it is expected that slope instability will occur in both cut slopes Y6 and Y24 through combination of IRS, SPA and CD since they are stable in sliding and toppling stability probability. While Y27 will be unstable due to sliding and combination of IRS, SPA and CD.

6.3. Weathering rates map

The weathering rates maps and their values for the geological formations (i.e. AR?nc1 & AR?nc2) are produced using spatial analysis (chapter 3.4.2). The results are shown in table 6.5, fig. 6.1 and 6.2.

Table 6.5: Weathering rates values of observed WE layers for different geological formation

OBSERVED WE	EXP.TIME (YEARS)	GEOLOGICAL FORMATIONS							
		AR?nc1		AR?nc2		AR?nc1		AR?nc2	
		∇RFRI	∇RCOH	∇RFRI	∇RCOH	$R_{app(WE)}$(FRI)	$R_{app(WE)}$(COH)	$R_{app(WE)}$(FRI)	$R_{app(WE)}$(COH)
SW	32.5	25	12	33	18				
MW		30	14	37	22	3.26	1.46	2.44	2.64
HW		41	18	56	29	7.03	2.81	12.79	4.41
CW		51	22	68	34	6.49	2.45	7.87	2.94
RS		74	29	109	47	14.88	4.40	26.94	8.99

Generally, the ∇RCOH and ∇RFRI increases as weathering rates increases (i.e. $R_{app(WE)}$(COH) and $R_{app(WE)}$(FRI)) from slightly weathered (SW) to residual soil (RS) for each geological formation (table 6.5). Though the increase is higher in AR?nc2 than AR?nc1 geological formation. The higher increases in $R_{app(WE)}$(COH) and $R_{app(WE)}$(FRI) of AR?nc2 geological formation portrays that cut slopes in this formation are more subjected to weathering and fail faster than the ones in AR?nc1 geological formation. Generally, the weathering rates of rock masses through cut slopes in the study area (i.e. tropical region) are very high even when calculated using observed WE (fig.0.6; appendix 3) compare to that of Mediterranean region. The weathering rate derived from observed WE (($R_{app(WE)}$) is between 0.183 and 0.543 (33 years of exposure time) compare to that of Mediterranean region which is between 0 and 0.244 (37 years of exposure time)[8]. This could be apportioned to the climatic condition of the tropical region (chapter 2.1.2.2). This is as expected as weathering in tropical areas is more intense resulting in thicker layers of weathered material (fig. 5.1 and 5.2).

[8] This is extracted from page 120 & 239 – 251 of Huisman (2006) book. It also shows the Rapp(WE) to be between 0 and 0.692 for 498 years of exposure time.

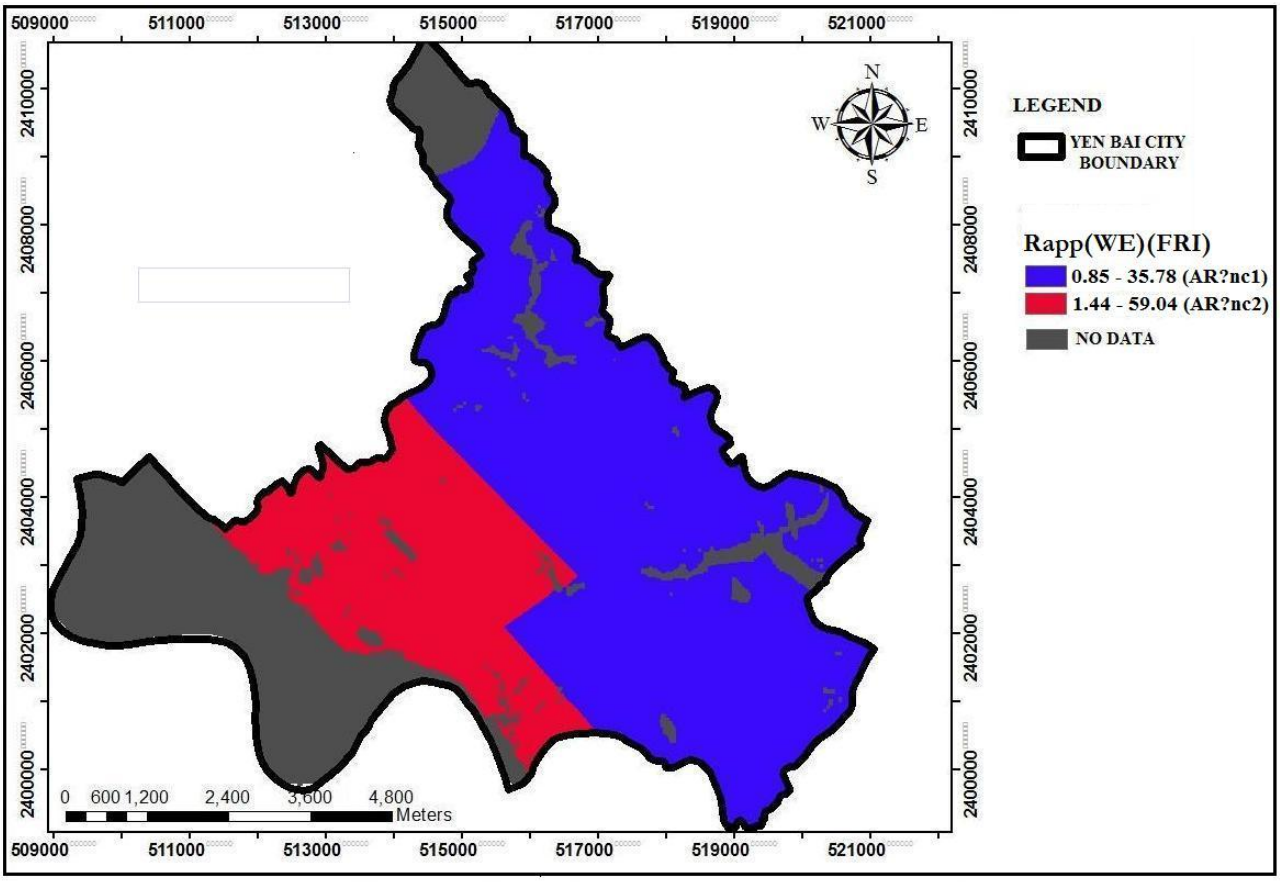

Figure 6.1: Weathering rates (RFRI) map for the study area

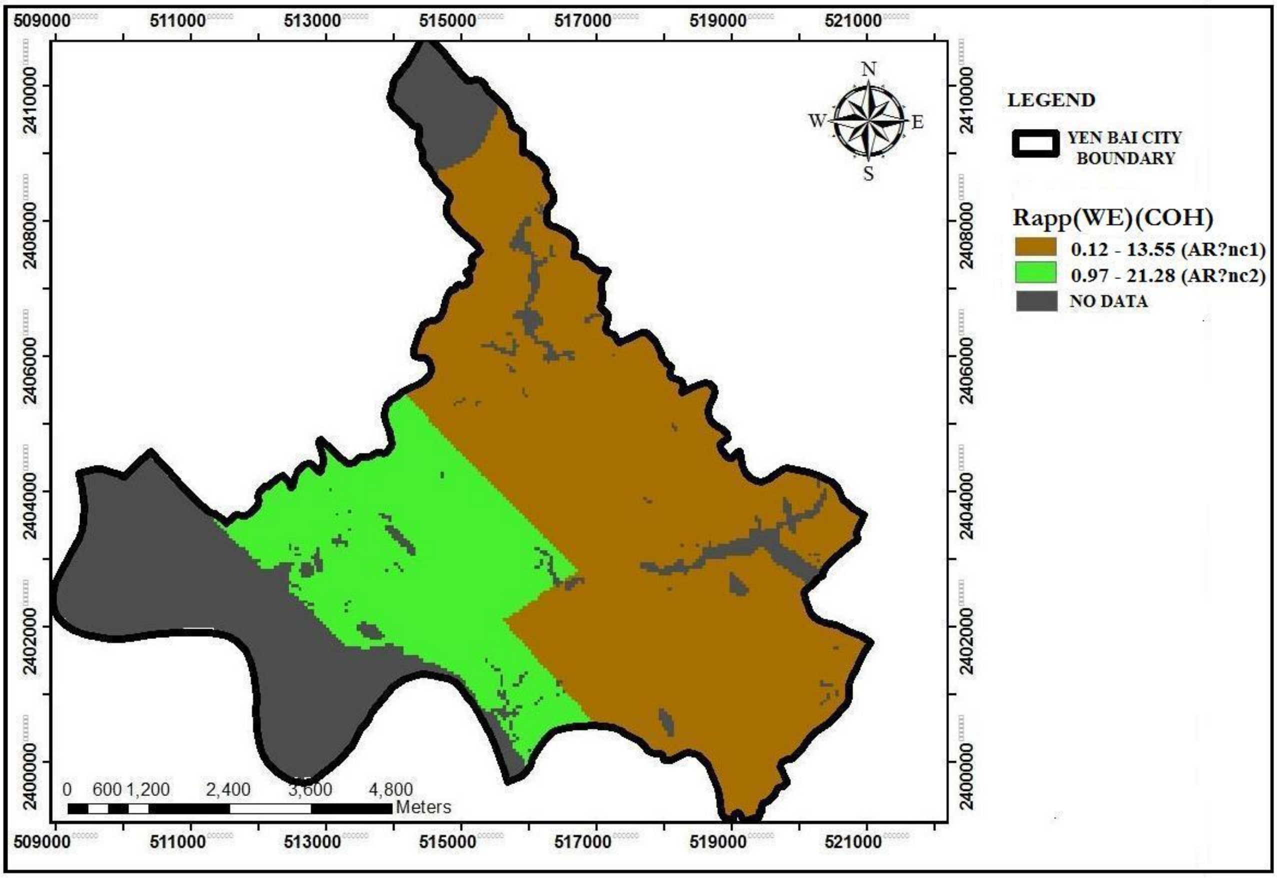

Figure 6.2: Weathering rates (RCOH) map for the study area

Table 6.6: Weathering rates values with equivalent probabilities ($R_{app(WE)}$(COH) and $R_{app(WE)}$(FRI) results from spatial analysis)

FORMATION		EXP.TIME	VRFRI	VRCOH	Rapp(WE)(FRI)	Rapp(WE)(COH)	PROBABILITY (%)	
							Rapp(WE)(FRI)	Rapp(WE)(COH)
AR?nc1	Maximum	32.5	54.57	20.66	35.78	13.55	50	50
	Actual		48.28	16.97	31.66	11.13	50	50
	Minimum		1.32	0.19	0.87	0.12	21	21
	Std error				8.27	2.91		
AR?nc2	Maximum		90.04	32.45	59.04	21.28	49	49
	Actual		76.31	28.93	50.04	18.97	48	48
	Minimum		2.19	1.48	1.44	0.97	25	22
	Std error				19.17	7.16		

Putting all the weathering rates ($R_{app(WE)}$(COH) and $R_{app(WE)}$(FRI)) values (table 6.6) into consideration, the ranges of weathering rates for the geological formations are as follows:

1 <= $R_{app(WE)}$(FRI) <= 36; 0 <= $R_{app(WE)}$(COH) <=14 --------------AR?nc1

1 <= $R_{app(WE)}$(FRI) <= 59; 1 <= $R_{app(WE)}$(COH) <=21 --------------AR?nc2

The probability of weathering rates (table 6.6) for each geological formation becomes

AR?nc1 => 0.21 - 0.50 (FRI); 0.21 – 0.50 (COH);

AR?nc2 => 0.25 – 0.49 (FRI); 0.22 – 0.49 (COH).

6.4. Discussion

From chapter 4, It could be seen that all the rock and soil masses in Yen Bai City show trait of a typical weathering classification in line with BS5390 (1999) and SSPC method. Though, a clear comparison between the climatic regions of where SSPC was developed (i.e. Mediterranean climate of Falset in Spain) and the present study area (i.e. tropical climate of Yen Bai City, Vietnam) shows that the rate of weathering is very high in the tropical region which could make each of the weathering profile layer's thickness to be higher than that of the Mediterranean region (i.e. highly and completely weathered and residual soil) (chapter 6.3).

The accessible parts of the rock and soil masses show that there are presence of geotechnical parameters like IRS, SPA, CD, observed WE, slope geometry (SD, SDD and H_{slope}) and other material and mass characteristics (chapter 3 and 4) upon which SSPC method is applicable. Hence, the method is applied on all the selected cut slopes for the purpose of slope stability and weathering rate assessments.

6.4.1. Degree of weathering of rock masses and its exposure time

The field observation, measurement and calculation results of the different cut slopes (chapter 4 and fig. 5.3) on the same rock masses (i.e. recent (0 to 5 years); medium (5 to 10 years) and old (20 to 33 years)) show difference in degree of weathering in terms of

- Observed WE,
- SFRI and SCOH with respect to exposure time after the excavation of the cut slopes.

Most of the selected cut slopes show significant change in observed WE (i.e. from slightly/moderately weathered to completely weathered or residual soil) after 20 years of their exposure. While some cut slopes show little or no apparent change in observed WE before or at 20 years of their exposure (e.g. cut slopes Y1 and Y4) (chapter 4, table 4.1 and 4.2). These show that the degree of weathering increases (upward) from slightly weathered to residual soil as the time of rock cut slope's exposure increases. However, it may not be apparent until well after 20 years.

The plotted graphs show that SFRI and SCOH reduce as exposure time increases (fig. 5.3a to d). Another view from the plotted graphs (fig. 5.3e to f) also shows that SFRI and SCOH reduce as observed WE reduce and vice versa. Hence, it can be deduced that the degree of weathering increases as the SCOH and SFRI decreases when exposed through excavation and this will happen as exposure time increases.

6.4.2. Slope stability

Generally, it could be deduced that different cut slopes have different IRS, SPA or CD (or their combination) which resulted in their larger values for SCOH and SFRI and higher calculated SSPC stability probability (or better stability) (table 5.1, 5.3 and 0.4 (appendix). There is implication that instability in the cut slopes of the area are likely to happen due to sliding and combination of IRS, SPA and CD. Moreover, OIS increases as height reduces towards the top of the weathering profile (i.e. RS; fig. 5.2) due to effect of H_{slope} on the stress in the rock mass of the cut slope. Slope failure is likely to happen around highly or completely weathered to residual layer zones of the cut slope due to heavy burden or stress. This failure due to stresses could be apportioned to increase in H_{slope}, weak bonds between the rock and soil fragments. Other weathering agents (i.e. erosion and plants roots) could also trigger the failure around these zones (chapter 4 and table 6.3).

A thorough look at the plotted graphs and tables in fig. 5.4, table 5.1, 5.3 and 0.4 (appendix 3) shows that COH_{SRM} and φ_{SRM} (i.e. SCOH and SFRI) of AR?nc2 geological formation is higher than that of AR?nc1. This could be adhered to:

- Presence of IRS, SPA and CD in favour of AR?nc2 geological formation.
- Favourable H_{slope} of AR?nc2 than that of AR?nc1 geological formation .e.g. AR?nc2 has average slope height of 14.20m while AR?nc1 has average height of 15.4m i.e. the lower the slope height, the higher the SCOH and SFRI, the more stable the slope (i.e. better OIS).
- From the field observation (chapter 4), it seems the rock masses of the cut slopes in AR?nc2 have more medium/coarse grained crystals like with lesser quantity of mica than that of AR?nc1 geological formation which could lead to better COH_{disc} and φ_{disc} (Wyllie & Mah, 2004).

The implication of the above mentioned observations/results is that the rock masses' cut slopes in AR?nc2 geological formation are likely to be more stable than those in AR?nc1 geological formation.

6.4.3. Weathering rate assessment

As explained earlier above, it had been be deduced that the degree of weathering increases as SCOH and SFRI decreases and exposure time increases. Hence, ∇SCOH and ∇SFRI with respect to exposure time are used in assessing the weathering rate of the Yen Bai City area (i.e. equations xxiii and xxiv). It is clear that the exponential graphs (fig. 5.4b & d) show the SCOH and SFRI to be more correlated with exposure time, which in extension proved that the logarithmic scale of exposure time is the best for the weathering rate of the study area (Colman, 1981; Huisman, 2006).

The ∇SCOH and ∇SFRI increases as exposure time increases (table 5.4 and fig. 5.5) and this is higher in AR?nc2 than AR?nc1 geological formation i.e. weathering rate ($R_{app(WE)}$(COH) and $R_{app(WE)}$(FRI)) in AR?nc2 geological formation is higher than that of AR?nc1 geological formation. This implies that the COH_{SRM} and φ_{SRM} values depleted from the rock masses increases as exposure time increases and is more prominent in AR?nc2 geological formation. This is buttressed by spatial analysis of weathering rate, where ∇RCOH and ∇RFRI increases as weathering rates increases (i.e. $R_{app(WE)}$(COH) and $R_{app(WE)}$(FRI)) from slightly weathered (SW) to residual soil (RS) for each geological formation (table 6.5). Though the increase is higher in AR?nc2 than AR?nc1 geological formation. The higher increase in weathering rate of AR?nc2 geological formation portrays that cut slopes in this formation are more subjected to weathering and fail faster than the ones in AR?nc1 geological formation. Hence, AR?nc2 geological formation is likely to be more liable to slope failure, landslides, creeps and other related disaster than AR?nc1 geological formation. Generally, the weathering rates of rock masses through cut slopes in the study area are very high. This could be apportioned to the climatic condition of the region (i.e. tropical region).

7. CONCLUSION AND RECOMMENDATION

7.1. Conclusions

Weathering of rock masses has a large influence on the geotechnical parameters of a rock mass. Weathering starts from the moment of exposure of a rock mass. The general objective of this study is to determine the rate of weathering of mostly already deeply weathered tropical rock and soil masses slopes in the area of Yen Bai City in Vietnam. Knowing the rate of weathering would allow better design of slopes as the future weathering can be incorporated in the design. The research questions based on this objective are answered as follows:

Research Question 1: Which of the existing methods will be used to establish the relationship between degree of weathering of a slope and its exposure time in the above stated deeply weathered tropical rock and soil masses?
Answer: The existing methods used are the SSPC (chapter 3.3 – 3.4.1.3) and Colman's formula based method (chapter 3.4.1.4 (equations (xxiii) – (xxiv)). The methods are applied using two perspectives – rock mechanics and spatial analyses. The degree of weathering in accordance with BS 5390 (1999) is determined for each slope (chapter 3.3.2 and 4). The derived friction and cohesion of a rock mass (SCOH and SFRI) from the SSPC method are plotted against the exposure time and the observed WE in order to determine the relationship between the degree of weathering of a slope and the exposure time (fig. 5.3 and chapter 6.1). The results show that the SCOH, SFRI and observed WE factor reduce as the exposure time increases. Based on this relationship, the weathering rate ($R_{app(WE)}$(COH) and $R_{app(WE)}$(FRI)) are assessed with Colman's formula.

The SCOH and SFRI values for the cut slopes have a better correlation with exposure time exponentially than linearly (fig. 5.4). The weathering rates results show that there is increase in $R_{app(WE)}$(COH) and $R_{app(WE)}$(FRI) as ∇SCOH, ∇SFRI and degree of weathering increase (weathering increases from slightly weathered to residual soil) with increase in exposure time (table 5.4, fig. 5.5 and table 6.5).

Research Question 2: Does the time of exposure of a slope over periods up a few dozen years cause a difference in degree and rate of weathering of a rock mass in the tropical region?
Answer: Up to 20 years of exposure, visually the weathering degree seems not to increase. However, the weathering process is in progress as is shown by a change in friction and cohesion (∇SCOH and ∇SFRI) occurring between 0 and 20 years (fig.5.3a & c; 5.4a - d).

Visually change in the degree of weathering becomes visible after 20 years of slope's exposure (chapter 4, table 4.1 and 4.2). Generally, there is reduction in friction and cohesion (SCOH and SFRI), IRS, SPA and CD at the start of weathering, and continues as exposure time of slope increases (fig. 5.3 and 5.4). There are also increases in ∇SCOH, ∇SFRI (i.e. it portraits reduction of SCOH and SFRI), $R_{app(WE)}$(COH) and $R_{app(WE)}$(FRI) as exposure time increases. A comparison between the weathering rate ($R_{app(WE)}$) of tropical and Mediterranean areas shows that the former is very rapid / high (chapter 6.3). This is as expected as weathering in tropical areas is more intense resulting in thicker layers of weathered material (fig. 5.1 and 5.2).

Research Question 3: How stable are the slopes of the rock and soil masses?
Answer: Some cut slopes have a better stability due to, in particular a higher IRS and SPA, while others have a better stability due to higher IRS with a high CD (table 5.1, 5.3 and 0.4 (appendix). The cut slopes of the rock and soil masses in AR?nc2 geological formation are more stable than that of the AR?nc1 geological formation due to high SCOH and SFRI, low H_{slope} and better rock mineral compositions (chapter 6.4.2). Generally, the cut slopes in the area become unstable after some period of exposure time (i.e. 30 years) due to high depletion of COH_{SRM} and φ_{SRM} as a result of rapid weathering rate in the area. It is seriously liable to failure when its degree of weathering degenerated to highly, completely weathered or residual soil (the failure could be triggered by

weathering agents like human, rainfall and erosion). A slope in the Yen Bai area is generally made at the maximum angle and slope height that can be sustained in the material at the time of exposure for the top soil layers. In the deeper layers, i.e. in slightly or moderately weathered material, the slope angle and height are not at the maximum at time of exposure, but progressive weathering due to exposure will weather these materials to highly or completely weathered in about 30 years. The slope angle and height cannot be sustained by highly or completely weathered material and the slope will fail.

Research Question 4: Whether the difference in susceptibility to weathering between two geological formations and within the materials of the selected slopes can be determined from field observations?
Answer: The study shows that the rock and soil materials with low SCOH and SFRI are more susceptible to weathering than the one with high SCOH and SFRI. A comparison between granitic and schist materials of the same geotechnical units of the same cut slope in the area shows that granitic materials with higher SCOH and SFRI will be less susceptible to weathering (fig. 5.3). The medium-grained schist is also more susceptible to weathering than medium/coarse-granite due to presence of mica contents in the schist (chapter 4, table 4.1 and 4.2). The high mica contents of the schist materials also resulted in its weak bond, which allows more integral discontinuities to become mechanical. A comparison between cut slopes of the two geological formations (i.e. AR?nc1 and AR?nc2) show that most of the AR?nc1 geological formation are more susceptible to weathering than those ones in the AR?nc2 geological formation. This is due to low SCOH and SFRI, much presence of mica schist, high degree of weathering, which signifies high clay contents, reduction in IRS, low SPA and CD.

7.2. Recommendations

The study shows that it is possible to determine the rate of weathering of recently exposed deeply weathered tropical rock and soil masses' slopes in Yen Bai City in Vietnam using SSPC and Colman's formula based methods. However, in order improve the workability of the study, the following recommendations are made:

- Use of remote sensing tool like thermal infrared camera in degree of weathering characterization. It helps in describing degree of weathering in the higher inaccessible parts of the rock slope faces and clear boundary between the degrees of weathering layers.
- Determine the heights of the cut slopes more accurately.
- There is need for further study over time series of measurement of geotechnical parameters using SSPC method to enhance accuracy and proper prediction of weathering rates of the study area.

➢ **Limitations of the study**

The SSPC method uses visual observation and measurement in determining the basic geotechnical parameters of rock and soil masses, which may be influenced by human bias and depend on experience and expertise of the person making the assessment.

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APPENDICES

Appendix 1: Photographs for the inspected cut slopes

Figure 0.1: A typical excavator machine used for the cutting of slopes in the research area

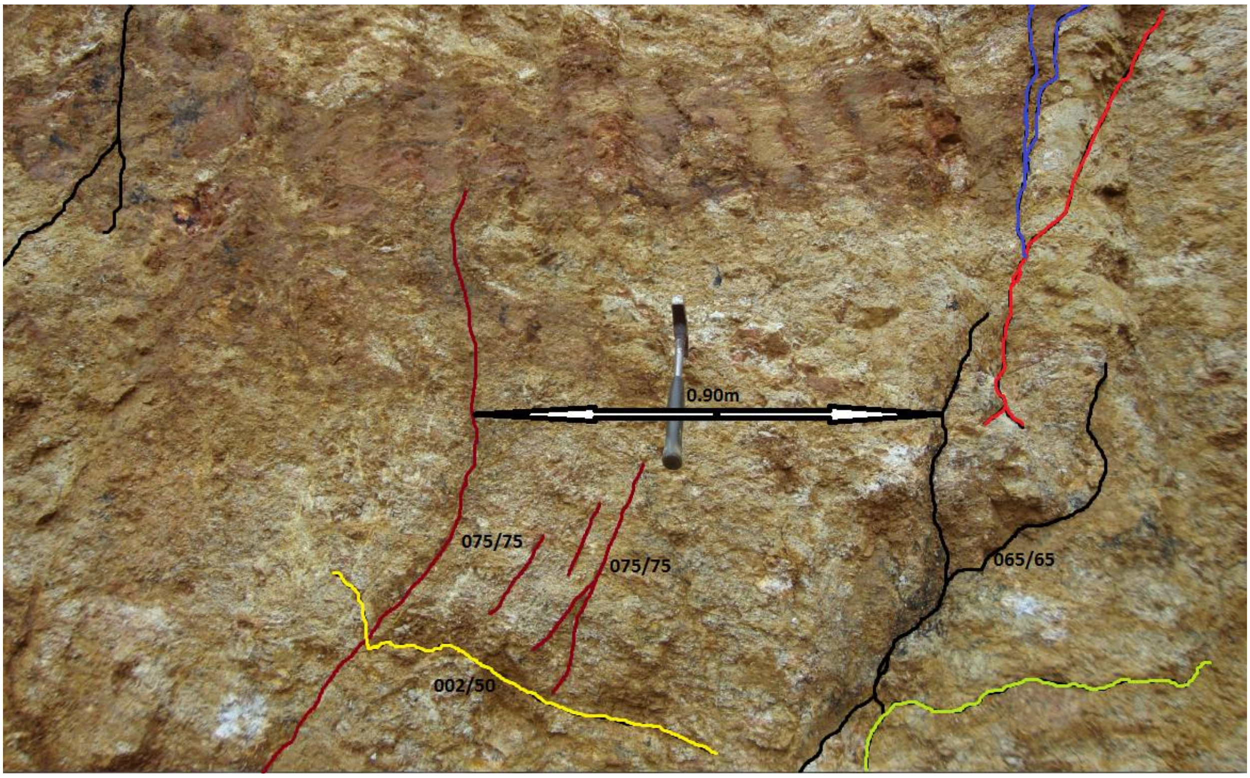


Figure 0.2: Discontinuities' orientation and spacing for the geotechnical units of recent part of Slope Y1.

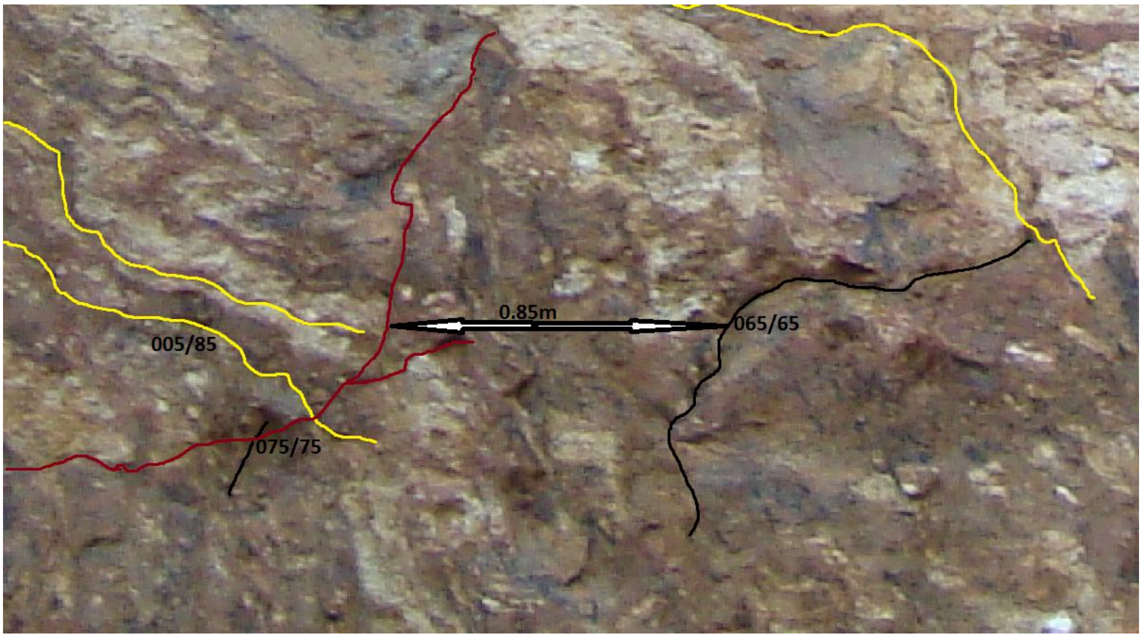


Figure 0.3: Discontinuities' orientation and spacing for the geotechnical units of recent part of Slope Y1

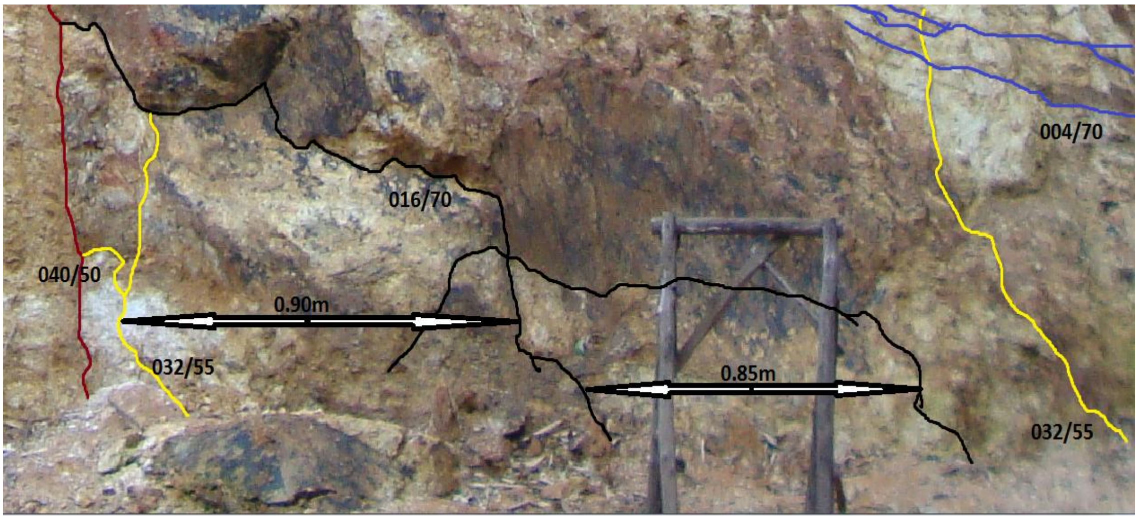


Figure 0.4: Discontinuities' orientation and spacing for the geotechnical units of recent part of Slope Y1

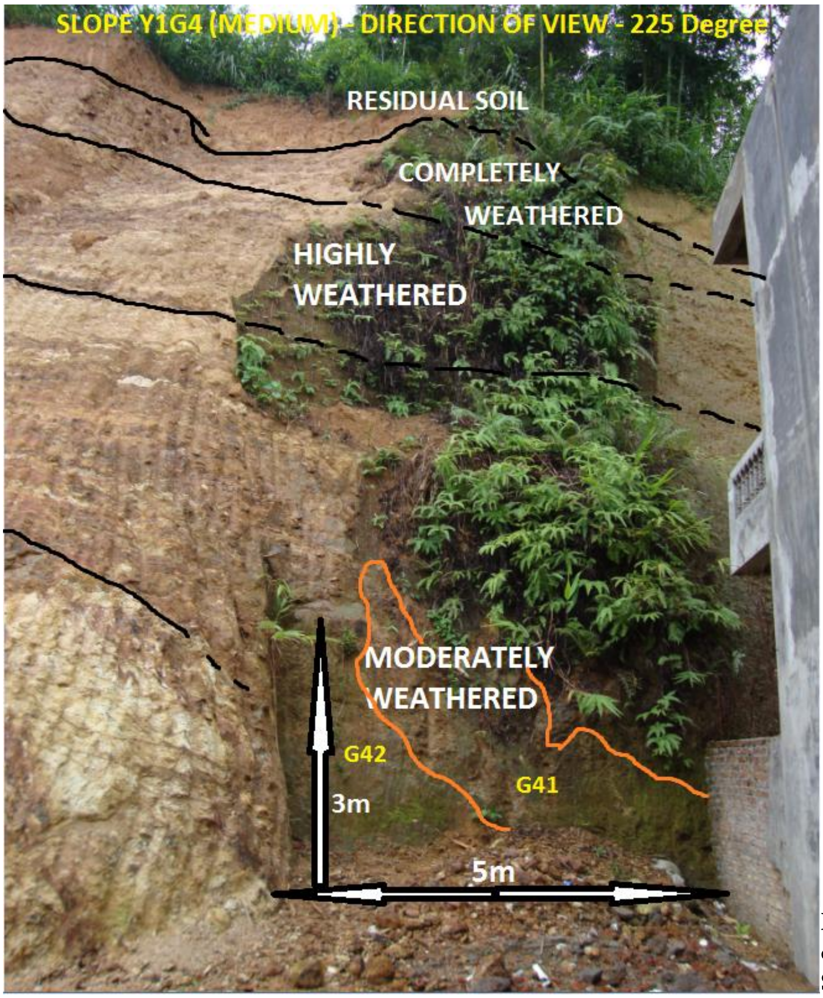


Figure 0.5: The different lithologies and degrees of weathering for the medium cut of Slope Y1 (Direction of view - 225^{O})

Figure 0.6: The old cut of Slope Y1 (Direction of view - 225^{O})

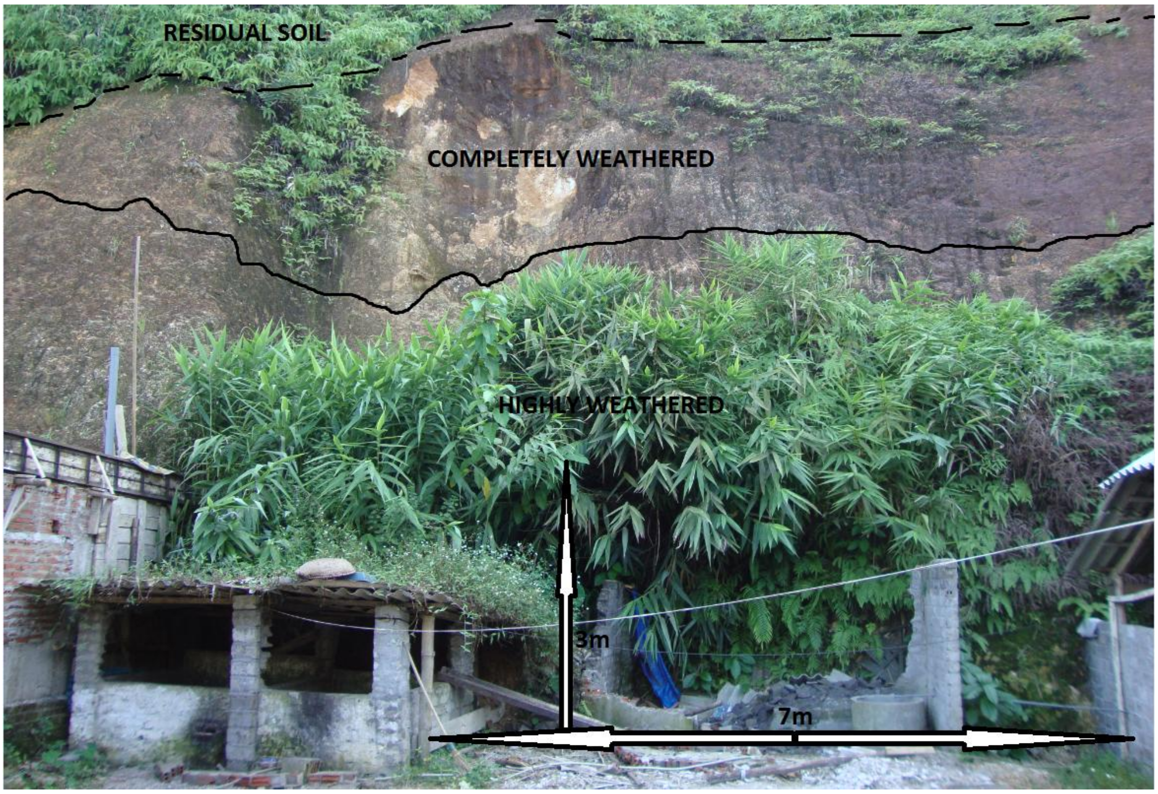


Figure 0.7: The different lithologies and degrees of weathering for the old cut of Slope Y1 (Direction of view - 225^{O})

Figure 0.8: Small block size that has large Intact Rock Strength (IRS) from geotechnical unit(s) of Cut slope Y1

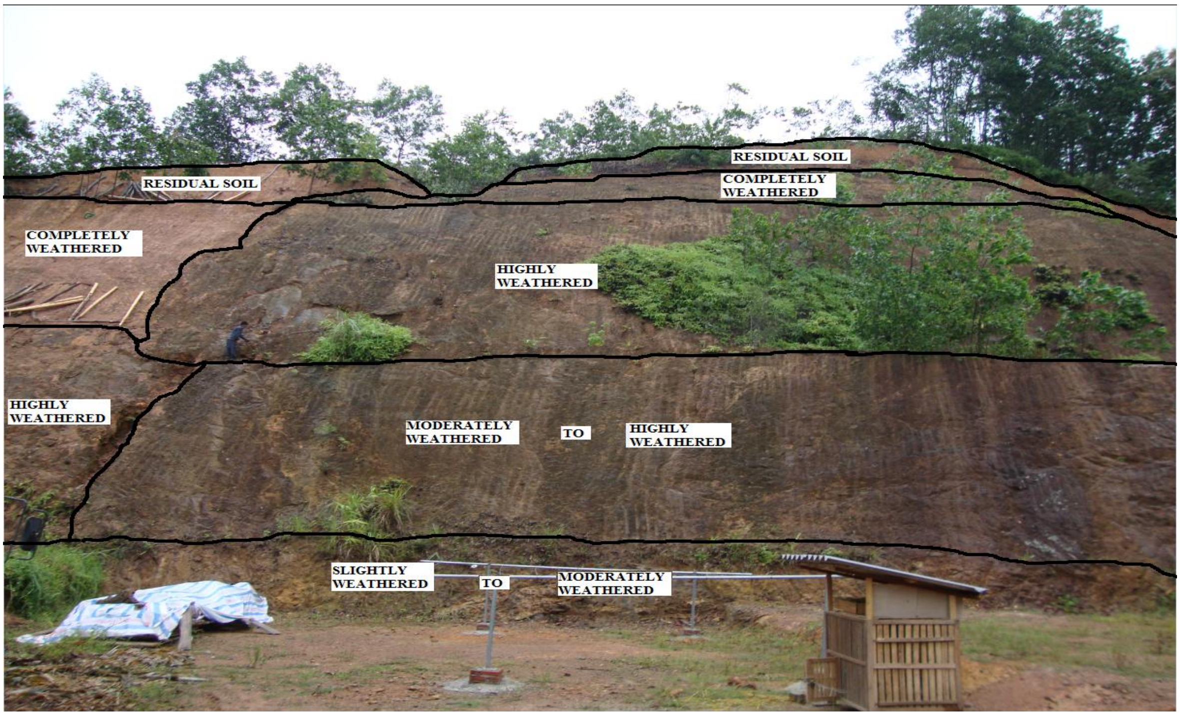


Figure 0.9: The different lithologies and degrees of weathering for the recent cut of Slope Y2 (Direction of view - 100^{O})

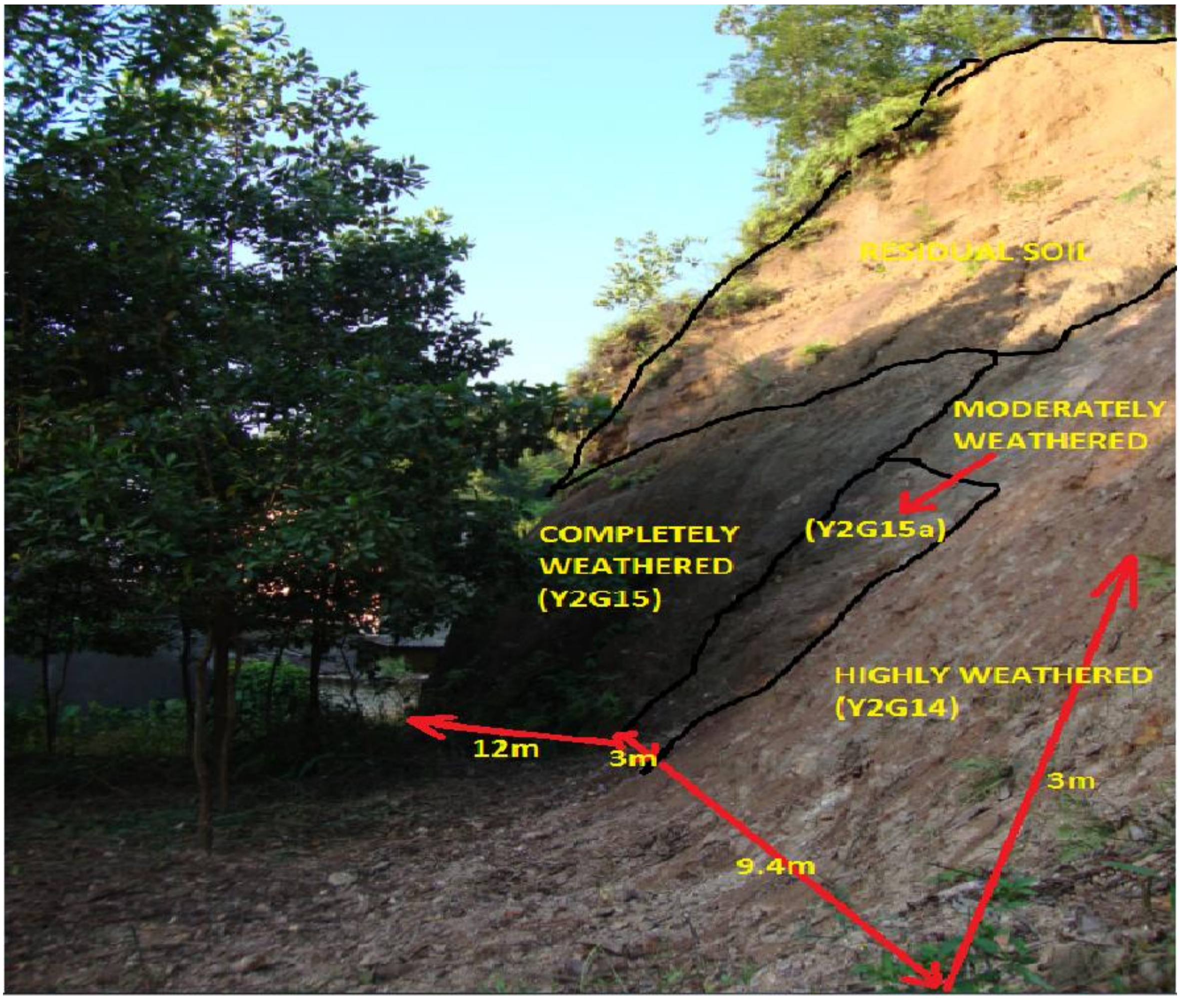


Figure 0.10: The different lithologies and degrees of weathering for old and some part of recent cut of Slope Y2 (Direction of view - 100^{O})

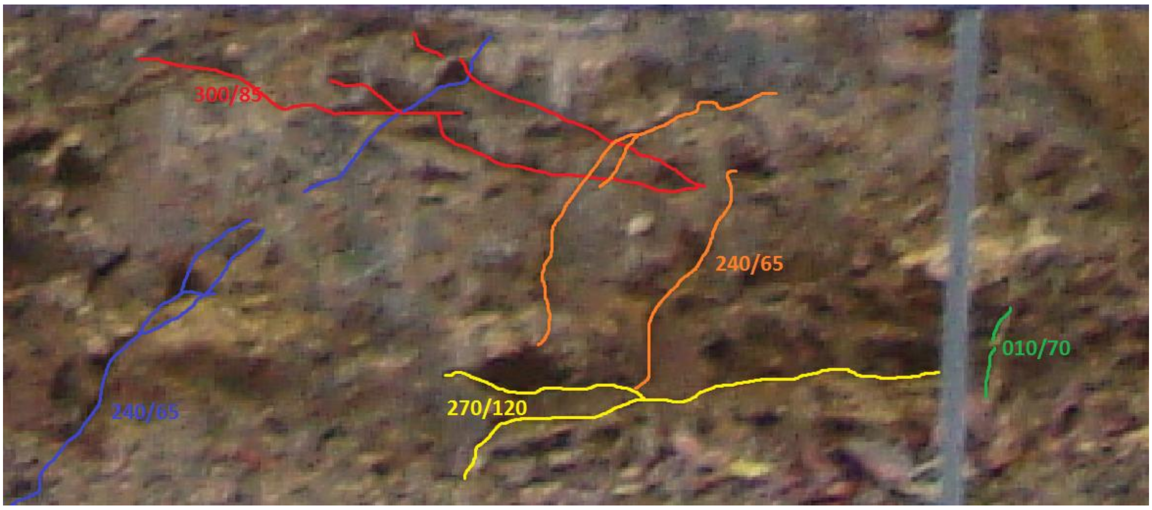


Figure 0.11: Discontinuities' orientation for the geotechnical unit G12-1 of recent part of Slope Y2

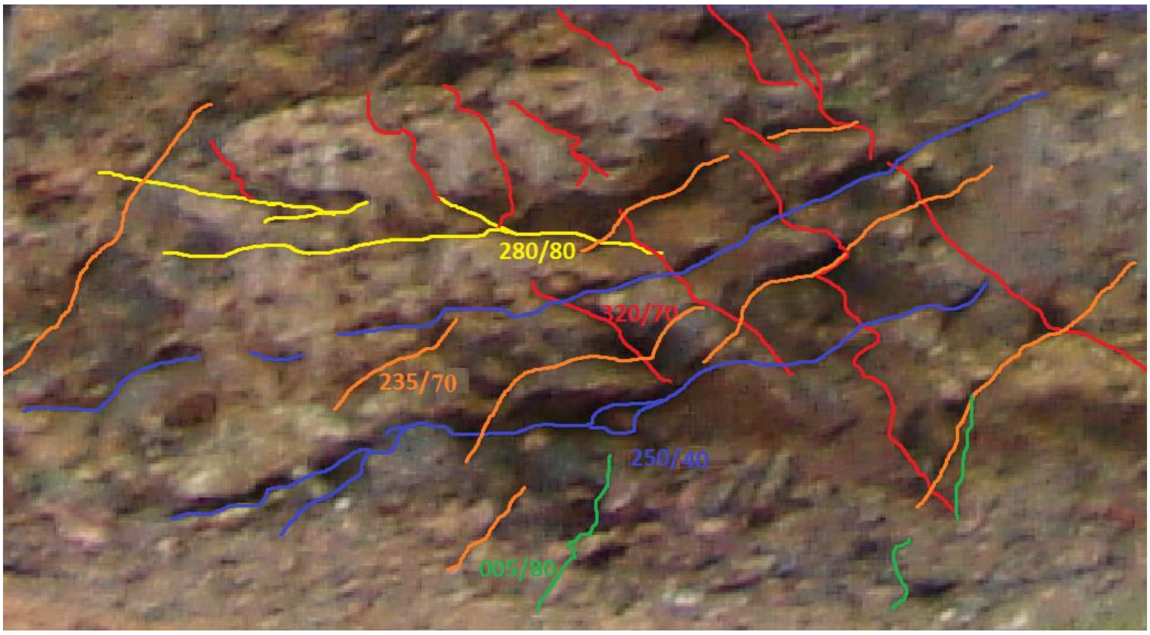


Figure 0.12: Discontinuities' orientation for the geotechnical unit G12-2 of recent part of Slope Y2

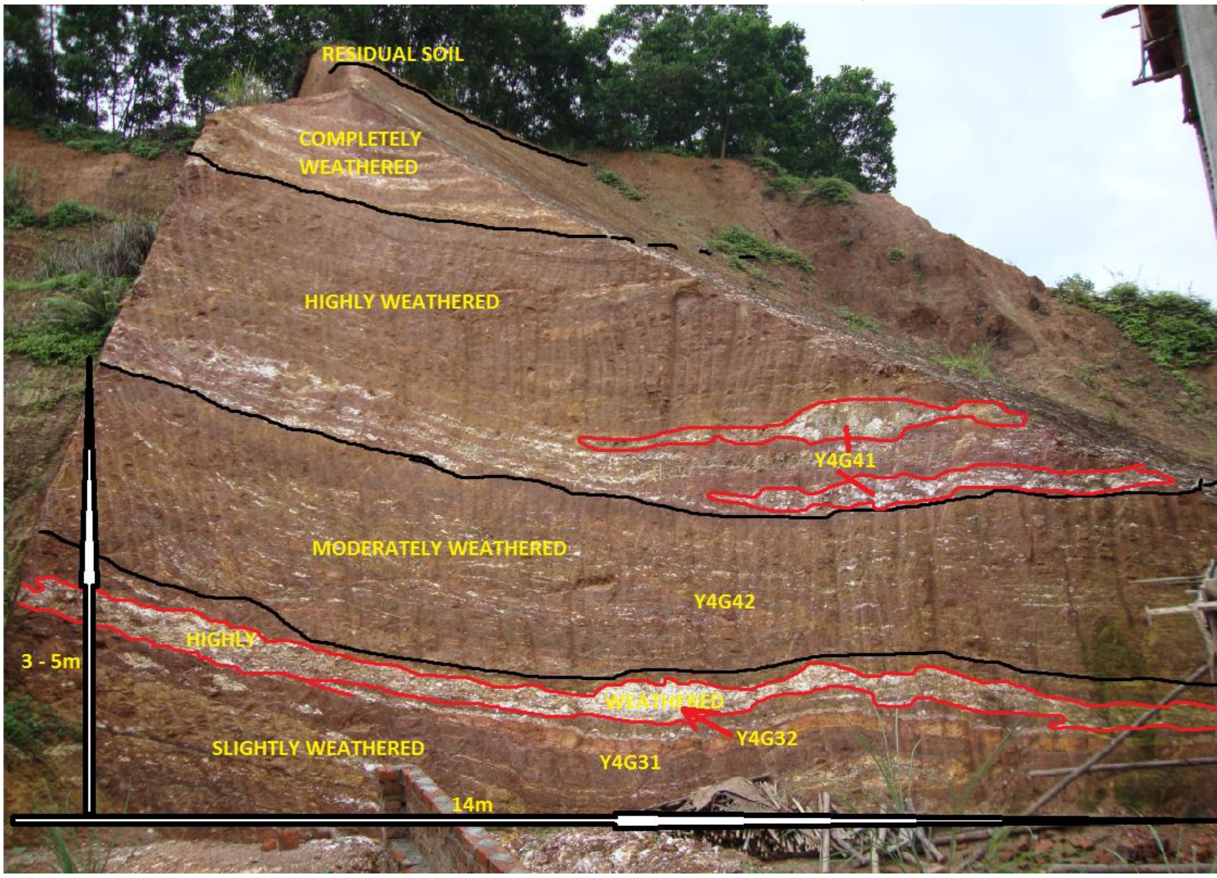


Figure 0.13: The different lithologies and degrees of weathering for the recent cut of Slope Y4 (Direction of view - 185^{O})

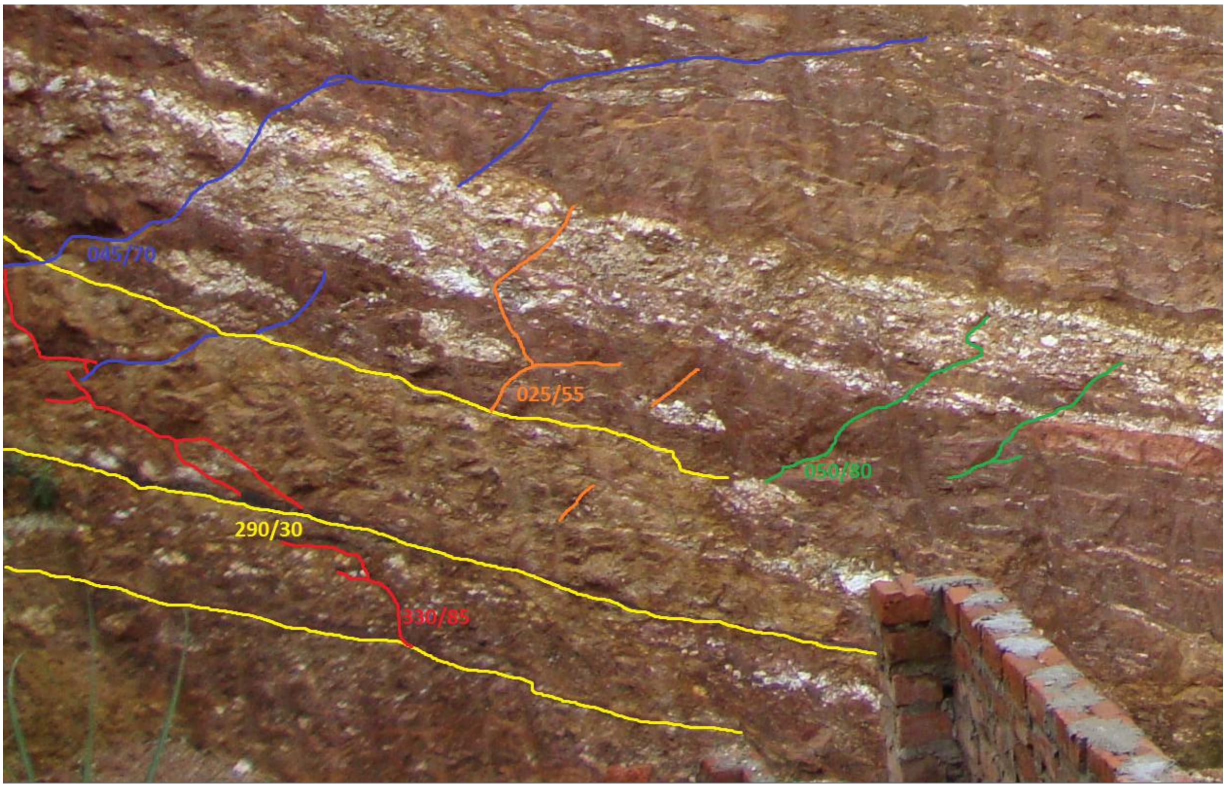


Figure 0.14: Discontinuities' orientation for the geotechnical units of recent part of Slope Y4

Figure 0.15: Discontinuities' orientation for the geotechnical units of medium part of Slope Y4

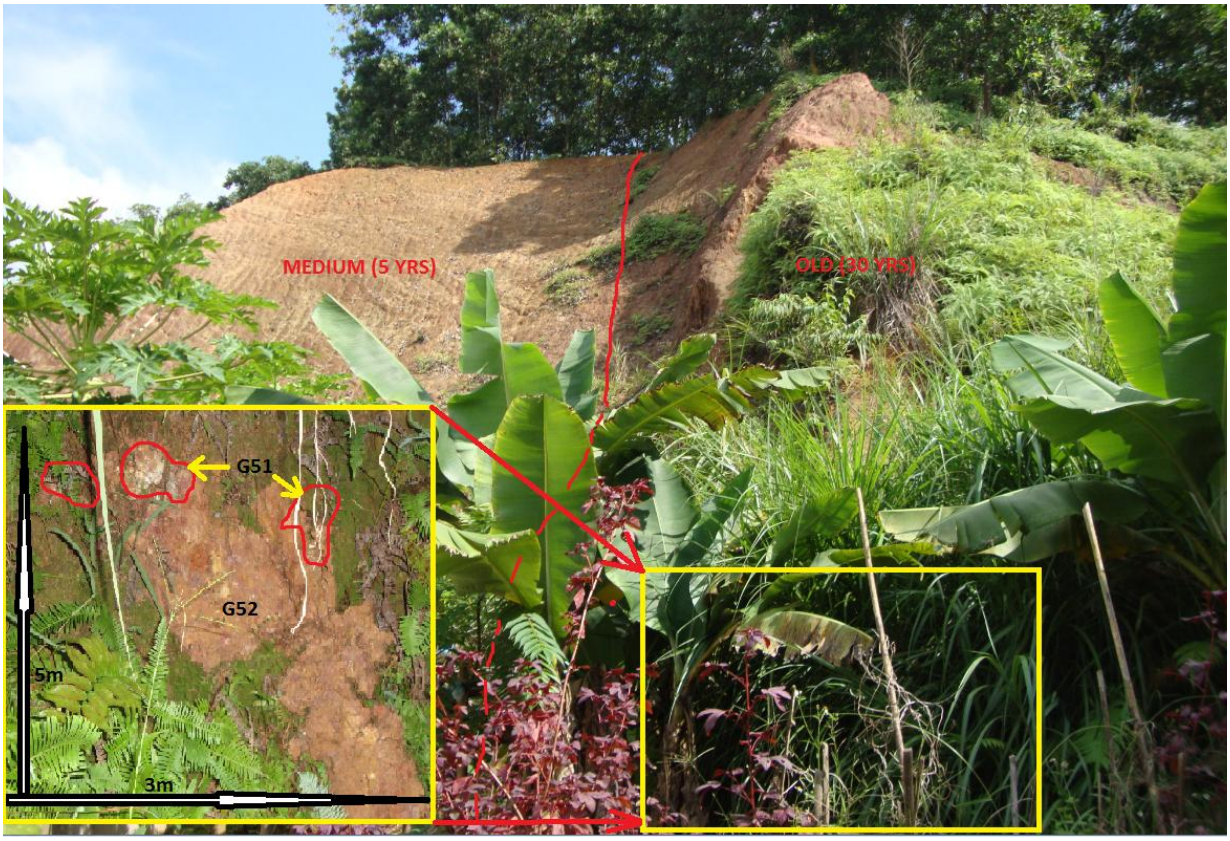


Figure 0.16: The old cut of Slope Y4 (Direction of view - 145^{O})

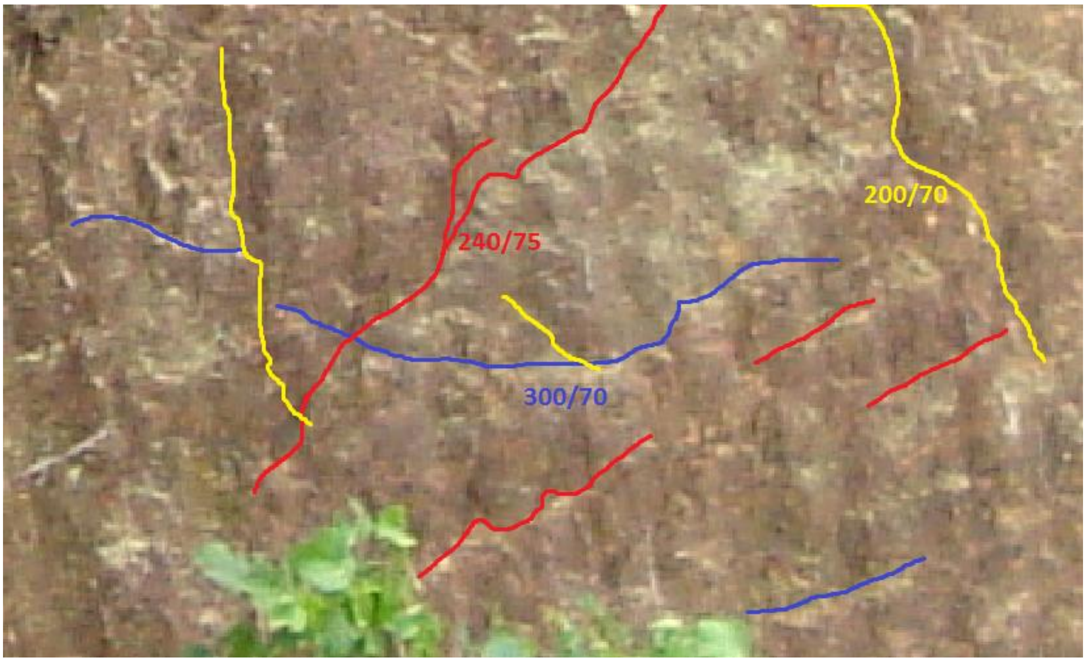


Figure 0.17: Discontinuities' orientation for the geotechnical units of Slope Y6

Cut slope Y11

The Cut slope Y11 (fig. 0.18 & 0.19) is located at Group 16, Dong Tam commune, beside Ha Huy Tap street, Yen Bai city (Easting: 516377; Northing: 2403752). The rock mass length and height are approximately 100m by 16m. The slope was excavated (using a mechanical excavator; no visible excavation damage) for building and road construction purpose, which makes only 30m of its length to be easily accessible while the remaining length is not easily accessible because they are directly behind existing buildings. The rock mass is in the AR?nc1 paleo-proterozoid geological formation and consists of porphyritic granite (feldspar) & crystalline biotite-schist with medium grain size and well-developed undulose foliation. The granite has white with black patches colour while the biotite-schist has colours varying from reddish black to brown. The different lithologies are shown in fig. 0.18 & 0.19. The rock mass of slope Y11 has two cut slopes excavated at different times; denoted recent and an old cut. The recent cut slope is five years old while the old cut slope is thirty years old.

(a) THE RECENT CUT SLOPE - The recent cut slope (fig. 0.18 & 0.19) is accessible with total mapped length of 12m; SDD and SD angle of 150^0 and 79^0 respectively. The slope has large problem because the top part is unstable as shown by the slit (indicated at the center and right hand top side in fig 0.18). The direction of view of the slope is 330^0 and the accessible (mapped) part of this slope (up to 3m) has one geotechnical unit – G1, which is divided into two sub-geotechnical units G11 and G12. G11 is porphyritic granite, which has white with black patches colour. Its SPA are 0.010m, 0.015m, 0.045m and 0.06m; the SDD_{disc} and SD_{disc} (i.e. joint orientations) are $62^0/40^0$, $100^0/50^0$, $150^0/60^0$,$150^0/75^0$ and $230^0/80^0$; persistent >3m along strike and dip; large-scale roughness(Rl) is wavy, small-scale roughness(Rs) is rough stepped; infill material(lm) is fine clay and no karst (Ka). The WE for the unit is highly weathered. While G12 is crystalline biotite-schist, which has its colour varying from reddish black to brown. Its SPA are 0.10m, 0.10m and 0.20m; the SDD_{disc} and SD_{disc} (i.e. joint orientations) are $130^0/70^0$, $150^0/70^0$ and $220^0/30^0$; persistent >3m along strike and dip; large-scale roughness (Rl) is wavy, small-scale roughness (Rs) is rough stepped; infill material (lm) is fine clay and no karst (Ka). The WE for the unit is highly weathered.

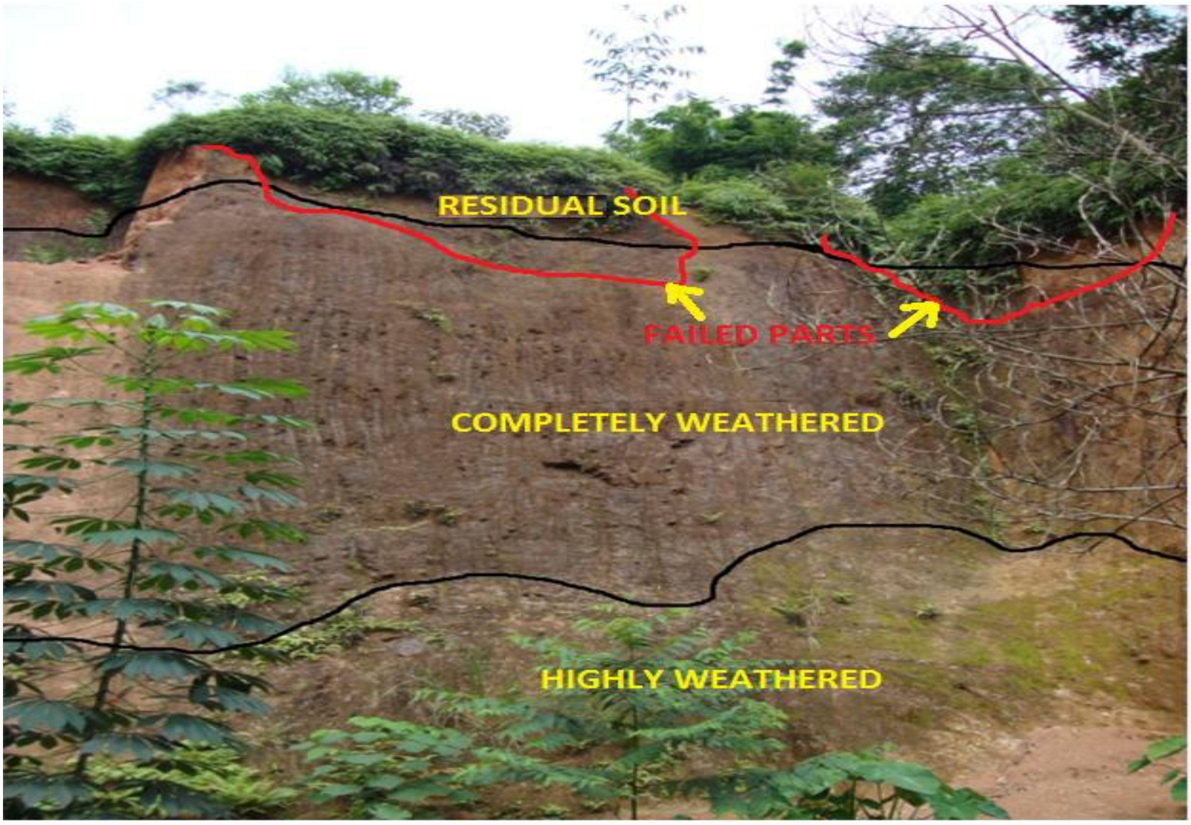


Figure 0.18: The different lithologies and degrees of weathering for the recent cut of Slope Y11 (Direction of view - 330^{O})

Figure 0.19: The different lithologies and degrees of weathering of Slope Y11 (Direction of view - 330^{O})

(b) THE OLD CUT SLOPE - The old cut slope (fig. 0.19) is not easily accessible with total mapped length of 5m. The parent formation materials, SDD, and SD angle are the same as the recent slope. The accessible (mapped) part of this slope (up to 3m) has one geotechnical unit – G2, which is divided into two sub-geotechnical units G21 and G32. The slope face is covered with algae, ferns and bushes, which makes the characterization of the discontinuities impossible. It is assumed that the SDD_{disc}, SD_{disc} and SPA of the unit are the same as the G1 geotechnical unit of the recent slope. G21 is crypto – crystalline kaolinite clay, which has white colour. Its SPA are 0.005m; large-scale roughness (Rl) is wavy, small-scale roughness (Rs) is smooth stepped; infill material (lm) is clay and no karst (Ka). The WE is completely weathered. While G32 is silty clay, which has its colour varying from red to light brown. Its SPA is 0.002m; persistent >3m along strike and dip; large-scale roughness (Rl) is slightly wavy, small-scale roughness (Rs) is smooth undulating and no karst (Ka). The WE for the unit is residual soil. The residual soil has 7.5mm average thickness with field strength of 0.2MPa. Some parts of the residuals soil sheared off while the roots of the surface grown plants hold the remaining parts together.

Cut slope Y12

The Cut slope Y12 (fig. 0.20) is located at Group 15, Dong Tam commune, Yen Bai city (Easting: 516537; Northing: 2403860). The rock mass length and height are approximately 50m by 16m. The slope was excavated (using a mechanical excavator; no visible excavation damage) for building and road construction purpose. The rock mass is in the AR?nc1 paleo-proterozoid geological formation and consists of porphyritic granite (quartz) & crystalline schist (intercalated with different rock minerals like amphibolites and mica) with medium grain size and well-developed undulose foliation. The granite has white colour while the schist with different rock minerals have colours varying from reddish brown to dull purple. The different lithologies are shown in fig. 34. The rock mass of slope Y12 has two cut slopes excavated at different times; denoted recent and an old cut. The recent cut slope is seven years old while the old cut slope is thirty years old.

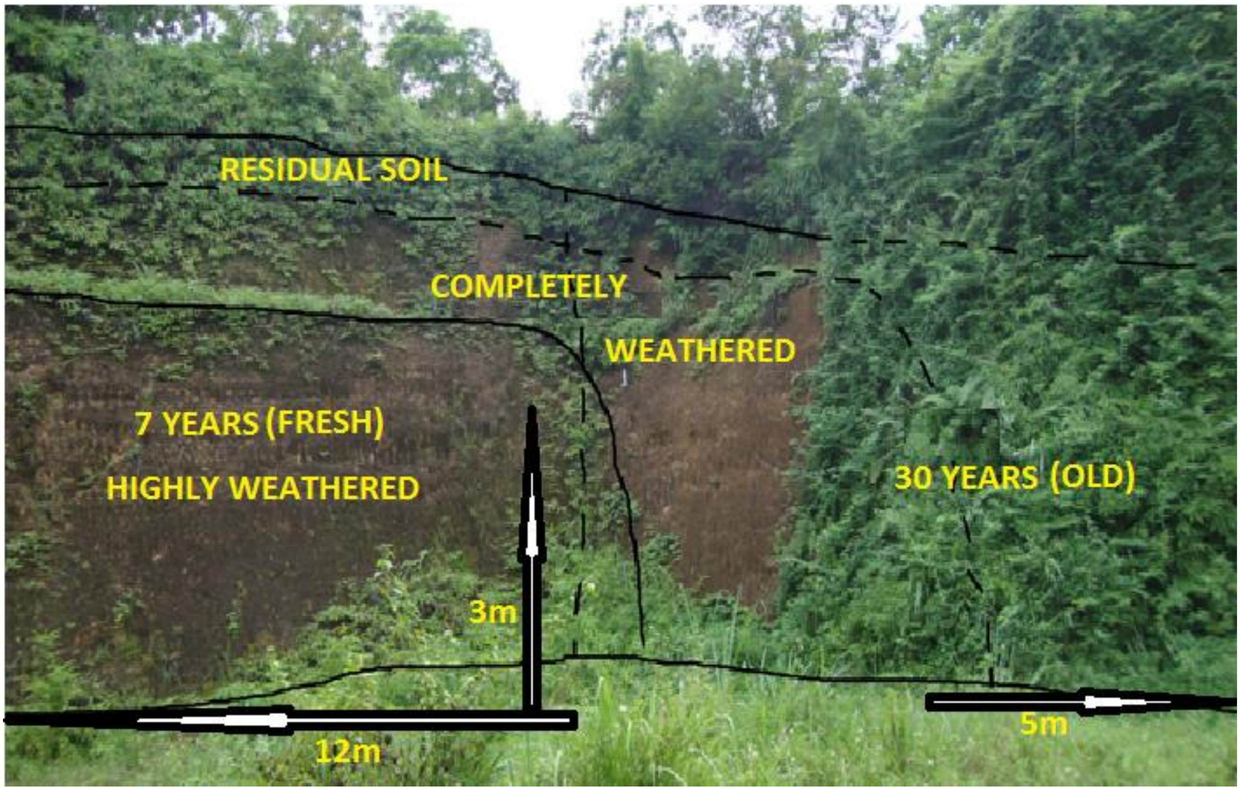


Figure 0.20: The different lithologies and degrees of weathering of Slope Y12 (Direction of view - 210^{O})

(a) THE RECENT CUT SLOPE - The recent cut slope (fig. 0.20) is accessible with total mapped length of 12m; SDD and SD angle of 030^{0} and 76^{0} respectively. The slope was cut into steps along its height to enhance its stability. The height and SD angle of the first step (bench) is approximately 10m and 79^{0} respectively. The direction of view of the slope is 210^{0} and the accessible (mapped) part of this slope (up to 3m) has one geotechnical unit – G1, which is divided into three sub-geotechnical units G11, G12 and G13. G11 is porphyritic granite (Quartz), which has white colour. Its SPA are 0.008m, 0.015m,0.01m, 0.03m and 0.12m; the SDD_{disc} and SD_{disc} (i.e. joint orientations) are 010^{0}/85^{0}, 020^{0}/35^{0}, 029^{0}/70^{0}, 235^{0}/65^{0} and 340^{0}/60^{0}; persistent >3m along strike and dip; large-scale roughness (Rl) is wavy, small-scale roughness (Rs) is rough undulating; infill material

(lm) is fine clay and no karst (Ka). The WE for the unit is highly weathered. G12 is crystalline mica-schist, which has reddish brown with tainted black colour. Its SPA are 0.08m and 0.10m; the SDDdisc and SDdisc (i.e. joint orientations) are $010^0/85^0$, $235^0/65^0$ and $340^0/60^0$; persistent >3m along strike and dip; large-scale roughness (Rl) is wavy, small-scale roughness (Rs) is rough undulating; infill material (lm) is fine clay and no karst (Ka). The WE for the unit is highly weathered. While G13 is crystalline amphibolitic-schist, which has its colour varying from reddish brown to dull purple. Its SPA are 0.06m, 0.09m and 0.11m. It is assumed that the SDDdisc and SDdisc of the unit are the same as the G12 sub-geotechnical unit. The WE for the unit is also highly weathered.
(b) THE OLD CUT SLOPE - The old cut slope (fig. 0.20) is not easily accessible with total mapped length of 5m. The parent formation materials, slope dip direction, and dip angle are the same as the recent slope. The accessible (mapped) part of this slope (up to 3m) has one geotechnical unit – G2, which is divided into two sub-geotechnical units G21 and G22. The slope face is covered with algae, ferns and bushes, which makes the characterization of the discontinuities impossible. It is assumed that the SDDdisc and SDdisc of the unit are the same as the G1 geotechnical unit of the recent slope. G21 is crypto – crystalline weathered quartz, which has white with yellow stain colour. Its SPA is 0.005m; large-scale roughness (Rl) is wavy, small-scale roughness (Rs) is smooth stepped; infill material (lm) is clay and no karst (Ka). The WE is completely weathered. While G22 is silty clay, which has brown colour. Its SPA is 0.002m; persistent >3m along strike and dip; large-scale roughness (Rl) is wavy, small-scale roughness (Rs) is smooth undulating and no karst (Ka). The WE for the unit is residual soil.

Cut slope Y13

The Cut slope Y13 is located at Group 14, Dong Tam commune, Yen Bai city (Easting: 516865; Northing: 2404125) (fig. 0.21). The rock mass length and height are approximately 100m by 11m. The slope is easily accessible, well drained and excavated (using a mechanical excavator; no visible excavation damage) for building (though not yet built) and road construction purpose. The rock mass is in AR?nc1 paleo-proterozoid geological formation and consists of porphyritic biotitic granite (feldspar) & crystalline amphibolitic-schist with medium grain size and well-developed undulose foliation. The biotitic granite has colour varying from ash to black colour while the amphibolitic-schist has colour varying from reddish brown to dark purple. The different lithologies are shown in fig. 0.21. The rock mass of slope Y13 has two cut slopes excavated at different times; denoted recent and an old cut. The recent cut slope is one years old while the old cut slope is thirty years old.

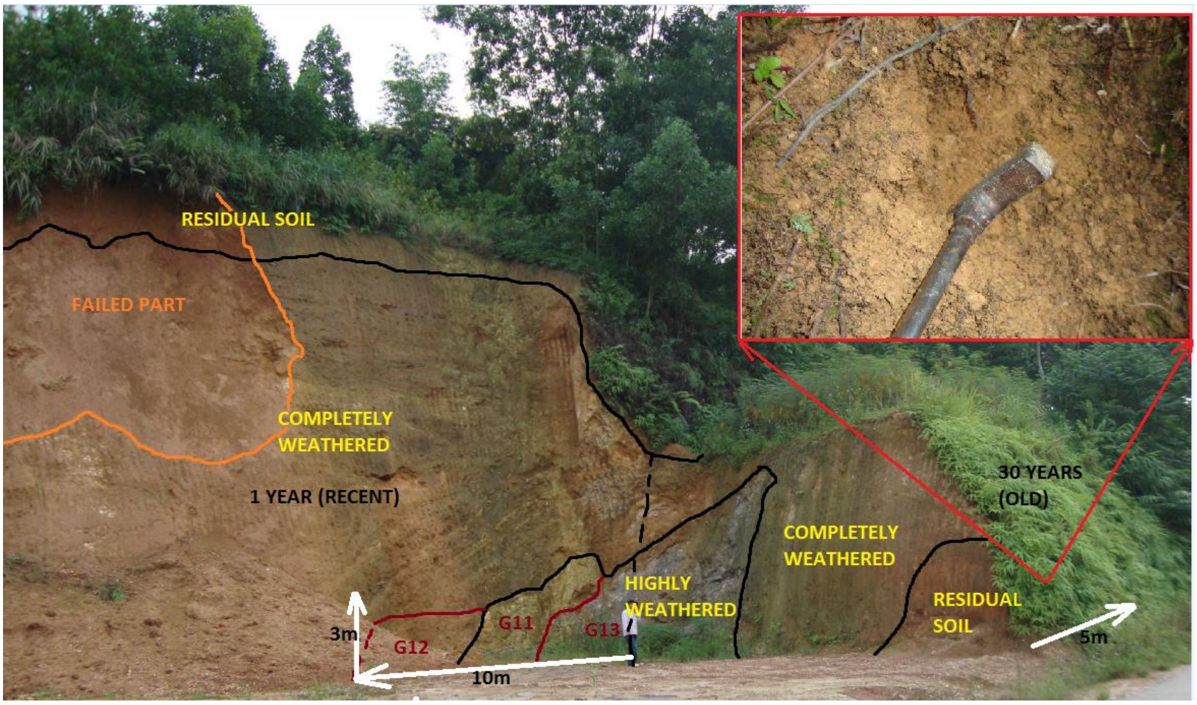


Figure 0.21: The different lithologies and degrees of weathering of Slope Y13 (Direction of view - 185^{O})

(a) THE RECENT CUT SLOPE - The recent cut slope (fig. 0.21) is accessible with total mapped length of 10m; SDD and SD angle of 005^0 and 80^0 respectively. The slope has large problem because the top part is unstable as shown by the slit (indicated at the left hand side in fig. 0.21). The direction of view of the slope is 185^0 and the accessible (mapped) part of this slope (up to 3m) has one geotechnical unit – G1, which is divided into three sub-geotechnical units G11, G12 and G13. G11 is biotitic granite, which has ash to black colour. Its SPA are 0.01m, 0.02m and 0.03m; the SDD_{disc} and SD_{disc} (i.e. joint orientations) are $002^0/40^0$, $003^0/65^0$, $060^0/75^0$ and $330^0/80^0$ (fig. 0.22); persistent >1m along strike and dip; large-scale roughness (Rl) is wavy, small-scale roughness (Rs) is rough stepped; infill material (lm) is fine clay and no karst (Ka). The WE for the unit is highly weathered. G12 is crystalline schist, which has reddish brown colour. It is assumed that the SDD_{disc} and SD_{disc} of the unit are the same as the G11 sub-geotechnical unit. Its SPA are 0.005m; large-scale roughness (Rl) is slightly wavy, small-scale roughness (Rs) is smooth undulating; infill material (lm) is fine clay and no karst (Ka). The WE for the unit is completely weathered. While G13 is crystalline amphibolitic-schist, which has its colour varying from reddish brown to dark purple. Its SPA is 0.05m, 0.10m and 0.15m. It is assumed that the SDD_{disc}, SD_{disc} and CD of the unit are the same as the G11 sub-geotechnical unit. The WE for the unit is also highly weathered.

(b) THE OLD CUT SLOPE - The old cut slope (fig. 0.21) is not easily accessible with total mapped length of 5m. The SD angle is 40^0 while the slope dip direction is the same as the recent slope. The accessible (mapped) part of this slope (up to 3m) has one geotechnical unit – G21 which is silty clay with brown colour. The slope face is covered with algae, ferns and bushes, which makes the characterization of the discontinuities impossible. Its SPA is 0.002m. It is assumed that the SDD_{disc}, SD_{disc} and CD of the unit are the same as the G12 sub-geotechnical unit of the recent slope. The WE for the unit is residual soil.

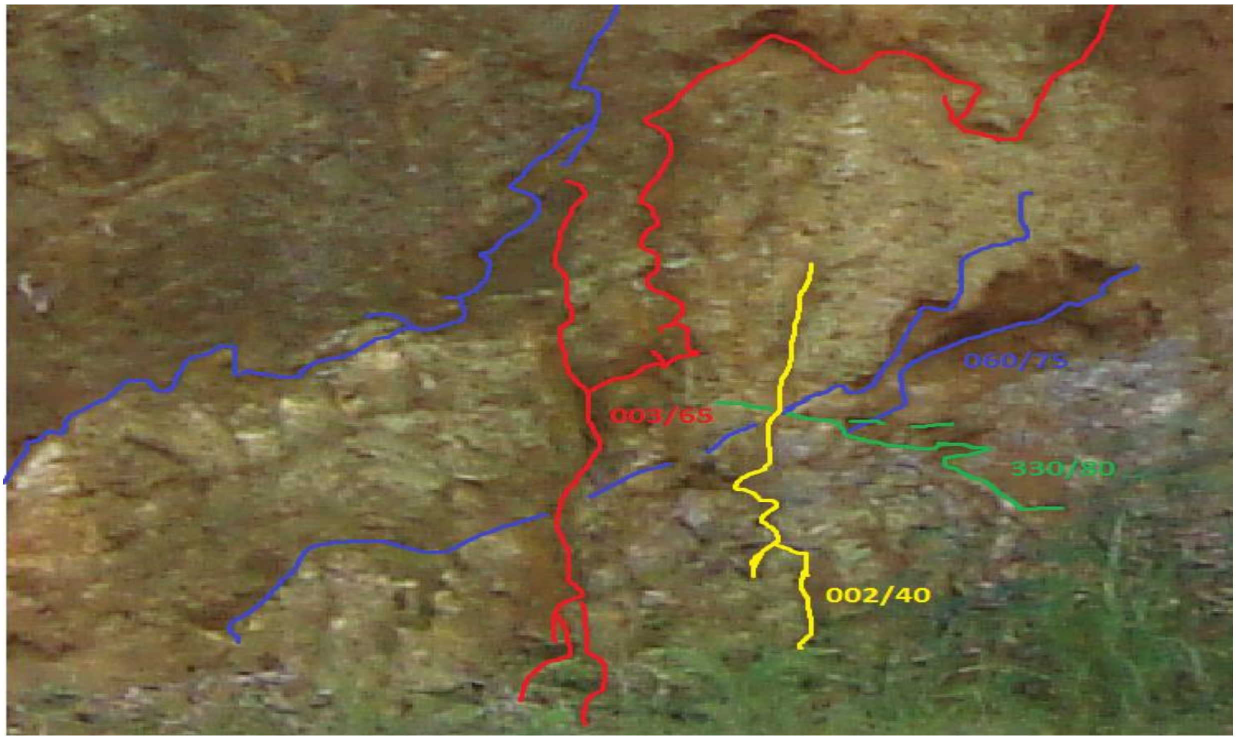


Figure 0.22: Discontinuities' orientation for the geotechnical units of Slope Y13

Cut slope Y14

The Cut slope Y14 is located at Group 38, Cuong Bac hamlet, Nam Cuong commune, Yen Bai city (Easting: 513542; Northing: 2404139) (fig. 0.23). The rock mass length and height are approximately 100m by 11m. The slope is stable, easily accessible, well drained and excavated (using a mechanical excavator; no visible excavation damage) for building (though not yet built) and road construction purpose. The rock mass is in AR?nc2 paleo-proterozoid geological formation and consists of porphyritic granite (feldspar) & crystalline schist (intercalated with different rock minerals like amphibolites) with medium grain size and well-developed undulose foliation. The granite has white colour, while the schist with different rock minerals have colours varying from reddish black to light brown. The different lithologies are shown in fig. 38. The rock mass of slope Y14 has two cut slopes excavated at different times; denoted recent and an old cut. The recent cut slope is two months old while the old cut slope is twenty years old.

(a) THE RECENT CUT SLOPE - The recent cut slope (fig. 0.23) is accessible with total mapped length of 13m; SDD and SD angle of 017^0 and 68^0 respectively. The direction of view of the slope is 197^0 and the accessible (mapped) part of this slope (up to 3m) has one geotechnical unit – G1, which is divided into three sub-geotechnical units G11, G12 and G13. G11 is porphyritic granite, which has white colour. Its SPA are 0.02m, 0.03m, 0.035m and 0.045m. It is assumed that the SDD_{disc}, SD_{disc} and CD of the unit are the same as the G12 sub-geotechnical unit. The WE for the unit is highly weathered. G12 is crystalline ferruginous schist, which has its colour varying from reddish to light brown. Its SPA are 0.06m, 0.07m and 0.10m; the SDD_{disc} and SD_{disc} (i.e. joint orientations) are $065^0/80^0$, $090^0/75^0$, $345^0/75^0$ and $050^0/60^0$; persistent >3m along strike and dip; large-scale roughness (Rl) is wavy, small-scale roughness (Rs) is rough undulating; infill material (lm) is fine clay and no karst (Ka). The WE for the unit is highly weathered. While G13 is crystalline amphibolitic-schist, which has its colour varying from reddish black to light brown. It is assumed that the SDD_{disc}, SD_{disc}, SPA and CD of the unit are the same as the G12 sub-geotechnical unit. The WE for the unit is also highly weathered.

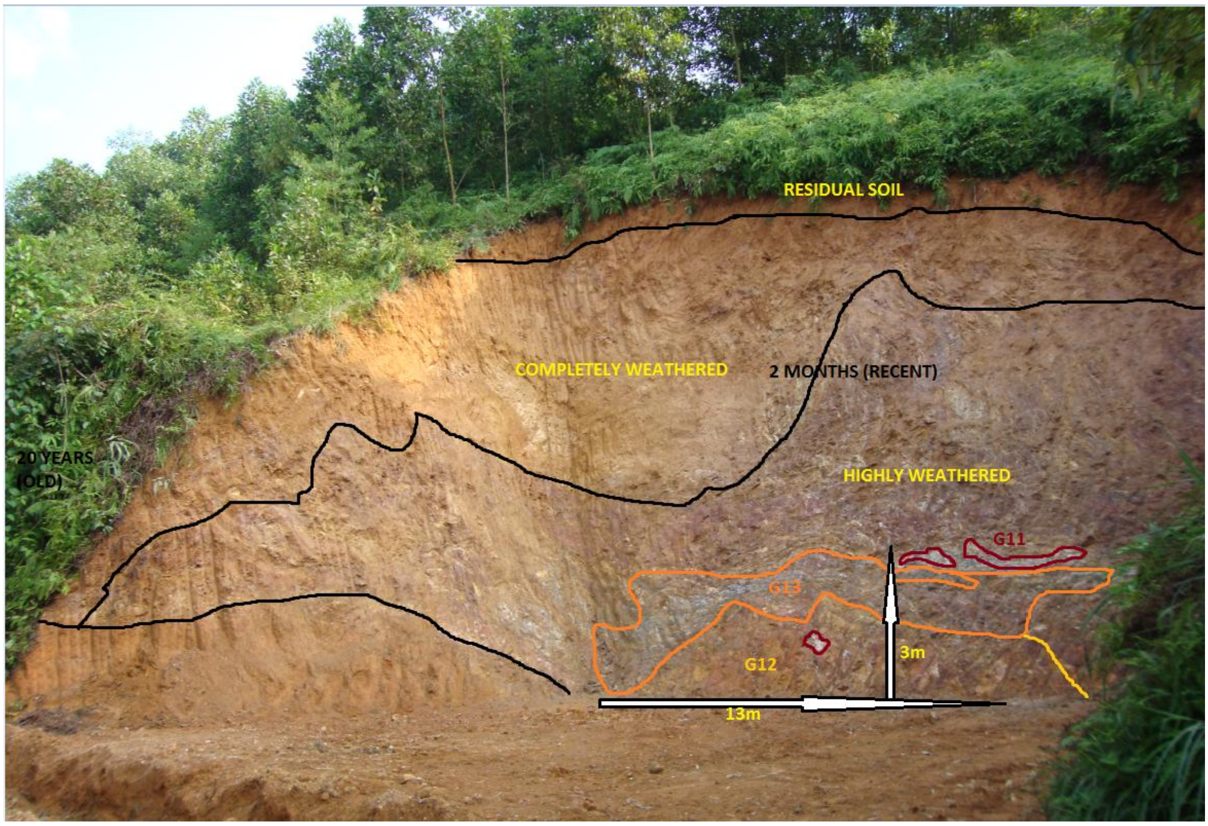


Figure 0.23: The different lithologies and degrees of weathering of Slope Y14 (Direction of view - 197^O)

(b) THE OLD CUT SLOPE - The old cut slope (fig. 0.23) is not easily accessible with total mapped length of 5m. The parent formation materials, SDD, and SD angle are the same as the recent slope. The accessible (mapped) part of this slope (up to 3m) has one geotechnical unit – G2, which is divided into two sub-geotechnical units G21 and G22. The slope face is covered with algae, ferns and bushes, which makes the characterization of the discontinuities impossible. Its SPA is 0.005m. It is assumed that the SDD_{disc}, SD_{disc} and CD of the unit are the same as the G1geotechnical unit of the recent slope. G21 is crypto – crystalline kaolinite clay, which has white colour while G22 is soil with schist fragment. The WE for the unit is also completely weathered.

Cut slope Y18

The Cut slope Y18 is located at Group 36, Yen Ninh commune, Yen Bai city (Easting: 514539; Northing: 2401955) (fig. 0.24). The rock mass length and height are approximately 60m by 15m. The slope is easily accessible, well drained and excavated (using a mechanical excavator; no visible excavation damage) for building (construction of the building is in progress) and road construction purpose. The rock mass is in AR?nc2 paleo-proterozoid geological formation and consists of porphyritic granite (cryptocrystalline quartz and feldspar) with fine to medium grain size. The granite has colours varying from white to pink. The different lithologies are shown in fig. 0.24. The rock mass of slope Y18 has two cut slopes excavated at different times; denoted recent and an old cut. The recent cut slope is one year old while the old cut slope is thirty years old.

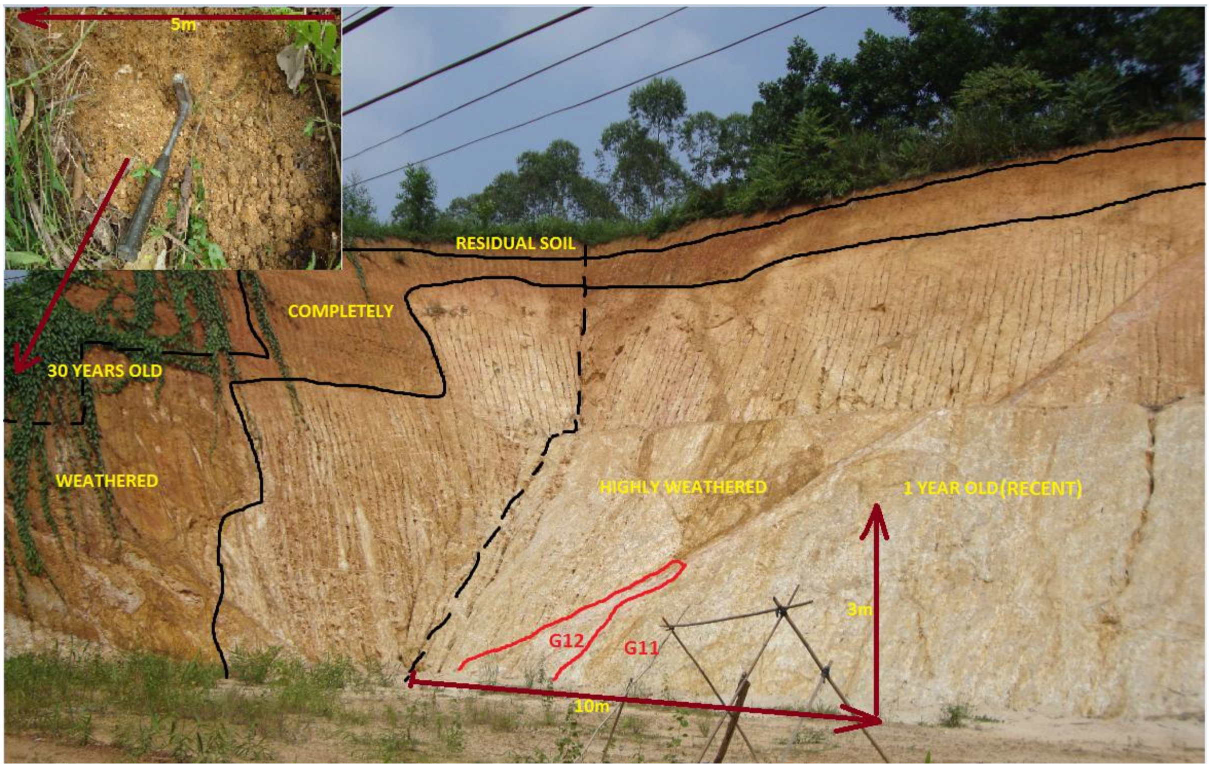


Figure 0.24: The different lithologies and degrees of weathering of Slope Y18 (Direction of view - 040^{O})

(a) THE RECENT CUT SLOPE - The recent cut slope (fig. 0.24) is accessible with total mapped length of 10m; SDD and SD angle of 220^{0} and 56^{0} respectively. The slope was cut into steps along its height to enhance its stability. The height and slope dip angle of the first step is approximately 7m and 60^{0} respectively. The direction of view of the slope is 040^{0} and the accessible (mapped) part of this slope (up to 3m) has one geotechnical unit – G1, which is divided into two sub-geotechnical units G11 and G12. G11 is porphyritic granite (feldspar), which has ash/white with brown stain colour. Its SPA are 0.045m, 0.020m, 0.030m, 0.050m, 0.010m. The SDD_{disc} and SD_{disc} (i.e. joint orientations) are 015^{0}/10^{0}, 028^{0}/65^{0}, 032^{0}/70^{0}, 290^{0}/60^{0} and 300^{0}/80^{0} (fig. 0.25); persistent >3m along strike and dip; large-scale roughness (Rl) is wavy, small-scale roughness (Rs) is smooth stepped; infill material (lm) is fine clay and no karst (Ka). The WE for the unit is highly weathered. While G12[9] is porphyritic granite (quartz), which has white with purple and pink stain colour. Its SPA are 0.080m. It is assumed that the SDD_{disc}, SD_{disc} and CD of the unit are the same as the G11sub-geotechnical unit of the recent slope persistent >3m along strike and dip; large-scale roughness (Rl) is wavy, small-scale roughness (Rs) is smooth stepped; infill material (lm) is fine clay and no karst (Ka). The WE for the unit is highly weathered.

(b) THE OLD CUT SLOPE The old cut slope (fig. 0.24) is not easily accessible with total mapped length of 5m. The SDD and SD angle are the same as the recent slope. The accessible (mapped) part of this slope (up to 3m) has one geotechnical unit – G13. It is soil with kaolinite clay and quartz fragment, which has colours varying from light brown to white. The slope face is covered with algae, ferns and bushes, which makes the characterization of the discontinuities impossible. Its SPA is 0.005m. It is assumed that the SDD_{disc}, SD_{disc} and

[9] The name of rock material for the sub-geotechnical unit G12 of Cut slope Y18 was erroneously assessed to be potassium feldspar during fieldwork. Nevertheless, corrected on 25/11/2010 (after the fieldwork) as quartz.

CD of the unit are the same as the G1 geotechnical unit of the recent slope. The WE for the unit is completely weathered.

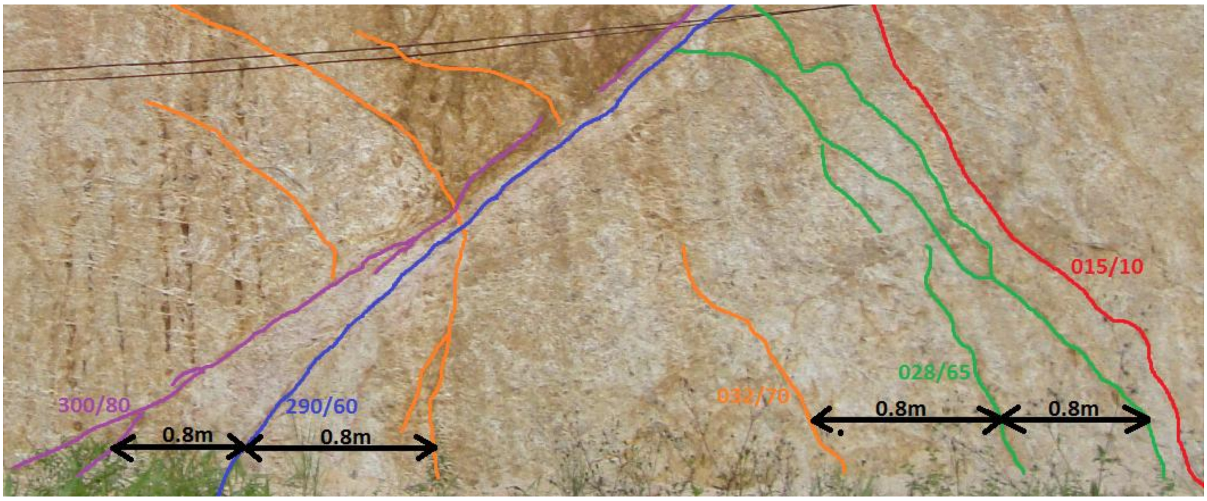


Figure 0.25: Discontinuities' orientation for the geotechnical units of Slope Y18

Cut slope Y20

The Cut slope Y20 is located at Group 30, Yen Ninh commune, Yen Bai city (Easting: 515263; Northing: 2401780) (fig. 0.26). The rock mass length and height are approximately 80m by 22m. The slope is not easily accessible, and excavated (using a mechanical excavator; no visible excavation damage) for building (not yet built) and road construction purpose. The rock mass is in AR?nc2 paleo-proterozoid geological formation and consists of porphyritic granite (feldspar) & crystalline schist (intercalated with different rock minerals like garnet and biotite) with medium grain size and well-developed undulose foliation. The granite has white with brown stain colour while the schist with different rock minerals has colours varying from reddish black to brown. The different lithologies are shown in fig. 0.26. The rock mass of slope Y20 has two cut slopes excavated at different times; denoted recent and an old cut. The recent cut slope is five years old while the old cut slope is thirty years old.

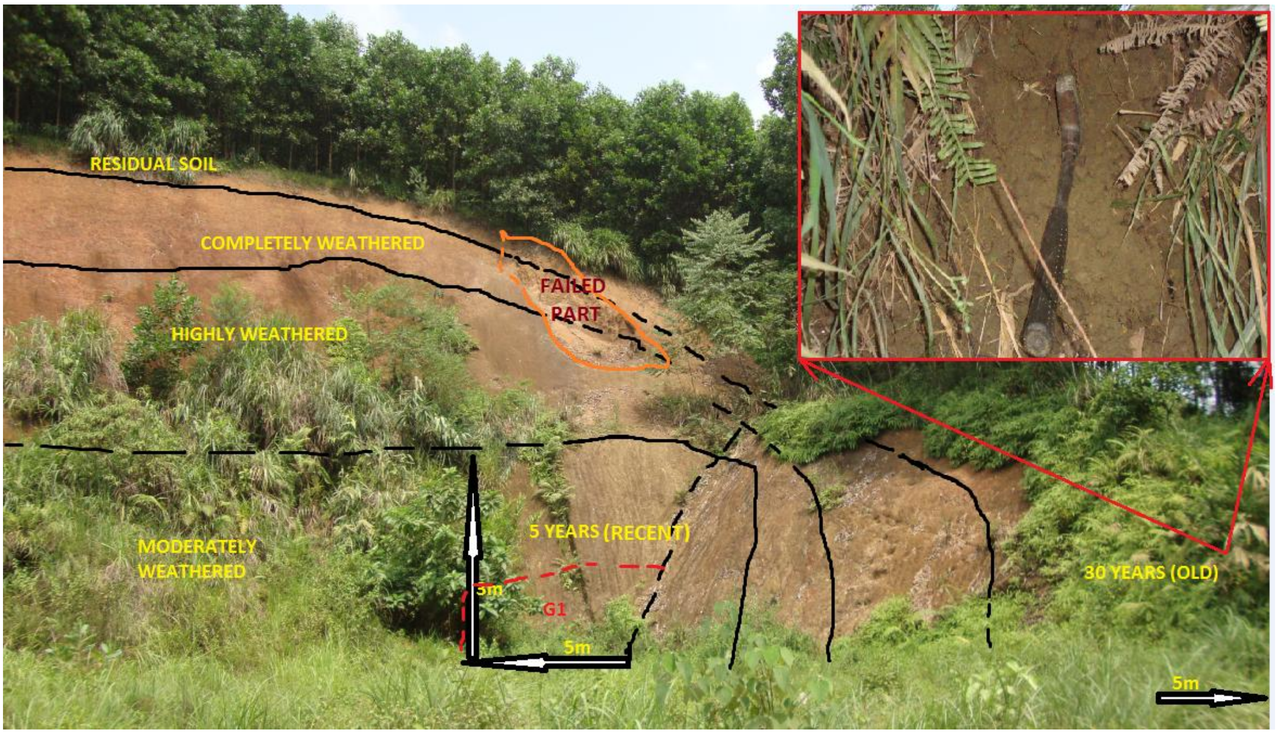


Figure 0.26: The different lithologies and degrees of weathering of Slope Y20 (Direction of view - 020^{O})

(a) THE RECENT CUT SLOPE - The recent cut slope (fig. 0.26) is accessible with total mapped length of 5m; SDD and SD angle of 200^0 and 56^0 respectively. The slope has small problem because the top part is unstable as shown by the slit (indicated at the right hand top side in fig. 0.26). The direction of view of the slope is 020^0 and the accessible (mapped) part of this slope (up to 3m) has one geotechnical unit – G1, which is divided into two sub-geotechnical units G11 and G12. G11 is porphyritic granite, which has white with brown stain colour. Its spacing of discontinuity sets are 0.05m and 0.06m; the SDD_{disc} and SD_{disc} (i.e. joint orientations) are $170^0/65^0$, $260^0/45^0$, $276^0/70^0$ and $330^0/85^0$; persistent >3m along strike and dip; large-scale roughness (Rl) is wavy, small-scale roughness (Rs) is rough stepped; infill material (lm) is fine clay and no karst (Ka). The WE for the unit is moderately weathered. While G12 is crystalline garnet-biotite-schist, which has its colour varying from reddish black to brown. Its SPA are 0.07m, 0.08m and 0.10m. It is assumed that the SDD_{disc}, SD_{disc} and CD of the unit are the same as the G11 sub-geotechnical unit. The degree of weathering for the unit is moderately weathered.

(b) THE OLD CUT SLOPE - The old cut slope (fig. 0.26) is not easily accessible with total mapped length of 5m. The SDD and SD angle are the same as the recent slope. The accessible (mapped) part of this slope (up to 3m) has one geotechnical unit – G13 which is clay soil with dark brown colour. The slope face is covered with algae, ferns and bushes, which makes the characterization of the discontinuities impossible. Its SPA is 0.002m. It is assumed that the SDD_{disc}, SD_{disc} and CD of the unit are the same as the G1 geotechnical unit of the recent slope. The WE for the unit is residual soil. The average thickness of the residual soil is greater than 20mm with field strength of 0.147MPa.

Cut slope Y21

The Cut slope Y21[10] is located at Group 30, Yen Thinh commune, Yen Bai city (Easting: 515498; Northing: 2401611) (fig. 0.27). The rock mass length and height are approximately 30m by 10m. The slope is not accessible, and excavated (using a mechanical excavator; no visible excavation damage) for building and road construction purpose. The rock mass is in AR?nc2 paleo-proterozoid geological formation and consists of porphyritic granite (feldspar) & crystalline biotite-schist with medium grain size and well-developed undulose foliation. The granite has white with yellow stain colour while the schist with different rock minerals has colours varying from reddish black to brown. The different lithologies are shown in fig. 42. The rock mass of slope Y21 has two cut slopes excavated at different times; denoted recent and an old cut. The recent cut slope is 8 months old while the old cut slope is thirty years old.

(a) THE RECENT CUT SLOPE - The recent cut slope (fig. 0.27) has total mapped length of 10m; SDD and SD angle of 200^0 and 80^0 (rough estimation) respectively. The slope has large problem because the top part is unstable as shown by the slit (indicated at the top side in fig. 42). The direction of view of the slope is 020^0 and the accessible (mapped) part of this slope (up to 3m) has one geotechnical unit – G1, which is divided into two sub-geotechnical units G11 and G12. G11 is porphyritic granite, which has white with yellow stain colour. Its SPA is 0.005m; the SDD_{disc} and SD_{disc} (i.e. joint orientations) are $180^0/75^0$, $270^0/50^0$ and $295^0/55^0$; persistent >3m along strike and dip; large-scale roughness (Rl) is wavy, small-scale roughness (Rs) is rough stepped; infill material (lm) is clay and no karst (Ka). The WE for the unit is completely weathered. While G12 is crystalline biotite-schist, which has its colour varying from reddish black to brown. Its SPA are 0.06m, 0.08m and 0.10m. It is assumed that the SDD_{disc}, SD_{disc} and CD of the unit are the same as the G11 sub-geotechnical unit. The WE for the unit is completely weathered.

(b) THE OLD CUT SLOPE - The old cut slope (fig. 0.27) is not accessible with total mapped length of 5m. The slope dip direction and dip angle are the same as the recent slope. The accessible (mapped) part of this slope (up to 3m) has one geotechnical unit – G13 which is silty clay soil with light brown colour. The slope face is covered with algae, ferns and bushes, which makes the characterization of the discontinuities impossible. Its SPA is 0.002m. It is assumed that the SDD_{disc}, SD_{disc} and CD of the unit are the same as the G1geotechnical unit of the recent slope. The WE for the unit is residual soil.

[10] There is problem of inaccessibility to cut slope Y21 by non-indigene of the country; hence, the orientation of discontinuities are not measured accurately during fieldwork and the assessment was carried out by visual inspection from a distance of about 20m.

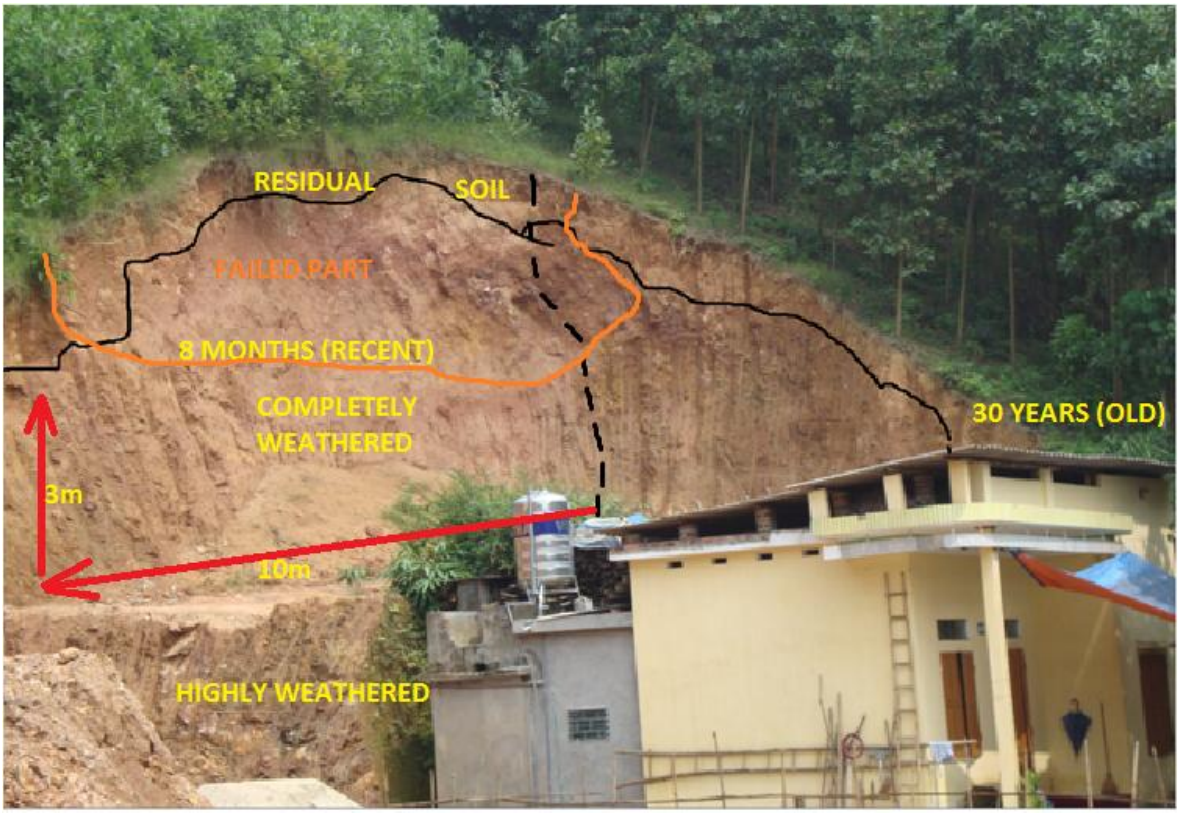


Figure 0.27: The different lithologies and degrees of weathering of Slope Y21 (Direction of view - 020^{O})

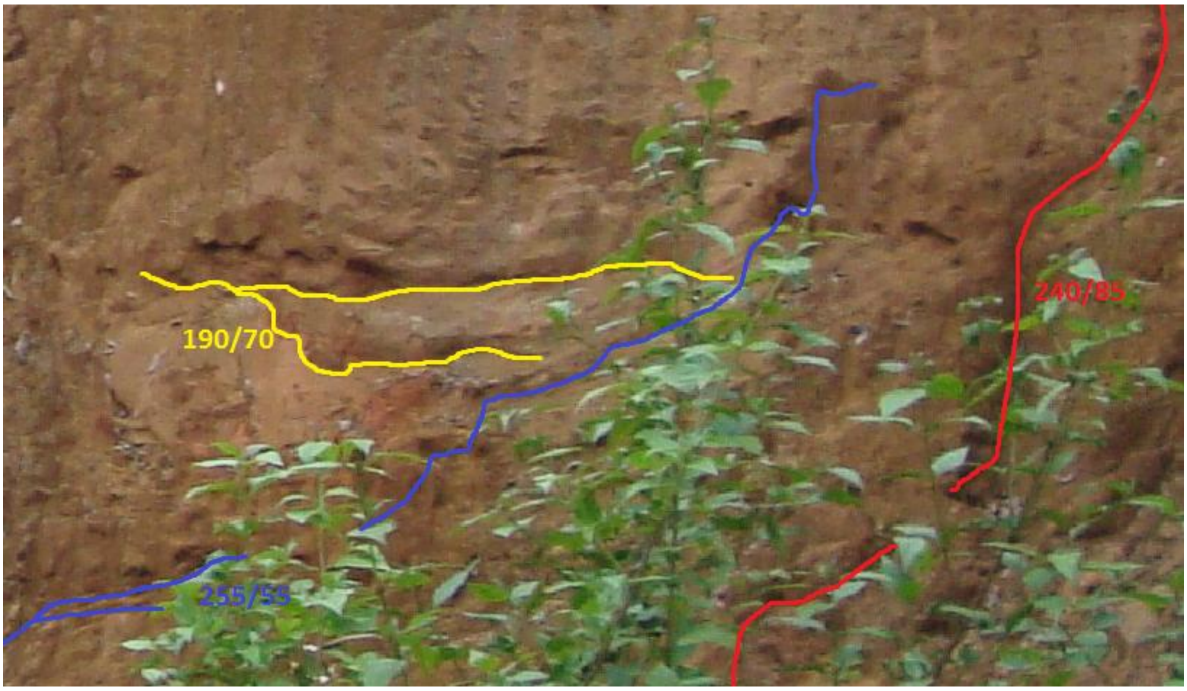


Figure 0.28: Discontinuities' orientation for the geotechnical units of Slope Y24

Figure 0.29: The old cut of Slope Y27 (Direction of view - 040^O)

Cut slope Y28

The Cut slope Y28 is located at Bao Yen hamlet, Minh Bao commune, Yen Bai city (Easting: 516002; Northing: 2406958) (fig. 0.30). The rock mass length and height are approximately 30m by 5.4m. The slope is easily accessible, well drained and was excavated (using an excavator machine; no visible excavation damage) for saw milling and road construction purpose. The rock mass is in the AR?nc1 paleo-proterozoid geological formation and consists of porphyritic granite (feldspar) & crystalline ferruginous schist with medium grain size and well-developed undulose foliation. The granite has white with yellow stain colour while the schist has colours varying from reddish to light brown. The different lithologies are shown in fig. 0.30. The rock mass of slope Y28 has two cut slopes excavated at different times; denoted recent and an old cut. The recent cut slope is two years old while the old cut slope is twenty-nine years old.

(a) THE RECENT CUT SLOPE - The recent cut slope (fig. 0.30) is accessible with total mapped length of 7m; SDD and SD angle of 105^0 and 82^0 respectively. The direction of view of the slope is 285^0 and the accessible (mapped) part of this slope (up to 3m) has one geotechnical unit – G1, which is divided into two sub-geotechnical units G11 and G12. G11 is porphyritic granite, which has white with yellow stain colour. Its SPA is 0.005m; the SDD_{disc} and SD_{disc} (i.e. joint orientations) are 010^0/70^0, 030^0/70^0, 125^0/45^0, 150^0/65^0 and 190^0/60^0 (fig. 0.31); persistent >3m along strike and dip; large-scale roughness (Rl) is wavy, small-scale roughness (Rs) is rough stepped; infill material (lm) is fine clay and no karst (Ka). The WE for the unit is highly weathered. While G12 is crystalline weathered schist, which has its colour varying from reddish to light brown. Its SPA are 0.07m, 0.10m and 0.10m. It is assumed that the SDD_{disc}, SD_{disc} and CD of the unit are the same as the G11 sub-geotechnical unit. The WE for the unit is highly weathered.

(b) THE OLD CUT SLOPE - The old cut slope (fig. 0.30) is accessible with total mapped length of 7m. The slope dip direction and dip angle are the same as the recent slope. The accessible (mapped) part of this slope (up to 3m) has one geotechnical unit – G21 that is sandy-clayey soil with colours varying from light to dark brown. The slope face is covered with algae, ferns and bushes, which makes the characterization of the discontinuities impossible. Its SPA is 0.002m. It is assumed that the SDD_{disc}, SD_{disc} and CD of the unit are the same as the G1 geotechnical unit of the recent slope. The WE for the unit is residual soil.

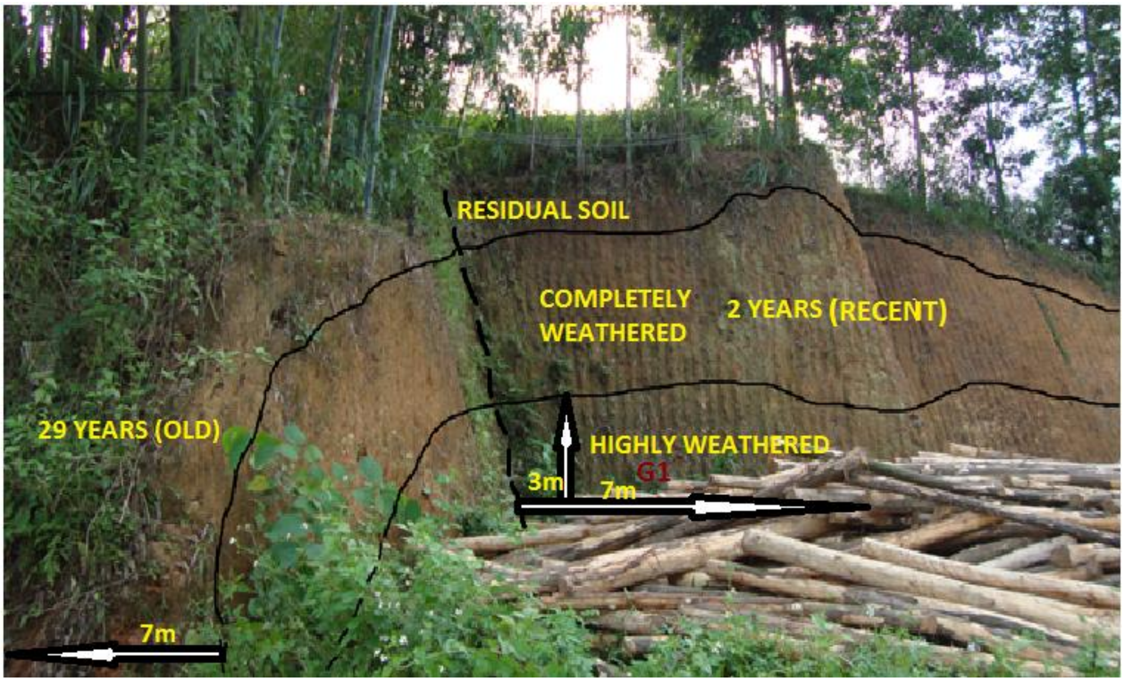


Figure 0.30: The different lithologies and degrees of weathering of Slope Y28 (Direction of view - 285^{O})

Figure 0.31: Discontinuities' orientation for the geotechnical units of Slope Y28

Cut slope Y33

The Cut slope Y33 is located at Group 21, Dong Tam commune, Yen Bai city (Easting: 516436; Northing: 2403370) (fig. 0.32). The rock mass length and height are approximately 40m by 12m. The slope is easily accessible, well drained and was excavated (using an excavator machine; no visible excavation damage) for building and road construction purpose. The rock mass is in the AR?nc1 paleo-proterozoid geological formation and consists of porphyritic granite (feldspar) & crystalline mica-schist with medium grain size and well-developed undulose foliation. The granite has white with yellow stain colour, while the mica-schist has colours varying from reddish black to brown. The different lithologies are shown in fig. 0.32. The rock mass of slope Y33 has two cut slopes excavated at different times; denoted recent and an old cut. The recent cut slope is six months old while the old cut slope is thirty-three years old.

(a) THE RECENT CUT SLOPE - The recent cut slope (fig. 0.32) is accessible with total mapped length of 5.5m; SDD and SD angle of 295^0 and 74^0 respectively. The direction of view of the slope is 115^0 and the accessible (mapped) part of this slope (up to 3m) has one geotechnical unit – G1, which is divided into two sub-geotechnical units G11 and G12. G11 is porphyritic granite, which has white with yellow stain colour. Its SPA are 0.005m; the SDD_{disc} and SD_{disc} (i.e. joint orientations) are 040^0/80^0, 165^0/65^0, 285^0/85^0 and 315^0/60^0; persistent >3m along strike and dip; large-scale roughness (Rl) is wavy, small-scale roughness (Rs) is rough stepped; infill material (lm) is clay and no karst (Ka). The WE for the unit is moderately weathered. While G12[11] is crystalline mica-schist, which has its colour varying from reddish black to brown. Its SPA are 0.04m, 0.05m, 0.07m and 0.10m. It is assumed that the SDD_{disc}, SD_{disc} and CD of the unit are the same as the G11 sub-geotechnical unit. The WE for the unit is moderately weathered.

(b) THE OLD CUT SLOPE - The old cut slope (fig. 0.32) is accessible with total mapped length of 5.5m. The slope dip direction is the same as the recent slope, while the slope dip is 35^0. The accessible (mapped) part of this slope (up to 3m) has one geotechnical unit – G21 that is clay soil with colours varying from light to dark brown. The slope face is covered with algae, ferns and bushes, which makes the characterization of the discontinuities impossible. Its SPA is 0.002m. It is assumed that the SDD_{disc}, SD_{disc} and CD of the unit are the same as the G1 geotechnical unit of the recent slope. The WE for the unit is residual soil.

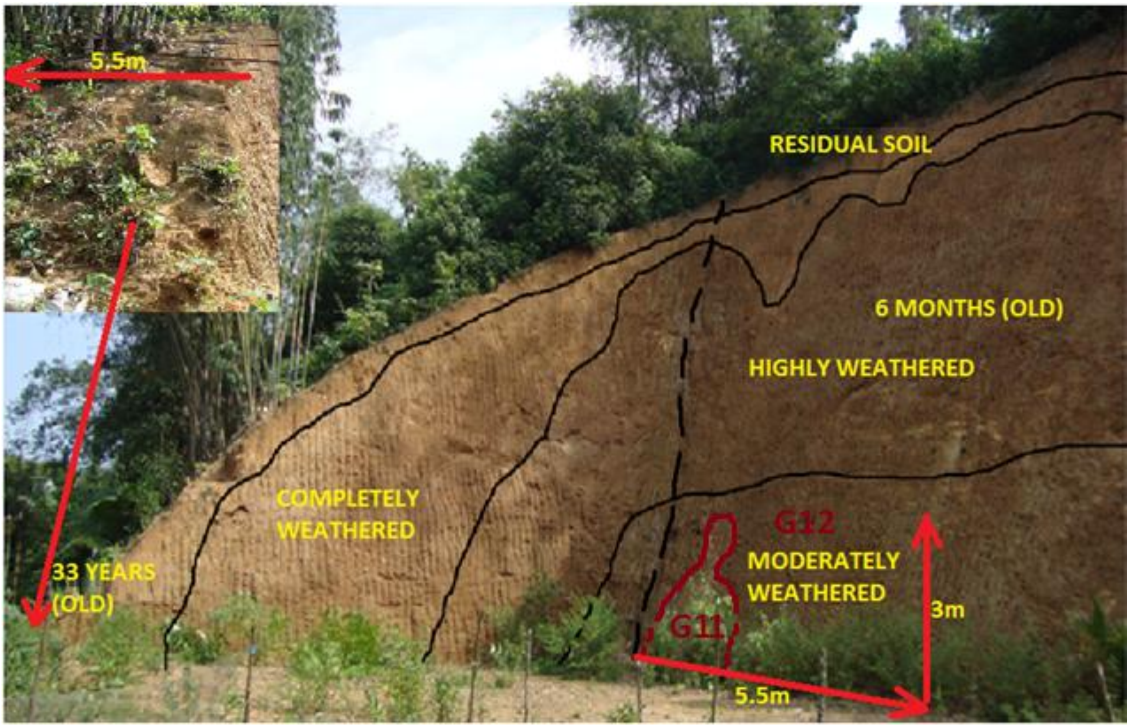


Figure 0.32: The different lithologies and degrees of weathering of Slope Y33 (Direction of view - 115^O)

The remaining other slopes that are inspected, but not selected are shown below from fig. 0.33 to fig. 0.52.

[11] The state of weathering for the geotechnical units of recent cut slope Y33G12 was erroneously assessed as slightly/moderately weathered during fieldwork. Nevertheless, corrected on 25/11/2010 as moderately weathered (after the fieldwork).

Figure 0.33: Cut slope Y3

Figure 0.34: Cut slope Y5

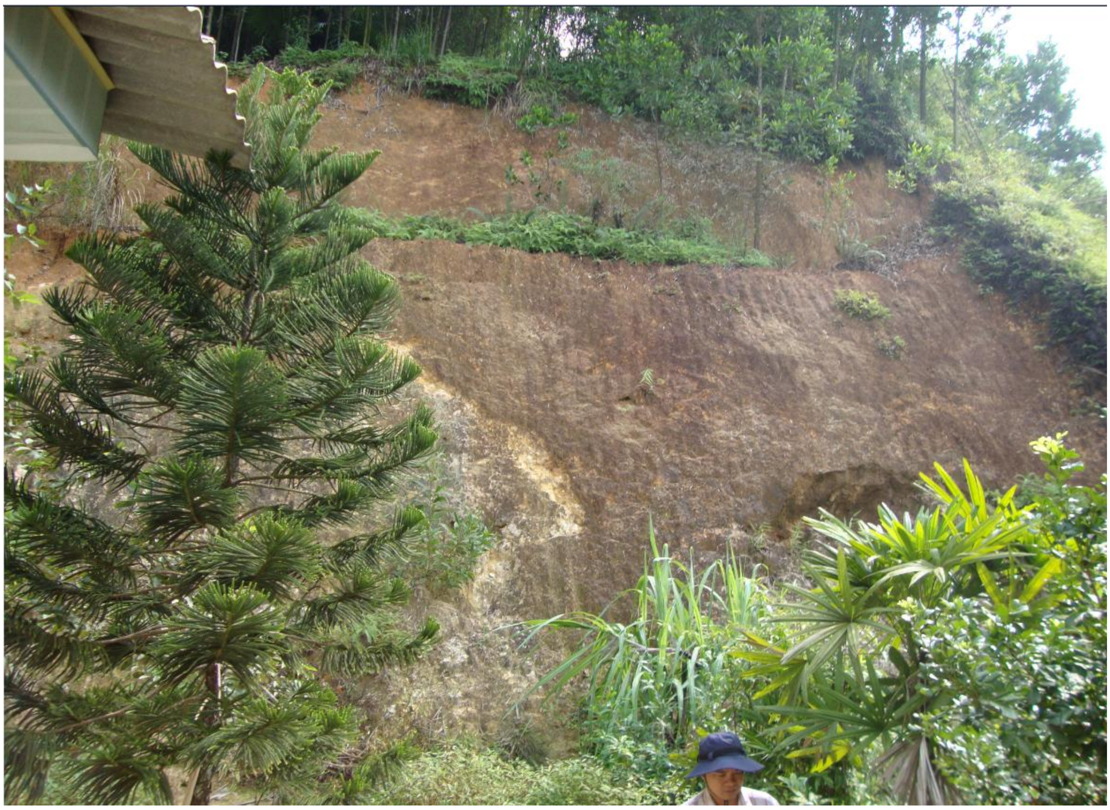


Figure 0.35: Cut slope Y7

Figure 0.36: Cut slope Y8

Figure 0.37: Cut slope Y9

Figure 0.38: Cut slope Y10

Figure 0.39: Cut slope Y15

Figure 0.40: Cut slope Y16

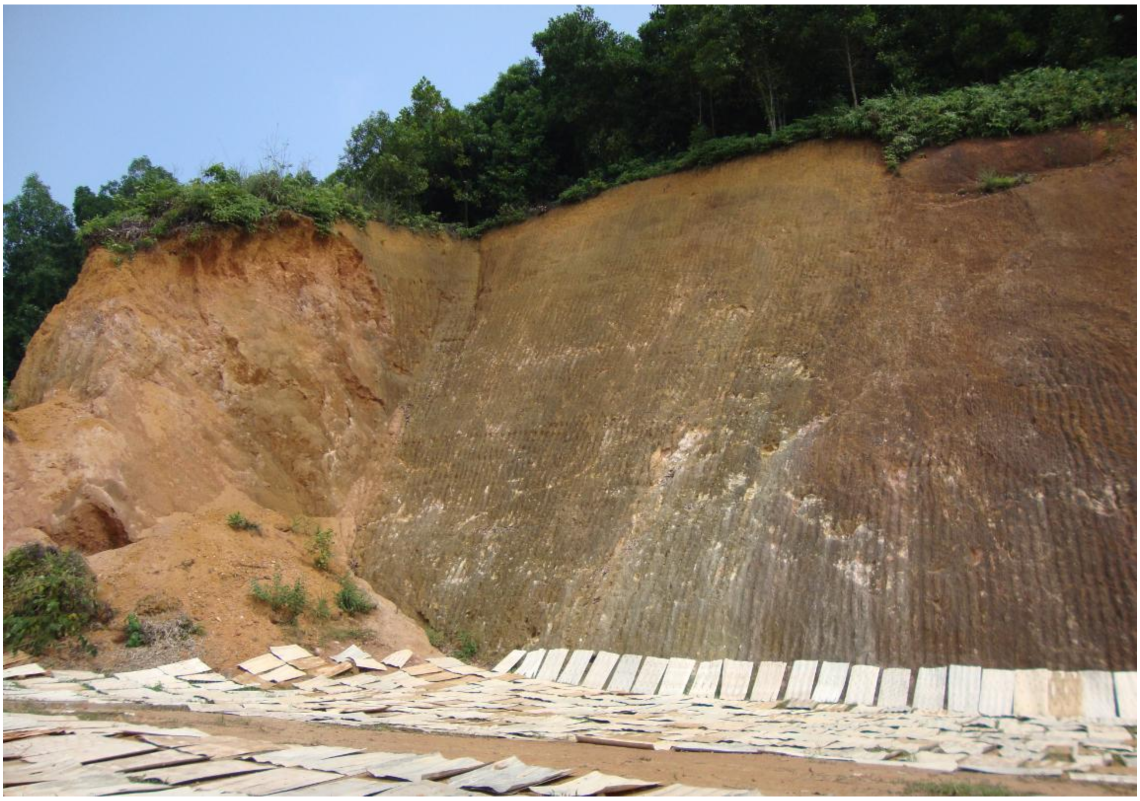


Figure 0.41: Cut slope Y17

Figure 0.42: Cut slope Y19

Figure 0.43: Cut slope Y22

Figure 0.44: Cut slope Y23

Figure 0.45: Cut slope Y25

Figure 0.46: Cut slope Y26

Figure 0.47: Cut slope Y29

Figure 0.48: Cut slope Y30

Figure 0.49: Cut slope Y31

Figure 0.50: Cut slope Y32

Figure 0.51: Cut slope Y34

Figure 0.52: Cut slope Y35

Weathering profile images – it show the location of where each image of weathering classification (i.e. degree of weathering is cropped out for profiling purpose.

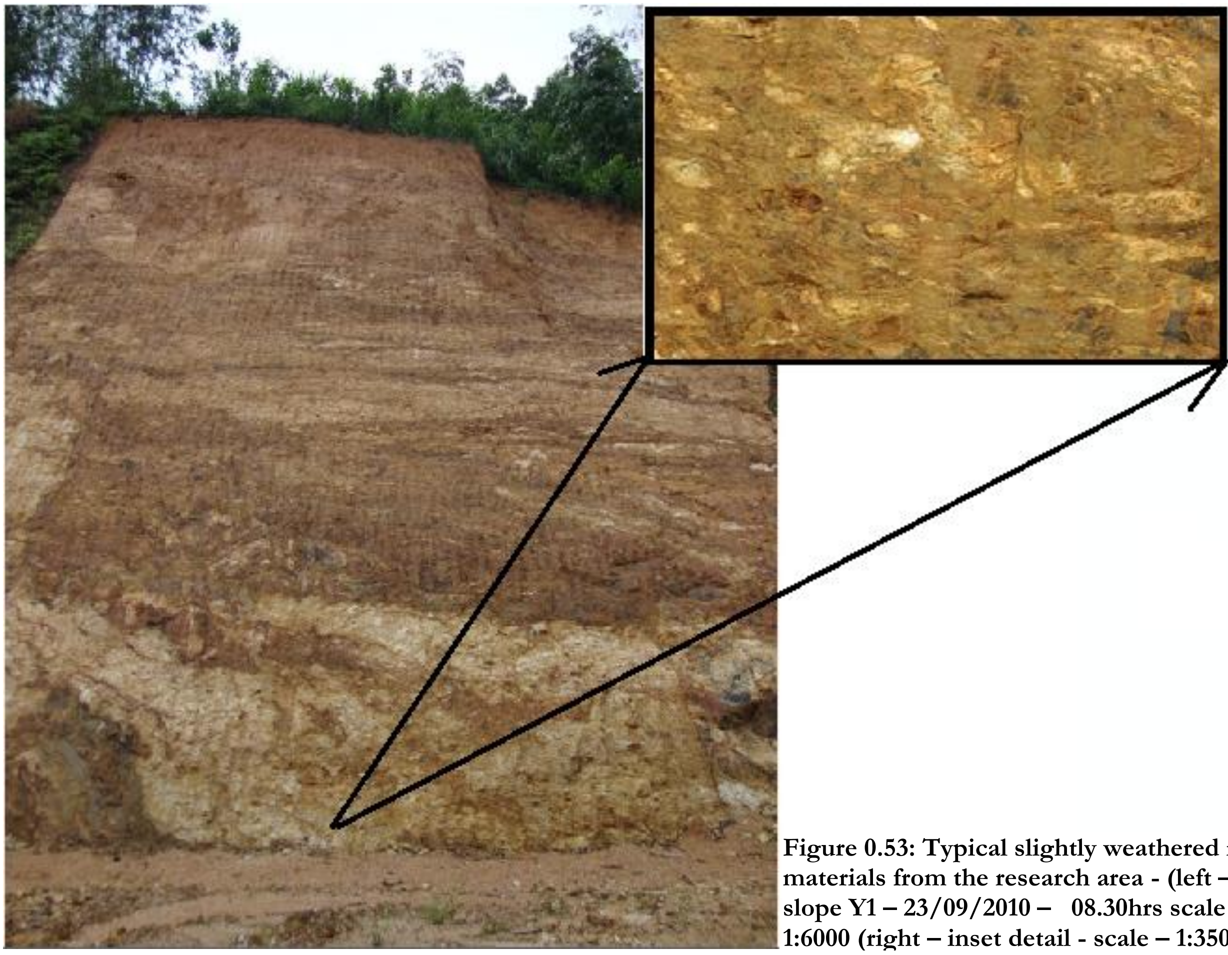


Figure 0.53: Typical slightly weathered rock materials from the research area - (left – cut slope Y1 – 23/09/2010 – 08.30hrs scale – 1:6000 (right – inset detail - scale – 1:3500)

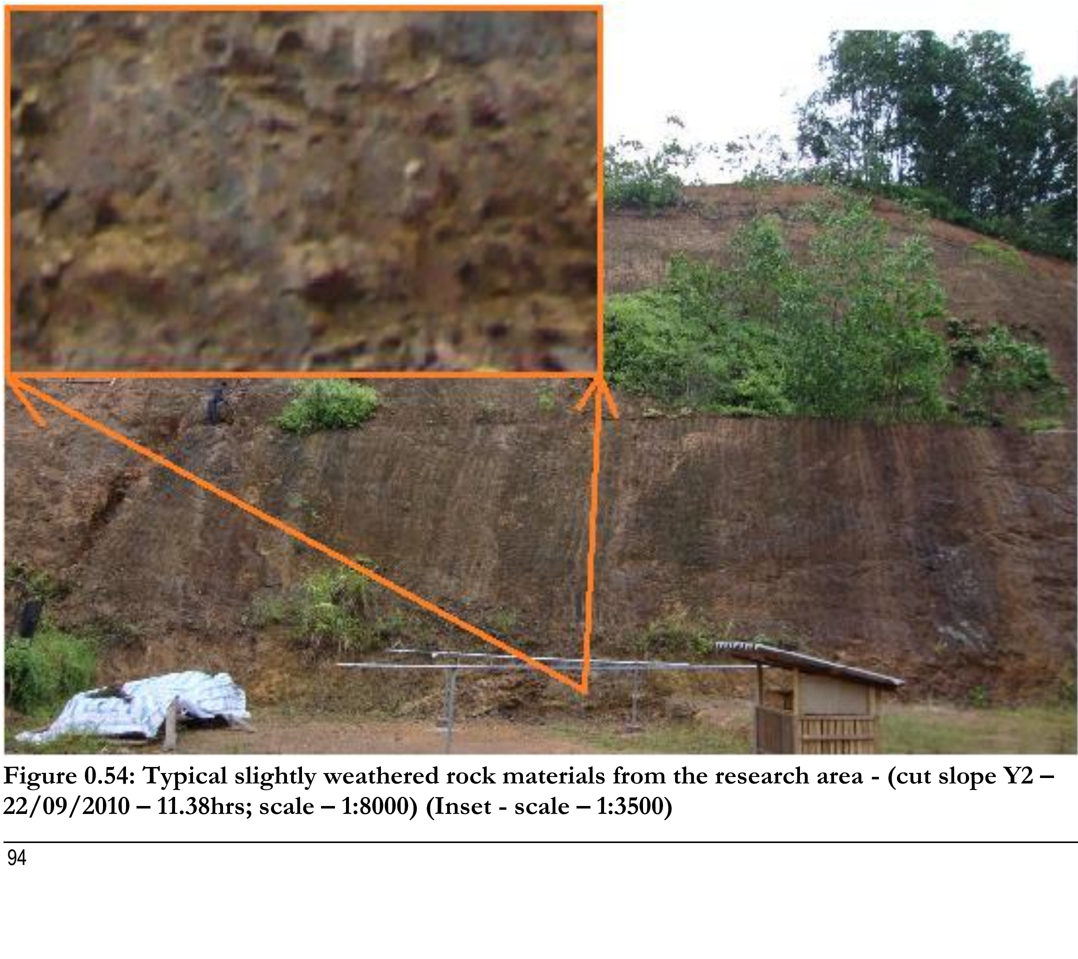


Figure 0.54: Typical slightly weathered rock materials from the research area - (cut slope Y2 – 22/09/2010 – 11.38hrs; scale – 1:8000) (Inset - scale – 1:3500)

Figure 0.55: Typical moderately weathered rock materials from the research area - cut slope Y1 – 27/09/2010 – 10.00hrs; Scale – 1:6000)

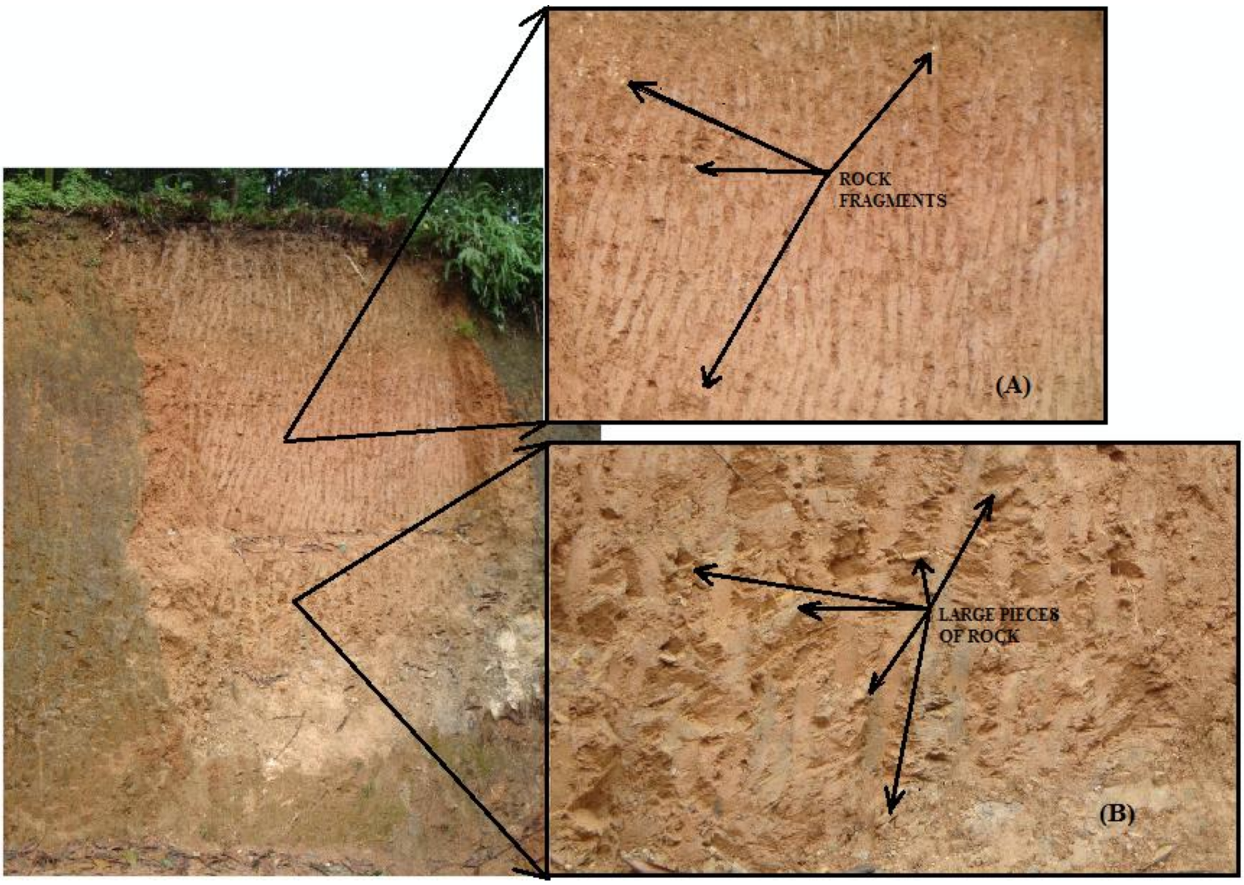


Figure 0.56: Typical (A) completely (B) highly weathered rock materials from the research area – inspected cut slope – 23/09/2010 – 15.38hrs; Scale – 1:10000)

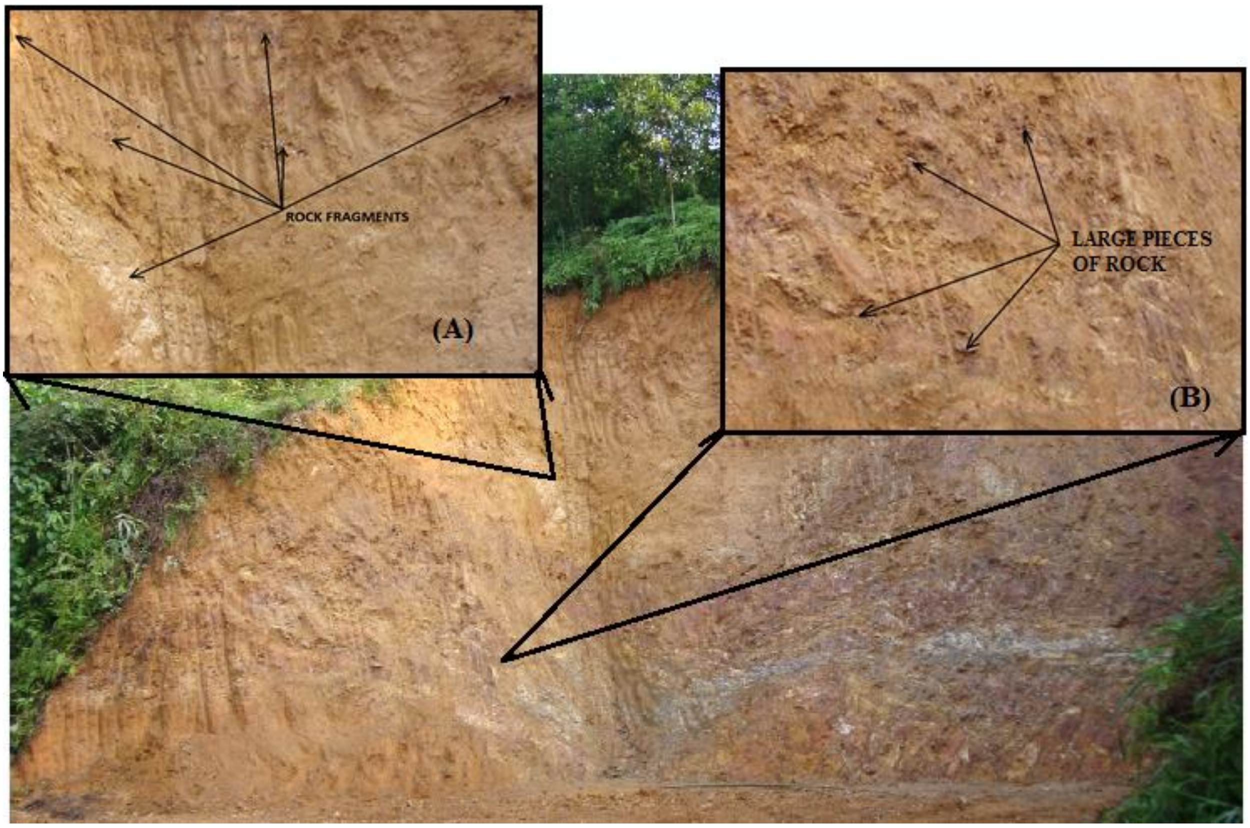


Figure 0.57: Typical (A) completely (B) highly weathered rock materials from the research area – cut slope Y14 – 02/10/2010 – 08.35hrs; Scale – 1:8000)

Appendix 2: Stereoplot for the first three selected cut slopes

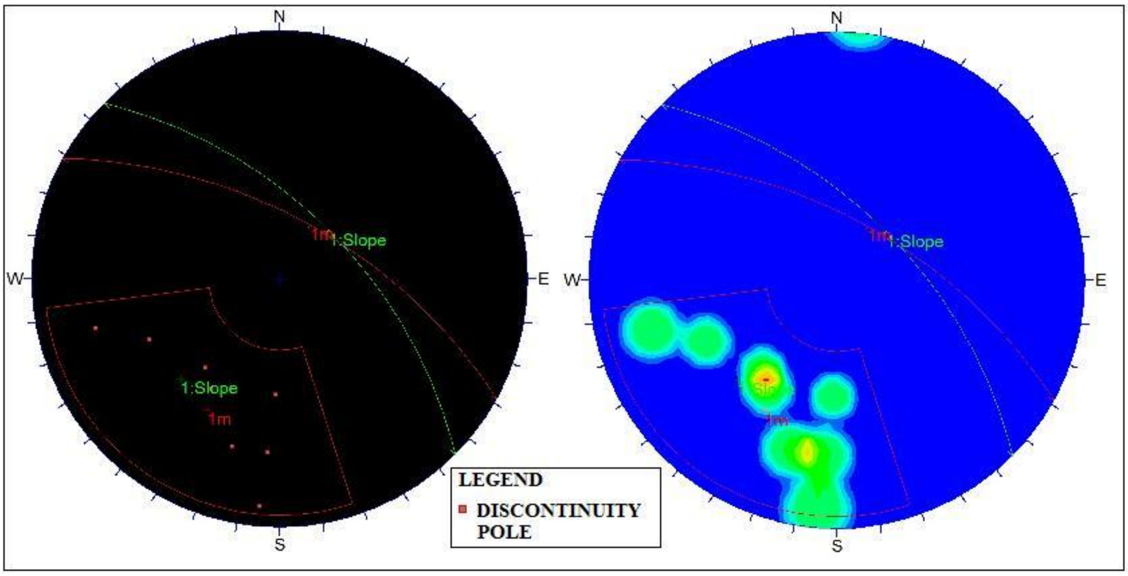


Figure 0.58: Cut slope Y1

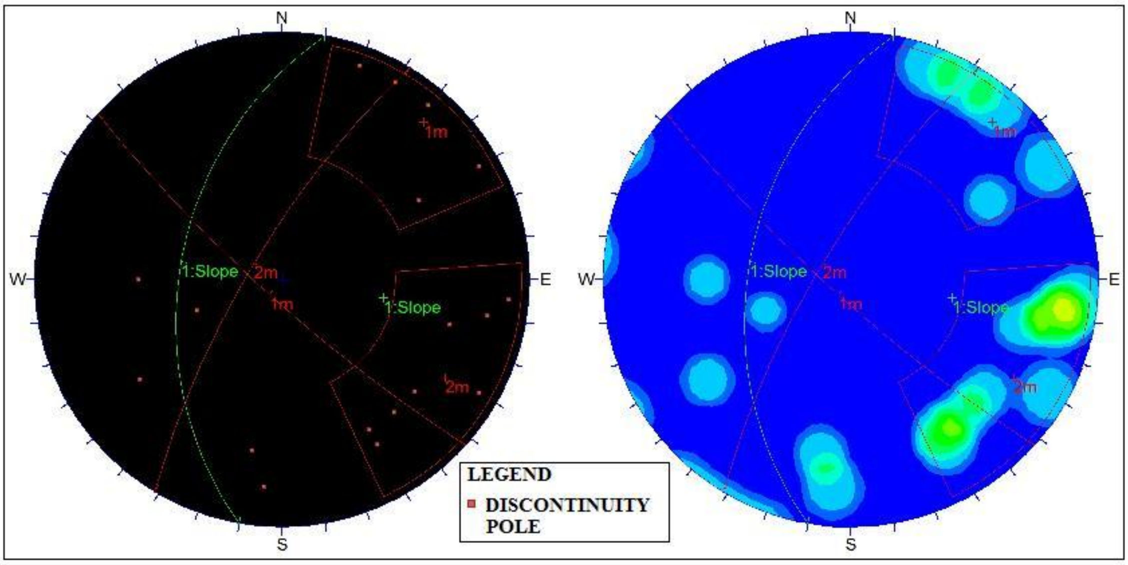


Figure 0.59: Cut slope Y2

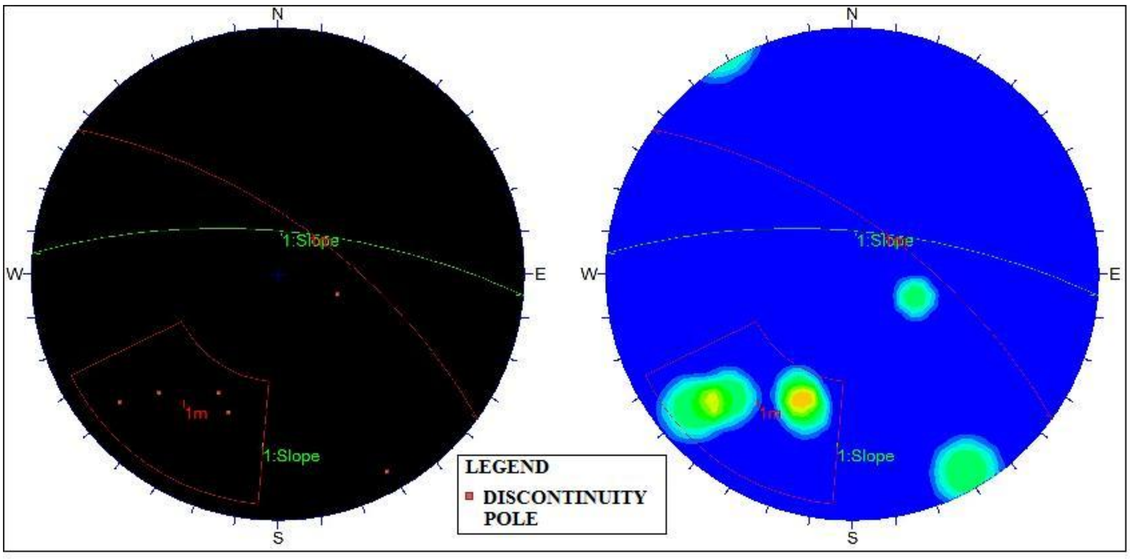


Figure 0.60: Cut slope Y4

Appendix 3: Information about results of SSPC method and weathering rates of the cut slopes

Table 0.1: Weathering data for the cut slopes

ID	E	N	IRS	SDD	SD	H	WE	SFRI	SCOH
Y1G11	514163	2402181	1.25	45	59	17	0.95	31	17
Y1G12	514163	2402181	3.13	45	59	17	0.90	30	17
Y1G21	514163	2402181	1.25	45	59	17	0.95	31	17
Y1G22	514163	2402181	3.13	45	59	17	0.90	30	17
Y1G31	514163	2402181	1.25	45	59	17	0.95	31	17
Y1G32	514163	2402181	3.13	45	59	17	0.90	30	17
Y1G41	514163	2402181	1.25	45	59	17	0.90	29	16
Y1G42	514163	2402181	3.13	45	59	17	0.90	29	16
Y1G51	514163	2402181	150.00	45	59	17	0.62	34	14
Y1G52	514163	2402181	75.00	45	59	17	0.62	22	9
Y2G11-1	516543	2402132	31.25	280	45	23	0.90	16	8
Y2G11-2	516543	2402132	75.00	280	45	23	0.90	28	13
Y2G12-1	516543	2402132	75.00	280	45	23	0.95	27	13
Y2G12-2	516543	2402132	31.25	280	45	23	0.90	17	9
Y2G13-1	516543	2402132	75.00	280	45	23	0.90	28	13
Y2G13-2	516543	2402132	150.00	280	45	23	0.95	37	15
Y2G14	516543	2402132	75.00	280	61	23	0.62	21	9
Y2G15a-1	516543	2402132	75.00	280	64	19	0.9	26	12
Y2G15a-2	516543	2402132	31.25	280	64	19	0.90	16	8
Y2G15b-1	516543	2402132	75.00	280	64	19	0.35	20	8
Y4G11	516120	2403428	75.00	325	37	17	0.62	21	9
Y4G12	516120	2403428	3.13	325	37	17	0.90	10	5
Y4G21	516120	2403428	75.00	325	37	17	0.62	21	9
Y4G22	516120	2403428	8.75	325	37	17	0.90	11	6
Y4G31	516120	2403428	75.00	325	37	17	0.62	21	9
Y4G32	516120	2403428	8.75	325	37	17	0.95	13	7
Y4G41	516120	2403428	75.00	325	37	17	0.62	22	9
Y4G42	516120	2403428	75.00	325	37	17	0.62	22	9
Y4G51	516120	2403428	31.25	325	37	17	0.35	10	5
Y4G52	516120	2403428	3.13	325	37	17	0.35	3	2
Y6G11	513893	2403913	150.00	210	66	11	0.90	31	17
Y6G12	513893	2403913	8.75	210	66	11	0.90	13	7
Y6G12(2)	513893	2403913	8.75	210	66	11	0.90	10	6
Y6G21	513893	2403913	150.00	210	66	11	0.62	35	14
Y6G22	513893	2403913	8.75	210	66	11	0.62	35	6
Y11G11	516377	2403752	75.00	150	79	16	0.62	23	10
Y11G12	516377	2403752	1.25	150	79	16	0.62	11	10
Y11G21	516377	2403752	75.00	150	79	16	0.35	21	9
Y11G32	516377	2403752	1.25	150	79	16	0	3	2
Y11G32(1)	516377	2403752	0.20	150	79	16	0	2	1
Y12G11	516537	2403860	75.00	30	76	16	0.62	23	10
Y12G12	516537	2403860	1.25	30	76	16	0.62	8	4
Y12G13	516537	2403860	8.75	30	76	16	0.62	10	6
Y12G21	516537	2403860	75.00	30	76	16	0.35	21	9
Y12G22	516537	2403860	1.25	30	76	16	0	3	2
Y12G22(1)	516537	2403860	0.17	30	76	16	0	2	1
Y13G11	516865	2404125	8.75	5	80	15	0.62	6	3
Y13G12	516865	2404125	75.00	5	80	15	0.35	21	9
Y13G13	516865	2404125	3.13	5	80	15	0.62	11	6
Y13G21	516865	2404125	1.25	5	80	15	0	3	2
Y13G21(1)	516865	2404125	0.25	5	80	15	0	2	1
Y14G11	513542	2404139	150.00	17	68	10	0.62	37	16
Y14G12	513542	2404139	3.13	17	68	10	0.62	9	5
Y14G13	513542	2404139	1.25	17	68	10	0.62	8	5
Y14G21	513542	2404139	150.00	17	68	10	0.35	35	14
Y14G22	513542	2404139	3.13	17	68	10	0.35	4	2
Y14G23	513542	2404139	1.25	17	68	10	0.35	3	2
Y18G11	514539	2401955	150.00	220	60	15	0.62	38	16
Y18G12	514539	2401955	31.25	220	60	15	0.62	13	6
Y18G13	514539	2401955	150.00	220	60	3	0.35	35	14

Table 0.2: Weathering data for the cut slopes (Cont'd)

ID	E	N	IRS	SDD	SD	H	WE	SFRI	SCOH
Y20G11	515263	2401780	150.00	200	56	22	0.90	39	16
Y20G12	515263	2401780	31.25	200	56	22	0.90	16	8
Y20G12(1)	515263	2401780	8.75	200	56	22	0.90	11	6
Y20G13	515263	2401780	1.25	200	56	22	0	3	2
Y20G13(1)	515263	2401780	0.15	200	56	22	0	2	2
Y21G11	515498	2401611	150.00	200	80	10	0.35	35	14
Y21G12	515498	2401611	8.75	200	80	10	0.35	11	6
Y21G13	515498	2401611	1.25	200	80	10	0	3	2
Y21G13(1)	515498	2401611	0.11	200	80	10	0	3	2
Y24G11	517839	2401074	8.75	250	65	15	0.90	11	6
Y24G11-1	517839	2401074	31.25	250	65	15	0.90	17	8
Y24G12	517839	2401074	8.75	250	65	15	0.62	9	5
Y24G21	517839	2401074	1.25	250	65	15	0	3	2
Y24G21-1	517839	2401074	0.39	250	65	15	0	3	2
Y27G11	516423	2405547	75.00	220	65	19	0.95	27	12
Y27G12	516423	2405547	3.13	220	65	19	0.95	16	9
Y27G13	516423	2405547	150.00	220	65	19	0.95	37	15
Y27G21	516423	2405547	75.00	220	65	19	0.62	26	11
Y27G22	516423	2405547	3.13	220	65	19	0.62	11	6
Y27G23	516423	2405547	150.00	220	65	19	0.62	35	14
Y28G11	516002	2406958	150.00	105	82	5.4	0.62	35	14
Y28G12	516002	2406958	1.25	105	82	5.4	0.62	10	5
Y28G21	516002	2406958	1.25	105	82	5.4	0	3	2
Y28G22	516002	2406958	0.37	105	82	5.4	0	3	2
Y33G11	516436	2403370	150.00	295	74	12	0.90	36	15
Y33G12	516436	2403370	75.00	295	74	12	0.90	26	11
Y33G13	516436	2403370	1.25	295	35	12	0	3	2
Y33G14	516436	2403370	0.27	295	35	12	0	3	2

Table 0.3: Weathering rates for different cut slopes

ID	VSFRI	VSCOH	log(1+t)	$R_{app(WE)}$(SFRI)	$R_{app(WE)}$(SCOH)
Y1	11	5	1.49	7.47	3.69
Y2	19	8	1.45	12.83	5.64
Y4	9	4	1.49	6.25	2.87
Y6	9	4	1.20	5.95	2.68
Y11	12	6	1.41	8.54	4.13
Y12	11	5	1.38	7.55	3.66
Y13	11	6	1.48	7.98	3.98
Y14	10	5	1.32	13.26	5.92
Y18	18	8	1.48	12.79	5.34
Y20	17	10	1.41	14.07	8.46
Y21	22	10	1.48	15.50	7.38
Y24	10	7	1.38	7.03	4.90
Y27	12	5	1.40	8.19	3.67
Y28	14	7	1.45	9.66	4.75
Y33	22	11	1.53	15.43	7.61

Table 0.4: SSPC method results for the first three cut slopes

ID	WE	IRS(MPa)	IRS(L)	IRS(H)	SPA	SPA(L)	SPA (H)	CON	CON (L)	CON (H)	SFRI (deg)	SFRI (L)	SFRI (H)	SCOH (KPa)	SCOH (L)	SCOH (H)	OIS (deg)	OIS (L)	OIS (H)	VES
Y1G11	0.95	1.25	1.25	3.13	0.493	0.512	0.456	0.903	0.903	0.903	31	32	30	17	18	17	55	60	30	LP
Y1G12	0.90	3.13	1.25	8.75	0.493	0.512	0.433	0.587	0.587	0.587	30	30	28	17	17	15	30	35	8	LP
Y1G21	0.95	1.25	1.25	3.13	0.493	0.512	0.456	0.903	0.903	0.903	31	32	30	17	18	17	55	60	30	LP
Y1G22	0.90	3.13	1.25	8.75	0.493	0.505	0.433	0.587	0.587	0.587	30	30	28	17	17	9	30	35	8	LP
Y1G31	0.95	1.25	1.25	3.13	0.493	0.512	0.456	0.903	0.903	0.903	31	32	30	17	18	17	55	60	30	LP
Y1G32	0.90	3.13	1.25	8.75	0.493	0.493	0.433	0.587	0.587	0.587	30	29	28	17	16	9	30	25	8	LP
Y1G41	0.90	1.25	1.25	3.13	0.493	0.512	0.456	0.496	0.496	0.496	29	30	27	16	17	15	20	30	8	LP
Y1G42	0.90	3.13	1.25	8.75	0.493	0.512	0.003	0.496	0.496	0.496	29	30	28	16	17	15	25	30	8	LP
Y1G51	0.62	150.00	75.00	200.00	0.003	0.241	0.003	0.418	0.418	0.418	34	33	34	14	15	14	55	50	55	LP
Y1G52	0.62	75.00	31.25	150.00	0.003	0.347	0.003	0.587	0.587	0.587	22	29	35	9	15	15	4	10	55	LP
Y2G11-1	0.90	31.25	12.50	50.00	0.098	0.110	0.093	0.523	0.523	0.523	16	12	20	8	6	9	4	<5	<5	LPS
Y2G11-2	0.90	75.00	50.00	100.00	0.096	0.106	0.093	0.855	0.855	0.855	28	23	34	13	11	15	70	5	95	LPS
Y2G12-1	0.95	75.00	50.00	100.00	0.079	0.092	0.081	0.903	0.903	0.903	27	22	34	13	11	15	70	4	95	LPS
Y2G12-2	0.90	31.25	12.50	50.00	0.101	0.103	0.086	0.808	0.808	0.808	17	13	21	9	7	10	<5	<5	<5	LPS
Y2G13-1	0.90	75.00	50.00	100.00	0.101	0.103	0.086	0.808	0.808	0.808	28	22	33	13	11	15	80	<5	95	LPS
Y2G13-2	0.95	150.00	100.00	200.00	0.003	0.012	0.003	0.808	0.808	0.808	37	29	37	15	13	15	95	93	95	LPS
Y2G14	0.62	75.00	50.00	100.00	0.003	0.012	0.003	0.496	0.496	0.496	21	16	27	9	7	11	<5	<5	<5	LP
Y2G15a-1	0.90	75.00	50.00	100.00	0.100	0.110	0.091	0.523	0.523	0.523	26	21	32	12	10	14	<5	<5	<5	LP
Y2G15a-2	0.90	31.25	12.50	100.00	0.100	0.110	0.091	0.523	0.523	0.523	16	12	20	8	6	9	<5	<5	<5	LP
Y2G15b-1	0.35	75.00	50.00	100.00	0.003	0.110	0.003	0.315	0.315	0.315	20	20	26	8	9	11	<5	<5	<5	LP
Y4G11	0.62	75.00	50.00	150.00	0.003	0.006	0.003	0.440	0.440	0.440	21	15	35	9	6	14	60	<5	95	S
Y4G12	0.90	3.13	1.25	8.75	0.114	0.114	0.105	0.523	0.523	0.523	10	9	11	5	5	6	<5	<5	<5	S
Y4G21	0.62	75.00	50.00	150.00	0.003	0.006	0.003	0.440	0.440	0.440	21	15	35	9	6	14	60	<5	95	S
Y4G22	0.90	8.75	5.00	31.25	0.111	0.006	0.105	0.523	0.523	0.523	11	5	16	6	3	8	<5	<5	5	S
Y4G31	0.62	75.00	50.00	150.00	0.003	0.006	0.003	0.496	0.496	0.496	21	15	35	9	7	14	<5	<5	<5	SP
Y4G32	0.95	8.75	5.00	31.25	0.113	0.006	0.105	0.808	0.808	0.808	13	6	18	7	4	9	<5	9	<5	SP
Y4G41	0.62	75.00	50.00	150.00	0.011	0.006	0.003	0.523	0.523	0.523	22	15	35	9	7	14	<5	<5	5	SP
Y4G42	0.62	75.00	50.00	150.00	0.114	0.006	0.105	0.808	0.808	0.808	22	15	35	9	7	14	<5	<5	5	SP
Y4G51	0.35	31.25	12.50	75.00	0.003	0.006	0.003	0.413	0.413	0.413	10	6	21	5	3	9	<5	<5	<5	LP
Y4G52	0.35	3.13	1.25	8.75	0.003	0.505	0.003	0.413	0.413	0.413	3	29	5	2	16	2	<5	5	<5	LP

Table 0.5: Reference friction (RFRI) and cohesion (RCOH) for the cut slopes in each geological formation

FORMATION	ID	RFRI	RCOH	AVG (FRI)	AVG (RCOH)
AR?nc2	Y1	38	19	41	19
	Y6	31	14		
	Y14	38	17		
	Y18	67	28		
	Y20	23	11		
	Y21	47	22		
AR?nc1	Y2	34	15	27	13
	Y4	22	10		
	Y11	30	14		
	Y12	26	13		
	Y13	24	12		
	Y24	15	9		
	Y27	35	16		
	Y28	29	14		
	Y33	29	14		

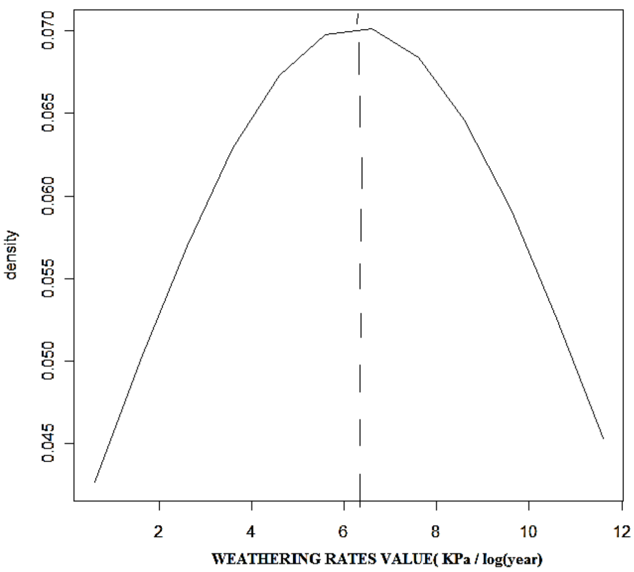


Figure 0.61: A typical normal distribution probability graph for the study area

Table 0.6: Weathering rates calculated using observed WE

FORMATION	CUT SLOPES		VWE	EXP.TIME (t)	Rapp(WE)
AR?nc1	Y2, Y4, Y11, Y12, Y13, Y24, Y27,	Maximum	0.70	33	0.46
		Actual	0.40		0.26
		Minimum	0.27		0.18
AR?nc2	Y1, Y6, Y14, Y18, Y20, Y21	Maximum	0.75		0.53
		Actual	0.49		0.34
		Minimum	0.27		0.18

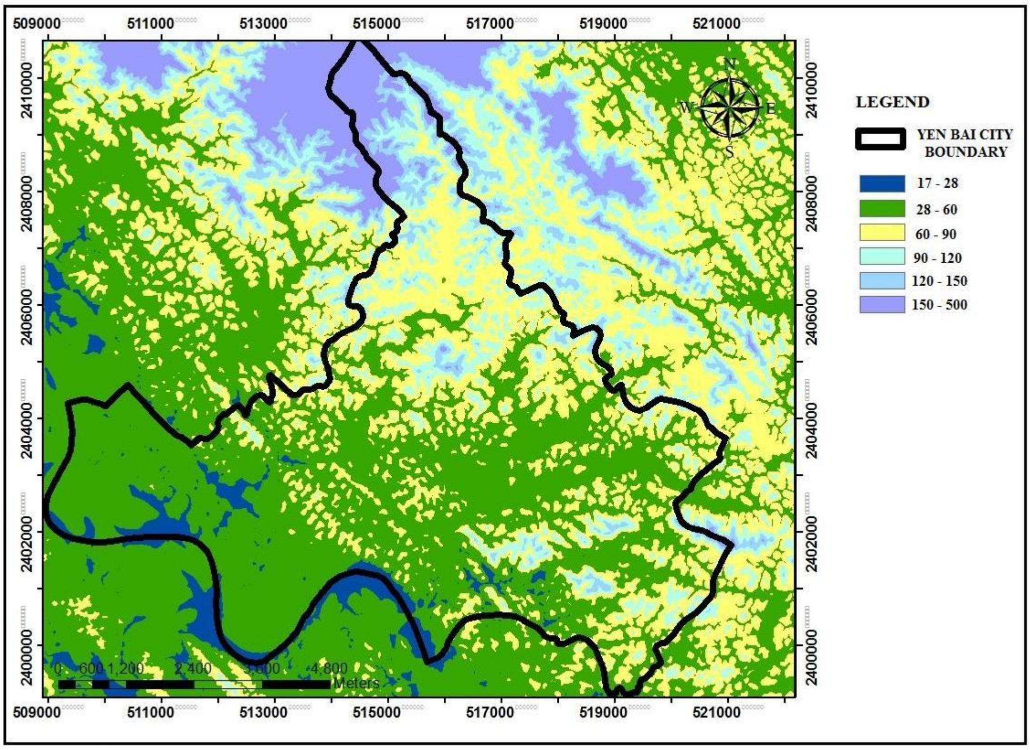


Figure 0.62: DEM map of the study area

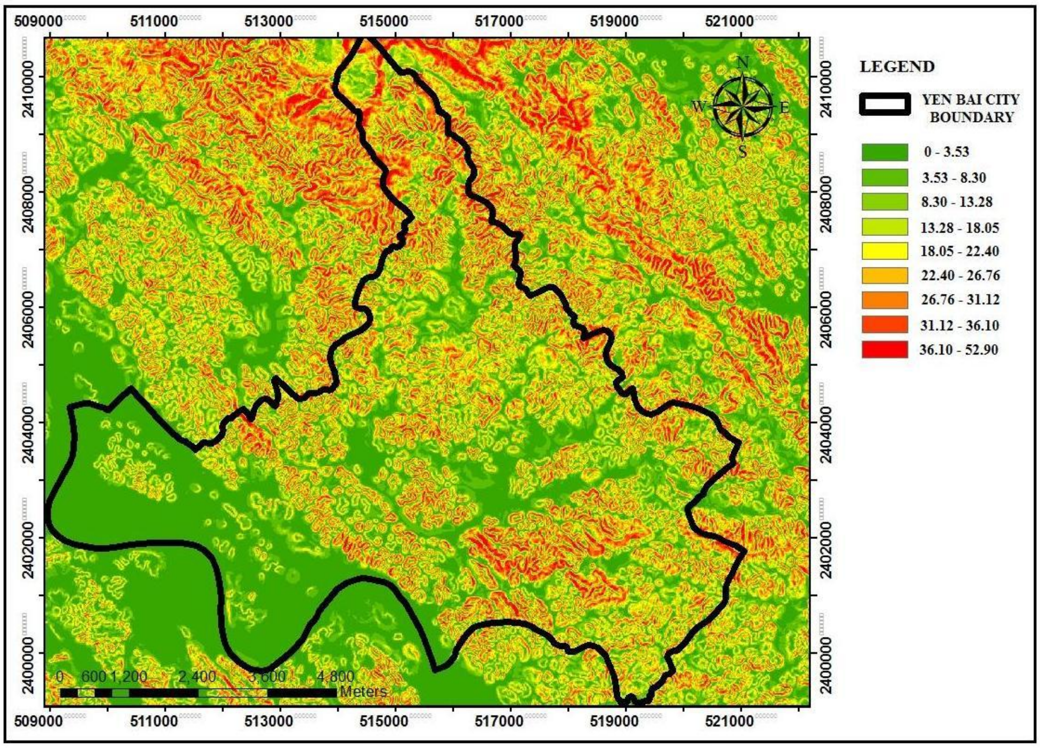


Figure 0.63: Slope map for the study area

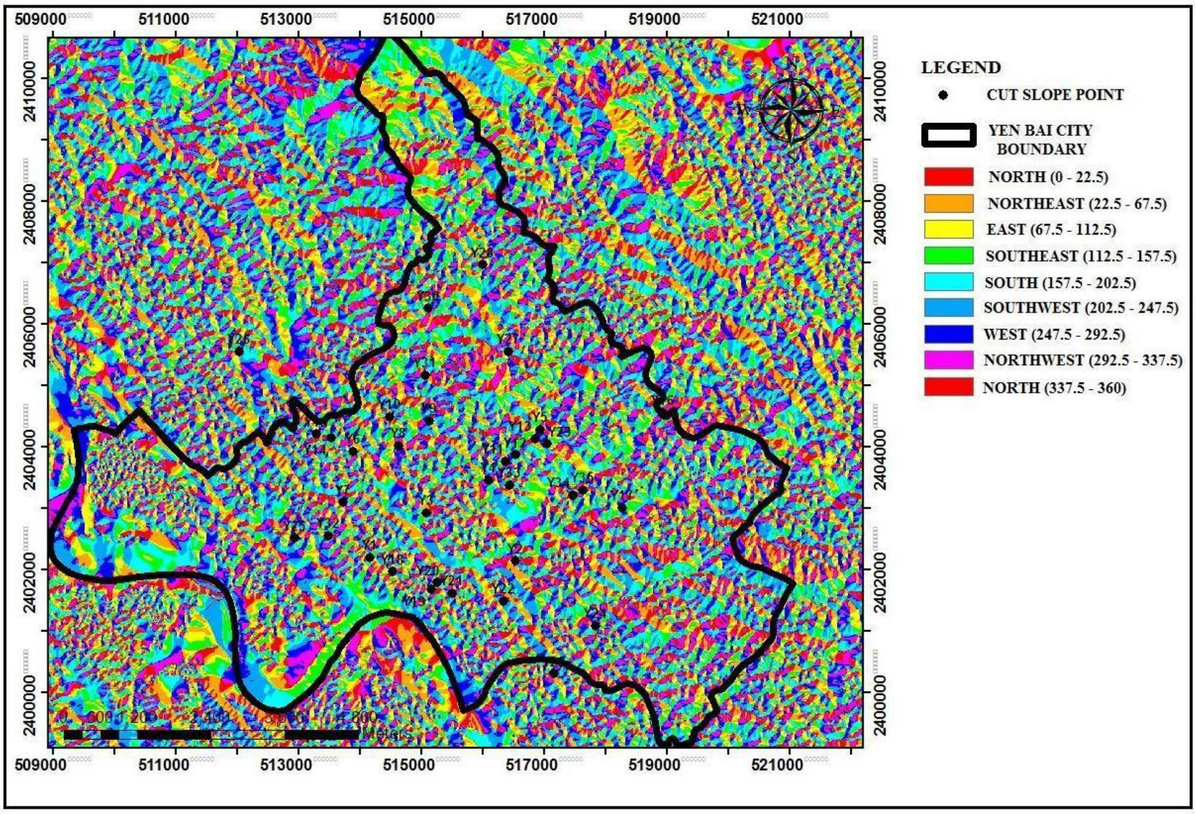


Figure 0.64: Slope aspect for the study area

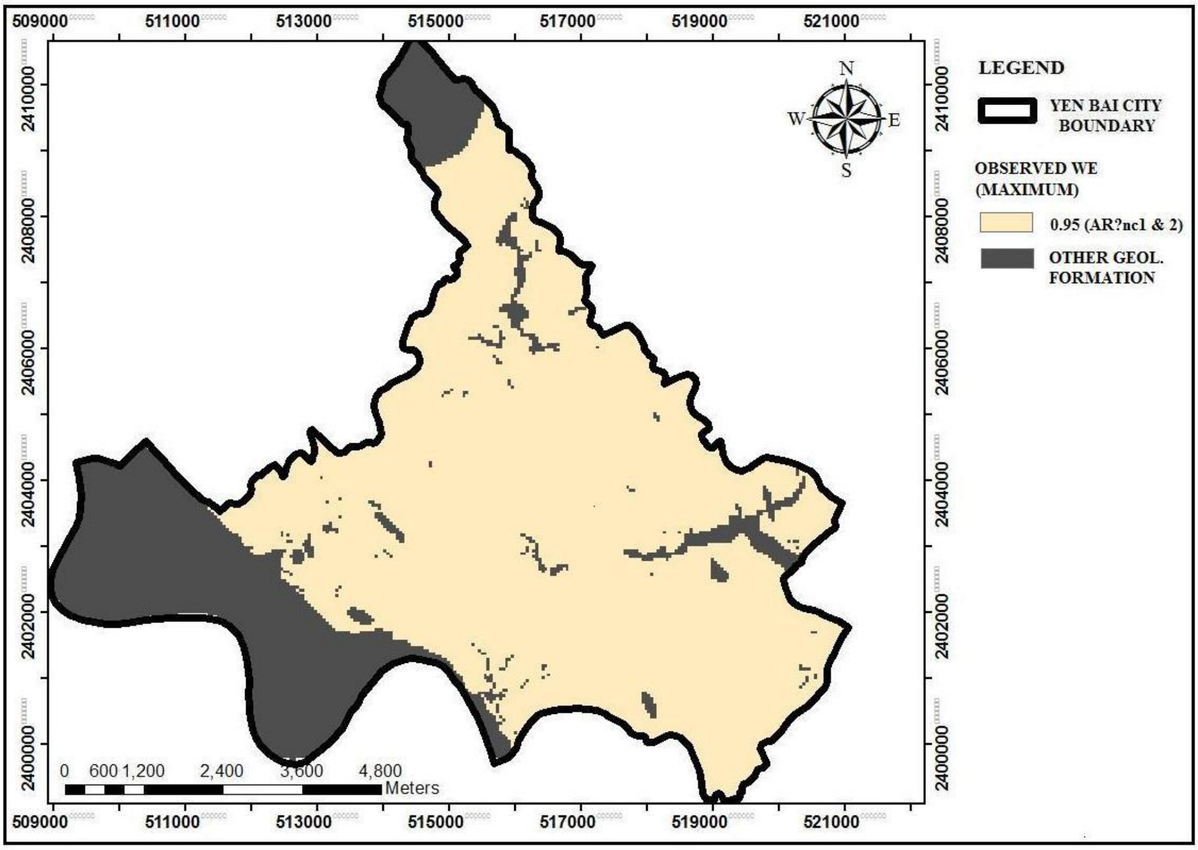


Figure 0.65: Observed WE map (maximum value)

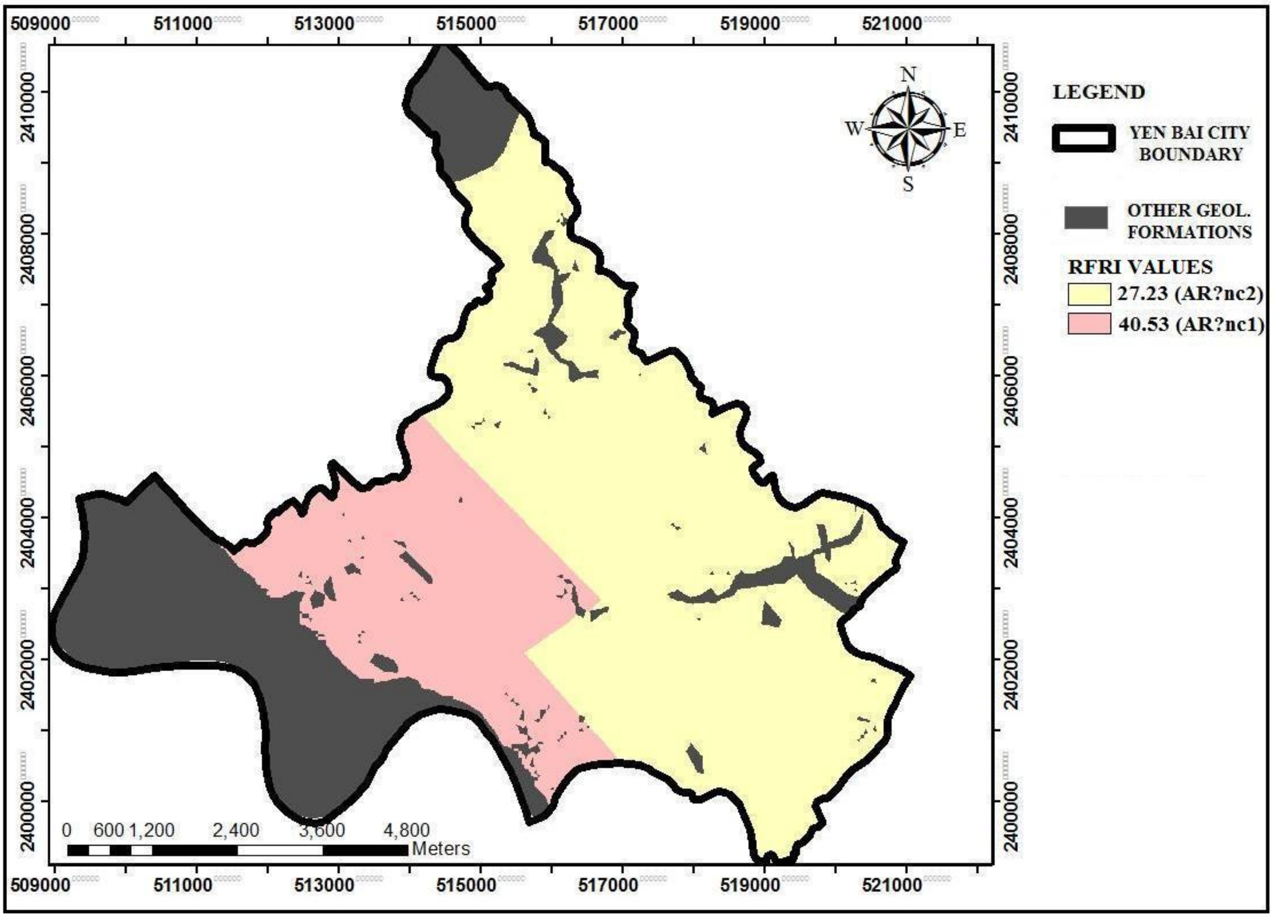


Figure 0.66: RFRI map for the area

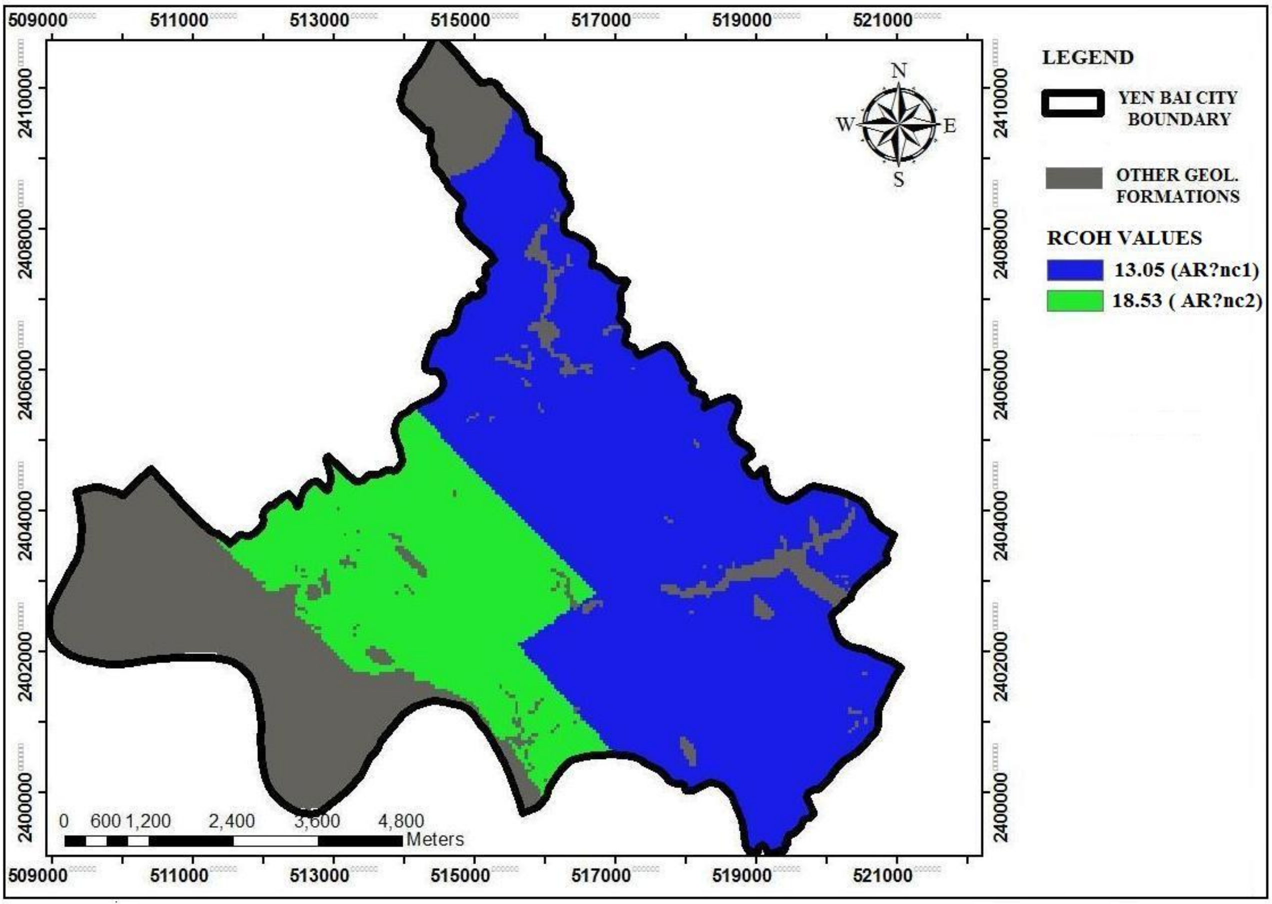


Figure 0.67: RCOH map for the study area

Appendix 4: SSPC method filled forms(as examples) for the cut slopes and normal distribution table

ITC GEO-ENGINEERING — exposure characterization — SSPC - SYSTEM

LOGGED BY: YEMI	DATE: 27/09/2010	TIME: 14:30 hr	exposure no: Y1G1

WEATHER CONDITIONS		LOCATION	
Sun:	(cloudy)/fair/bright	map no:	
Rain:	(dry)/drizzle/slight/heavy	Map coordinates: northing:	2402181N
		easting:	0514163E

METHOD OF EXCAVATION (ME)	
(tick) natural/hand-made (Excavator) ✓	1.00
pneumatic hammer excavation	0.76
pre-splitting/smooth wall blasting	0.99
conventional blasting with result: good	0.77
open discontinuities	0.75
dislodged blocks	0.72
fractured intact rock	0.67
crushed intact rock	0.62

DIMENSIONS/ ACCESSIBILITY				
Size total exposure:	(m)	l: 25	h: 17	d: 15??
mapped on this form	(m)	l: 7	h: 3	d: 0.3
Accessibility:			poor/ fair/ (good)	

FORMATION NAME: Metamorphic rock.

DESCRIPTION (BS 5930: 1981)

colour	grain size	structure & texture	weathering	NAME
Reddish black to light brown	0.2–6.0mm	(0.26–0.6m) Medium	S/M W	Schist (Amphibolitic Schist)

INTACT ROCK STRENGTH (IRS) (tick)	
< 1.25 MPa	Crumbles in hand
1.25 - 5 MPa	Thin slabs break easily in hand ✓
5 - 12.5 MPa	Thin slabs broken by heavy hand pressure
12.5 - 50 MPa	Lumps broken by light hammer blows
50 - 100 MPa	Lumps broken by heavy hammer blows
100 - 200 MPa	Lumps only chip by heavy hammer blows (Dull ringing sound)
> 200 MPa	Rocks ring on hammer blows. Sparks fly

sample number(s): Y1G12-1

WEATHERING (WE) (tick)	
unweathered	1.00
slightly ✓	0.95
moderately ✓	0.90
highly	0.62
completely	0.35

DISCONTINUITIES B=bedding C=Cleavage J=joint		1	2	3	4	5
Dip direction	(degrees)	005	0	0		
Dip	(degrees)	85	0	0		
Spacing (DS)	(m)	0.85	0.85	0.85		
Persistence along strike	(m)	>3	>15	>15		
Persistence along dip	(m)	>3	>3	>3		

EXISTING SLOPE? dip-direction/dip: 045°/59°; height: 17 m

Stability (tick): stable 1; small problems 2; large problems ✓ 3 (Slide on LHS)

CONDITION OF DISCONTINUITIES

			1	2	3
Roughness large scale (Rl) (on an area between 0.2 x 0.2 and 1 x 1 m2)	wavy: 1.00; slightly wavy: 0.95; curved: 0.85; slightly curved 0.80; straight 0.75		0.95	0.95	0.95
Roughness small scale (Rs) (on an area of 0.2 x 0.2 m2)	rough stepped 0.95; smooth stepped 0.90; polished stepped 0.85; rough undulating 0.80; smooth undulating 0.75; polished undulating 0.70; rough planar 0.65; smooth planar 0.60; polished planar 0.55		0.95	0.95	0.95
Infill material (Im)	cemented/cemented infill 1.07; no infill - surface staining 1.00; non softening & sheared material, e.g. free of clay, talc, etc.: coarse 0.95, medium 0.90, fine 0.85; soft sheared material, e.g. clay, talc, etc.: coarse 0.75, medium 0.65, fine 0.55; gouge < irregularities 0.42; gouge > irregularities 0.17; flowing material 0.05		0.65	0.65	0.65
Karst (Ka)	none 1.00; karst 0.92		1.00	1.00	1.00

notes:
1) For infill 'gouge > irregularities' and 'flowing material' small scale roughness = 0.55.
2) If roughness is anisotropic (e.g. ripple marks, striation, etc.) roughness should be assessed perpendicular and parallel to the roughness and directions noted on this form.
3) Non-fitting of discontinuities should be marked in roughness columns.

SUSCEPTIBILITY TO WEATHERING (SW)

degree of weathering:	date excavation:	remarks:	remarks:
S/M Weathered	2 months		Putting into Consideration low IRS for large block size.

Figure 0.68: SSPC form with ERM acquired field data

ITC GEO-ENGINEERING | reference rock mass calculation | SSPC - SYSTEM

CALCULATED BY: YEN | DATE: 27/09/2010 | exposure no: YG1

REFERENCE UNIT NAME: YG12-2

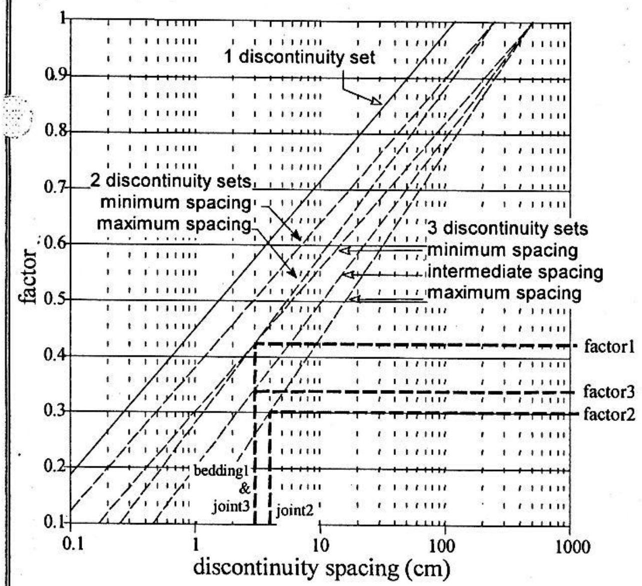
INTACT ROCK STRENGTH (RIRS)

RIRS = IRS (in MPa) / WE (correction for weathering) = 100 / 0.925 = 108.11

DISCONTINUITY SPACING (RSPA)

DISCONTINUITIES		1	2	3	4	5
Dip direction	(degrees)	005	0	0		
Dip	(degrees)	85	0	0		
Spacing (DS)	(m)	0.005	0.005	0.005		

The spacing parameter (SPA) is calculated based on the three discontinuity sets with the smallest spacings following figure:



SPA (see figure below) = factor1 * factor2 * factor3 = 0.2 * 0.11 * 0.10 = 0.002

corrected for weathering and method of excavation:

RSPA = SPA / (WE * ME) (with a maximum of 1.00)

RSPA = 0.002 / (0.925 * 1.00) = 0.002

CONDITION OF DISCONTINUITIES (RTC & RCD)

DISCONTINUITIES		1	2	3	4	5
Roughness large scale	(Rl)	0.95	0.95	0.95		
Roughness small scale	(Rs)	0.95	0.95	0.95		
Infill material	(Im)	0.65	0.65	0.65		
Karst	(Ka)	1.00	1.00	1.00		
Total	(Rl*Rs*Im*Ka = TC)	0.587	0.587	0.587		
RTC		0.596	0.596	0.596		

RTC is the discontinuity condition of a single discontinuity (set) in the reference rock mass corrected for discontinuity weathering.
RTC = TC / sqrt(1.452 - 1.220 * e^(-WE))

Weighted by spacing:

$$CD = \frac{\frac{TC_1}{DS_1}+\frac{TC_2}{DS_2}+\frac{TC_3}{DS_3}}{\frac{1}{DS_1}+\frac{1}{DS_2}+\frac{1}{DS_3}} = \frac{\frac{0.587}{0.005}+\frac{0.587}{0.005}+\frac{0.587}{0.005}}{\frac{1}{0.005}+\frac{1}{0.005}+\frac{1}{0.005}} = 0.587$$

corrected for weathering: RCD (with a maximum of 1.0165) = CD / WE = 0.587/0.925 = 0.634

REFERENCE UNIT FRICTION AND COHESION (RFRI & RCOH)

φ_{RRM} = RIRS * 0.2417 + RSPA * 52.12 + RCD * 5.779 (if RIRS > 132 MPa then RIRS = 132)

φ_{RRM} = 108.11 * 0.2417 + 0.002 * 52.12 + 0.634 * 5.779 = 29.92

coh_{RRM} = RIRS * 94.27 + RSPA * 28629 + RCD * 3593 (if RIRS > 132 MPa then RIRS = 132)

coh_{RRM} = 108.11 * 94.27 + 0.002 * 28629 + 0.634 * 3593 = 12537.94 Pa

notes: 1) For IRS (intact rock strength) take average of lower and higher boundary of class.
2) Roughness values should be reduced or shear strength has to be tested if discontinuity roughness is non-fitting.
3) WE = 1.00 for 'soil type' units, e.g. cemented soils, etc..
4) If more than three discontinuity sets are present in the rock mass then the reference rock mass friction and cohesion should be calculated based on the combination of those three discontinuities that result in the lowest values for rock mass friction and cohesion.

Figure 0.69: SSPC form with RRM calculations

ITC	ITC GEO-ENGINEERING	slope stability probability	SSPC - SYSTEM
	CALCULATED BY: YEMU	DATE: 27/09/2010	slope no: YIG1

YIG12-2	LOCATION	map no:	
	Map coordinates:	northing:	2402181N
		easting:	0514163E

DETAILS OF SLOPE

METHOD OF EXCAVATION (SME)		WEATHERING (SWE)			
(tick)		(tick)			
natural/hand-made (Excavator) ✓	1.00	unweathered	1.00	Slope dip direction (degrees):	045°
pneumatic hammer excavation	0.76	slightly ✓	0.95		
pre-splitting/smooth wall blasting	0.99	moderately	0.90	Slope dip (degrees):	59°
conventional blasting with result:		highly	0.62		
good	0.77	completely	0.35	Height (Hslope) (m)	17
open discontinuities	0.75				
dislodged blocks	0.72			:	
fractured intact rock	0.67				
crushed intact rock	0.62	note: SWE = 1.00 for 'soil type' units, e.g. cemented soil, etc.			

SLOPE UNIT NAME:

ORIENTATION INDEPENDENT STABILITY

INTACT ROCK STRENGTH (SIRS)

SIRS = RIRS (from reference rock mass) * SWE (weathering slope) = 108.11 * 0.925 = 100.00

DISCONTINUITY SPACING (SSPA)

SSPA = RSPA (from reference rock mass) * SWE (weathering slope) * SME (method of excavation slope)

SSPA = 0.002 * 0.925 * 1.00 = 0.002

CONDITION OF DISCONTINUITIES (SCD)

SCD = RCD (from reference rock mass) * SWE (weathering slope)

SCD = 0.634 * 0.925 = 0.587

SLOPE UNIT FRICTION AND COHESION (SFRI & SCOH)

φ_{SRM} = SIRS * 0.2417 + SSPA * 52.12 + SCD * 5.779 (if SIRS > 132 MPa then SIRS = 132)

φ_{SRM} = 100 * 0.2417 + 0.002 * 52.12 + 0.587 * 5.779 = 27.67 °

coh_{SRM} = SIRS * 94.27 + SSPA * 28629 + SCD * 3593 (if SIRS > 132 MPa then SIRS = 132)

coh_{SRM} = 100 * 94.27 + 0.002 * 28629 + 0.587 * 3593 = 11597.59 Pa

If SFRI < slope dip: MAXIMUM SLOPE HEIGHT (Hmax)

Maximum possible height: Hmax = 1.6 * 10^{-4} * coh_{SRM} * sin(slope dip) * cos (φ_{SRM}) / (1-cos(slope dip - φ_{SRM}))

Hmax = 1.6 * 10^{-4} * 11597.59 sin(59 °) * cos(27.67 °) / (1-cos(59 − 27.67 °)) = 9.6631 m

ratios:

φ_{SRM} / slope dip = 27.67 ° / 59 ° = 0.469

Hmax / Hslope = 9.6631 m / 17 m = 0.568

Probability stable: if SFRI > slope dip probability = 100 % else use figure for orientation independent stability: %

ORIENTATION DEPENDENT STABILITY

DISCONTINUITIES		1	2	3	4	5
Dip direction	(degrees)	005				
Dip	(degrees)	85				
With, Against, Vertical or Equal		WITH				
AP	(degrees)	83				
RTC (from reference form)		0.596				
STC = RTC * sqrt(1.452 - 1.220 * e^(-SWE))		0.59				
Probability stable:		100 %	%	%	%	%

Determination orientation stability:
calculation AP: ß = discontinuity dip, σ = slope dip-direction, τ = discontinuity dip-direction: δ = σ - τ: AP = arctan (cos δ * tan ß)

	stability:	sliding	toppling		stability:	sliding	toppling
AP > 84° or AP < -84°	vertical	100 %	100 %	AP < 0° and (-90° - AP + slope dip) < 0°	against	100 %	100 %
(slope dip+5°) < AP < 84°	with	100 %	100 % ✓	AP < 0° and (-90° - AP + slope dip) > 0°	against	100 %	use graph toppling
(slope dip-5°) < AP < (slope dip+5°)	equal	100 %	100 %				
0° < AP < (slope dip-5°)	with	use graph sliding	100 %				

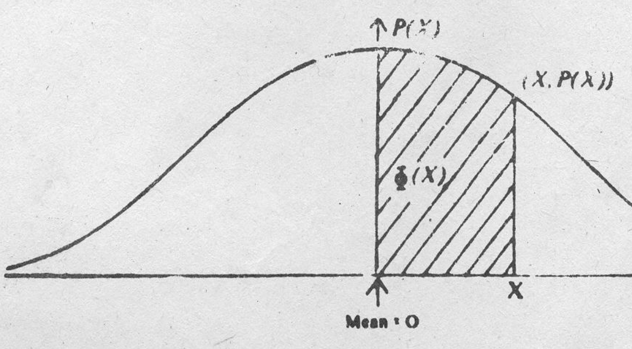
Figure 0.70: SSPC form with SRM calculations

Table 0.7: Z-score table showing probability values for Pr (Z) of weathering rates

TABLE 7: NORMAL DISTRIBUTION PROBABILITIES $X \rightarrow \Phi(X) = \int_0^X P(X)\,dX$

X	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
0.0	.0000	.0040	.0080	.0120	.0160	.0199	.0239	.0279	.0319	.0359	4	8	12	16	20	24	28	32	36
0.1	.0398	.0438	.0478	.0517	.0557	.0596	.0636	.0675	.0714	.0754	4	8	12	16	20	24	28	32	36
0.2	.0793	.0832	.0871	.0910	.0948	.0987	.1026	.1064	.1103	.1141	4	8	12	15	19	23	27	31	35
0.3	.1179	.1217	.1255	.1293	.1331	.1368	.1406	.1443	.1480	.1517	4	8	11	15	19	23	26	30	34
0.4	.1554	.1591	.1628	.1664	.1700	.1736	.1772	.1808	.1844	.1879	4	7	11	14	18	22	25	29	33
0.5	.1915	.1950	.1985	.2019	.2054	.2088	.2123	.2157	.2190	.2224	3	7	10	14	17	21	24	27	31
0.6	.2258	.2291	.2324	.2357	.2389	.2422	.2454	.2486	.2518	.2549	3	6	10	13	16	19	23	26	29
0.7	.2580	.2612	.2642	.2673	.2704	.2734	.2764	.2794	.2823	.2852	3	6	9	12	15	18	21	24	27
0.8	.2881	.2910	.2939	.2967	.2996	.3023	.3051	.3078	.3106	.3133	3	6	8	11	14	17	19	22	25
0.9	.3159	.3186	.3212	.3238	.3264	.3289	.3315	.3340	.3365	.3389	3	5	8	10	13	15	18	20	23
1.0	.3413	.3438	.3461	.3485	.3508	3531	.3554	.3577	.3599	.3621	2	5	7	9	12	14	16	18	21
1.1	.3643	.3665	.3686	.3708	.3729	.3749	.3770	.3790	.3810	.3830	2	4	6	8	10	12	14	16	19
1.2	.3849	.3869	.3888	.3907	.3925	.3944	.3962	.3980	.3997	.4015	2	4	5	7	9	11	13	15	16
1.3	.4032	.4049	.4066	.4082	.4099	.4115	.4131	.4147	.4162	.4177	2	3	5	6	8	10	11	13	14
1.4	.4192	.4207	.4222	.4236	4251	.4265	.4279	.4292	.4306	.4319	1	3	4	6	7	8	10	11	13
1.5	.4332	.4345	.4357	.4370	.4382	.4394	.4406	.4418	.4429	.4441	1	2	4	5	6	7	8	10	11
1.6	.4452	.4463	.4474	.4484	.4495	.4505	.4515	.4525	.4535	.4545	1	2	3	4	5	6	7	8	9
1.7	.4554	.4564	.4573	.4582	.4591	.4599	.4608	.4616	.4625	.4633	1	2	3	3	4	5	6	7	8
1.8	.4641	.4649	.4656	.4664	.4671	.4678	.4686	.4693	.4699	.4706	1	2	2	3	4	5	5	6	7
1.9	.4713	.4719	.4726	.4732	.4738	.4744	.4750	.4756	.4761	.4767	1	1	2	2	3	4	4	5	5
2.0	.4772	.4778	.4783	.4788	.4793	.4798	.4803	.4808	.4812	.4817	0	1	1	2	2	3	3	4	4
2.1	.4821	.4826	.4830	.4834	.4838	.4842	.4846	.4850	.4854	.4857	0	1	1	2	2	2	3	3	4
2.2	.4861	.4864	.4868	.4871	.4875	.4878	.4881	.4884	.4887	.4890	0	1	1	1	2	2	2	3	3
2.3	.4893	.4896	.4898	.4901	.4904	.4906	.4909	.4911	.4913	.4916	0	0	1	1	1	2	2	2	2
2.4	.4918	.4920	.4922	.4925	.4927	.4929	.4931	.4932	.4934	.4936	0	0	1	1	1	1	1	2	2
2.5	.4938	.4940	.4941	.4943	.4945	.4946	.4948	.4949	.4951	.4952	0	0	0	1	1	1	1	1	1
2.6	.4953	.4955	.4956	.4957	.4959	.4960	.4961	.4962	.4963	.4964	0	0	0	0	1	1	1	1	1
2.7	.4965	.4966	.4967	.4968	.4969	.4970	.4971	.4972	.4973	.4974	0	0	0	0	0	1	1	1	1
2.8	.4974	.4975	.4976	.4977	.4977	.4978	.4979	.4979	.4980	.4981	0	0	0	0	0	0	0	1	1
2.9	[illegible]	.4982	.4982	.4983	.4984	.4984	.4985	.4985	.4986	.4986	0	0	0	0	0	0	0	1	1
3.0	.4987	.4987	.4987	.4988	.4988	.4989	.4989	.4989	.4990	.4990									
3.1	.4990	.4991	.4991	.4991	[illegible]	.4992	.4992	.4992	.4993	.4993									
3.2	.4993	.4993	.4994	.4994	.4994	.4994	.4994	.4995	.4995	.4995									
3.3	.4995	.4995	.4995	.4996	[illegible]	.4996	.4996	.4996	.4996	.4997									
3.4	.4997	.4997	.4997	.4997	.4997	.4997	.4997	.4997	.4997	.4998									
3.5	.4998	.4998	.4998	.4998	.4998	.4998	.4998	.4998	.4998	.4998									
3.6	.4998	.4998	.4999	.4999	.4999	.4999	.4999	.4999	.4999	.4999									
3.7	.4999	.4999	.4999	.4999	.4999	.4999	.4999	.4999	.4999	.4999									
3.8	.4999	.4999	.4999	.4999	.4999	.4999	.4999	.4999	.4999	.4999									
3.9	.5000	.5000	.5000	.5000	.5000	.5000	.5000	.5000	.5000	.5000									
X	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9

$$P(X) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}x^2}$$



Values in the table give the probability Φ(X) that a Normally distributed random variable (X) with zero mean and unit variance will have a value between O and X.