DOI: http://doi.org/10.4038/jgssl.v23i1.66 *Journal of Geological Society of Sri Lanka Vol. 23-1 (2022), 55-67*

MECHANISM OF SLOW-MOVING SLOPE FAILURE IN KAHAGOLLA, SRI LANKA

UDENI B. AMARASINGHE

Department of Geology, University of Peradeniya, Peradeniya, Sri Lanka

Email of the author: udenia@sci.pdn.ac.lk

(Received 5th June 2020; accepted 1st May 2022)

ABSTRACT

The key to understanding the stability of slopes in residual soils lies in recognizing the behaviour of weak soil layers, underlying relict geological structural discontinuities inherited from the parent bed rock and highly permeable zones existing in the underlying bed rock. A clear understanding of the geological formation of such weak zones in the subsurface would help to assess stability of slopes with much more confidence and predict the depth of the potential slip surface materials. Detailed engineering geological and geophysical studies of the sub-surface of a slow-moving slope failure at Kahagolla, along Colombo-Badulla highway, Sri Lanka indicate that the sub surface of the slope mass had developed due to breakdown of underlying layers of garnet biotite sillimanite gneiss and a layer of impure crystalline limestone existing towards the head scarp. The test pits had shown that the slip surface had predominantly developed through the completely weathered garnet sillimanite biotite gneiss into sandy clayey silt layer. The rotary core drilling exploration reveals that the existence of a rock layer of impure crystalline limestone towards the head scarp which contain solution cavities supporting development of high pore water pressure below the slip surface material. The electrical resistivity studies indicated that the sub surface consists of loose upper layer and the lower layer of residual soil derived from weathered bed rock. Development and distribution of tensional cracks in the overlying beds control by the existence of two main joint discontinuity sets in the completely weathered rock and residual soil horizons. The study highlights the role of weak soils in the development of the slip surface, influence of solution cavities in the underlying marble bed rock on development of high pore water pressure and the soil weakening character of the relict discontinuities of the underlying rocks.

Keywords: *discontinuity, pore water pressure, scarp*

INTRODUCTION

Landslides are frequently observed during the heavy rainy periods on hill slopes of the central mountains of Sri Lanka underlain by Precambrian metamorphic rocks with meta-sedimentary/meta-igneous origin (Cooray, 1994). Some of the Sri Lankan slope failures are rapid while others are creep-type slow movements (Amarasinghe et. al. 2002). Both rapidly-moving and slow-moving landslides often cause loss of lives and destruction of infrastructure, public and private properties. So, the occurrence of landslides has become the major natural hazard in Sri Lanka, which causes annual loss of billions of rupees to the national economy. Some of those landslides occur in natural slope units while others take place in man-made cut slopes such as road cuttings, railway cuttings, back cuts of buildings and houses etc. Highway and railway traffic are frequently interrupted during heavy rains due to such slope failures and roads and railways become impassable for long periods (e.g. Pussellawa landslide had damaged Gampola – Nuwara Eliya road in 1980's; Kahagolla landslide had damaged Colombo-Badulla A-4 road; Watawala landslide had damaged the Colombo-Badulla railway line in 1990's).

Slow moving type slope failures are referred to as creep type slope failures. The movement consists of both horizontal and vertical components. Generally, the result is land subsidence due to vertical component and forming and widening ground tension cracks due to horizontal component of the movement. Young (1972) stated that soil creep is the slow down slope movement of the regolith as a result of the net effect of movements of its individual particles. Further, it was said that the surface layers move slowly downhill by the action of long-term plastic deformation. In Sri Lanka, creeping slope failures are confined to residual soils in gentle to medium slopes with the difference in the movement with failure/slip surfaces. The materials overlying the weathered bed rock are generally subjected to slow movements along a slip surface in Sri Lankan conditions. The rate of movement is slow and curved/circular as well as flat slip surfaces are commonly observed in Sri Lankan creeping slope failures. Terzaghi (1950) successfully described creeping slope failures as "continuous creep" referring to slow but continuously – distributed strain resulting from strain resulting from stress that is either external to the material affected or is caused by the weight of a considerable thickness of such materials. Slope failures is common in places where the formation of tension cracks in the floors, walls and gardens of houses and subsequent slow increase of openings of tension cracks. The slope movements cause those houses to be unsafe and unsuitable to live. Many villages are subjected to slope movements in the Central hills of Sri Lanka in the recent past. The roads and railways, which run across these slopes are subjected to slow land deformation/land subsidence and traffic becomes impassable during heavy periods of rains. The road subsidence location at Beragala, Kahagolla, Hunnasgiriya, Nawalapitiya, Pussellawa and railway line subsidence site at Watawala are some of such subsiding sites. School lands like Weldambala, Pooliyadda are also faced with land subsidence problem due to a slow creeping type landslide occurrence.

As far as slope stability analysis is concerned, understanding underlying exact causative factors and also predicting the depth to failure/slip surface in such a slope has become a very significant requirement. A particular emphasis is given to understand detection of weak soil layers, which will become failure surface materials during the failure of a slope. Weak soil layers are formed naturally by weathering processes, it will be important to study weathering profiles in the sub-surface of slopes. It is understood that the profile of weathering which has developed on a rock slope over a long period of geologic time has altered the strength and permeability characteristics of the slope so as to increase its susceptibility to failure (Deere and Patton 1971).

In the attempt of developing an alternative method of predicting depth to failure surface in a slope, a study of the soil weathering profile is particularly considered as significant as the slip surfaces are found to occur through weaker soil materials which exist in the subsurface residual soil weathering profile. Bhandari and Thayalan (1994) studied several Sri Lankan landslides in early 1990's and commented on the strong need to study weathering profiles in relation to landslide phenomenon and to develop guidelines to understand depth to a possible slip surface, the possible shape of the slip surface as well as predicting the mode of failure. Although, continuous rain fall is the main triggering factor of Sri Lankan slope failures, there are significant engineering geological factors as well. A slope sub-surface in downward direction generally consists of superficial transported/sedimentary soil deposits like colluviums/old landslide deposits, underlying residual soil layers, weathered bed rock and unweathered /fresh bed rock. The key questions remain to be answered are how Sri Lankan landslides occur as the first-time shear failures in residual soil weathering profiles as well as how old landslides lie on residual soil weathering profiles become reactivated with respect to principles of soil mechanics and engineering geology.

A slope failure or a landslide occur when shear stress as the driving force exceeds the resisting force or the shear strength/shear resistance of the weakest shear strength soil materials existing in the slope subsurface. In general, when a slope failure takes place a shear plane/ sliding surface develops due to shear strain which is formed due to shear stress. This shear plane/ slip surface tends to develop along the soil layer of lowest shear strength. Most of the Sri Lankan landslides are either rotational type or translational type of slope failure or combination of above failure types (Dahanayake, 1994). In both cases, the slope movement of the landslides takes place along a sliding/shear surface. It is well known that a shear/sliding surface is formed due to increasing shear stress and pore water pressure resulting in decreasing effective stress and subsequently development of shear strain particularly along weakest soil layers or discontinuities of the weathered rock materials of lowest shear strength. Deere and Patten (1971) found that slope failures in residual soil and weathered rock are common in humid temperate and tropical climates, particularly during periods of intense rain fall. The profile of weathering which has developed on a rock mass over a long period of geologic time has altered the strength and permeability characteristics of the slope so as to increase its susceptibility to failure. They had further stated that relict geological structural features/discontinuities such as joints, bedding planes, foliation planes, and fault planes, which have been inherited from the original bed rock mass further reduce the stability of the slope. The key to understanding the stability of slopes in residual soils lies in recognizing the roles of weathering profiles, groundwater and relict structures.

It is understood that a geotechnical study of slope stability of past landslides of Sri Lanka is of great importance to develop and derive guidelines/ criteria to assess and analyse stability of any given unfailed slope unit. When the stability of a given slope is analysed, next to geometry of the slope, shear strength parameters along the slip surface / shear surface are to be accurately determined. Then a question arises on how to understand the possible slip surface material of relatively lowest shear strength or shear resistance. If there are certain engineering geological factors which could be used as the basis to understand the possible slip surface material is yet to be known in the Sri Lankan context. On the other hand in order to calculate the factor of safety of a slope, determination of shear strength parameters along a possible slip surface material is essentially required. This understanding directs towards a need to predict a possible slip surface material in a slope sub-surface weathering profile. In order to fulfill this requirement sub-surface residual weathering profiles are significantly to be geotechnically investigated in relation to the sites of major past Sri Lankan landslides and find how a weak residual soil layer as well as relict geological discontinuities play a role in formation of a shear/sliding/slip/rupture surface as well as main and minor/side scarps to trigger a movement of landslide during a period of intense rain fall.

The present study is focused on the road subsidence site located 10 km from along the Haputale –Bandarawela upper road at Kahagolla in the Badulla –Colombo highway (A4). The average elevation of the location is about 1430 m from the MSL (Figure 1). The main landslide body extends about 650 m with not very much steep in slope. Road subsidence has been periodically observed in every high rainfall period with vertical and horizontal components of movement. Ground Penetration Radar (GPR) observations could identify some of active slip surfaces and their depths from the ground surface (Dissanayake et al., 2017). It necessitates analysis of stability of such slow-moving landslides to stabilize such slope failures and design landslide controlling measures. A particular emphasis on carrying out a thorough geotechnical engineering study of sub-surface residual soil weathering profile of a well-known past landslide site in Kahagolla and aiming to understand how a shear/sliding surface/discrete boundary shear plane is formed in a slope sub-surface, to find engineering geological factors which could be useful to pinpoint possible slip surface materials, and also to find whether the relict geological discontinuities have also got a role to play in the development of a shear surface as well as to cause tensional failure to influence a movement of a landslide. Kahagolla slope failure has a long history beginning from 1930's. It was observed that the road is damaged periodically due to subsidence up to about 1 m with opening of tension cracks on the road surface during and just after rainy periods. The sloping land is found to be stationary during dry periods. Residual soils as products of weathering of the underlying bed rock, there exist both low shear strength weak soil layers which naturally become low shear strength due to solid mineral particle characteristics to become the slip/shear surface horizon as well as planes of weaknesses along the pre-existing discontinuity planes in the parent bed rock structure. These pre-existing discontinuity planes have survived physical and chemical weathering processes and known as relict discontinuity planes. It is also significant also to understand the influence of those relict discontinuity planes on the development of slope failures and movements. It is not only needed to understand how a first-time shear failure takes place due to development of rupture/shear/slip surface along the weak soil layers but also to understand how an old landslide becomes reactivated in a rainy period.

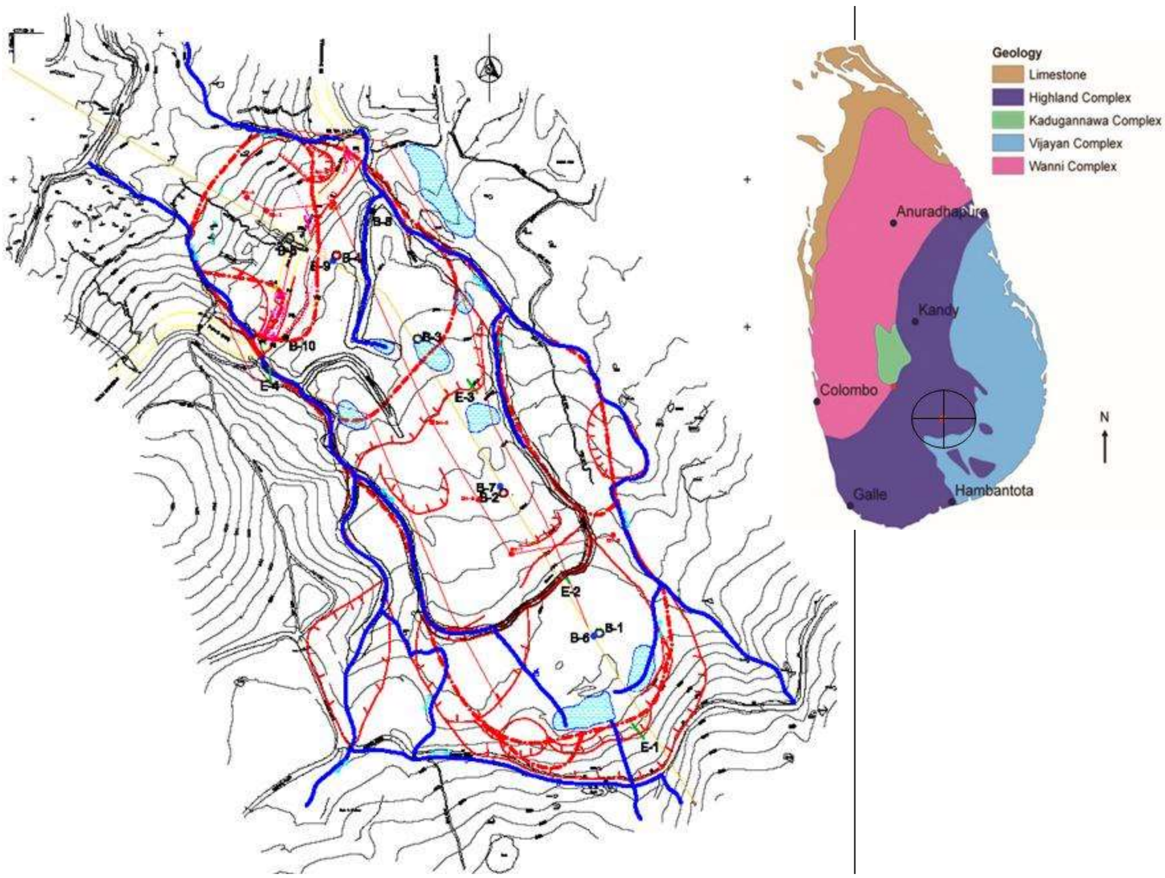


Figure 1: Location map of the Kahagolla Landlslide (modified after Wijesinghe and Jayasundara, 2020)

MATERIALS AND METHODS

Landslide site at Kahagolla has been chosen and the landslide site was systematically studied using aerial photograph and topographic and geological maps. A thorough review of relevant literature including newspaper information, text books, journal papers, investigation reports, conference papers was carried out on general geotechnical and soil mechanical aspects of past landslides. Surveying and leveling were carried out in the landslide site. A pilot/ reconnaissance engineering geological site investigation was carried out at the landslide site to get an overall understanding of the lithology, underlying geological structure, hydrogeological condition, geomorphology, and the composition of the soil overburden materials. During this stage of investigation interviews were conducted with government officers and other villagers who possess eye witness and first- hand information on the nature of the landslide occurrences.

Under the detailed engineering geological site investigation, seismic refraction geophysical surveys along the longitudinal direction of the landslide at Kahagolla has been carried out to study the depth to the hard bed rock mass as well as to detect horizons of the subsurface soil-rock weathering profile. The geophysical seismic refraction studies at Kahagolla landslide was effectively done to detect subsurface soil and rock horizons. The detailed geological mapping was also carried out perpendicular to the strike of foliation layers and engineering geological data on rock types, dip and strike of foliation plane, strike and dip of joint planes, joint spacing , infilling in joints, degree of weathering, thickness of colluviums, thickness and composition of residual soil horizons of the soil overburden, depth to the water table, seepages, depth to the perched water table, tension cracks, main/head scarp of the landslide in crown area, minor lateral scarps at sides of the landslide body, erratic boulders, points of land upheaval, etc. were collected and plotted on the base map. An engineering geological map was produced for each landslide site.

Subsurface exploration was carried out using rotary core drilling method as well as digging about three trial/test exploration pits using laborers in the area. In the detailed engineering geological research six bore holes were drilled using rotary drilling method. Drill holes were placed along the central logitiudinal axis while trial/test pits were located one close to the main scarp are and one close to the left lateral scarp and one close to the right lateral scarp area. Rotary core drilling revealed the subsurface geotechnical condition. The trial/test pits had helped to study the subsoil-rock weathering profile and also to detect shear/sliding surfaces of the landslides. Trial/test pits were also used to collect undisturbed box samples for subsequent direct shear strength test at the soil engineering laboratory at the Faculty of Engineering, University of Peradeniya. Using the steep soil profiles naturally exposed at the main and minor lateral scarps as well as the walls of trial pits, it was possible to study the sub –soil-rock residual weathering profile up to and somewhat below the shear/sliding/slip surface soil materials. All the soil horizons were classified as IA, IB, and IC horizons according to the international classification system suggested by Deere and Patton (1971). Disturbed soil samples were also collected from each soil horizon for subsequent grain size analysis (sieve analysis and hydrometer analysis) as well as determination of Atterburg limits (Plastic limit and liquid limit) at the soils engineering laboratory. These tests were also performed on undisturbed box samples obtained from the slip surface area.

As it was already mentioned above undisturbed box soil samples were collected carefully from the slip/shear surface soil materials which were encountered during digging of trial/test pits located close to main and lateral scarps of the landslide for determining shear strength of the shear/slip surface soil materials. When performing this task slip surfaces were carefully detected based on presence of polished or slickensided planar surfaces or newly formed directed soil fabrics which formed due to shear strain. In the soil engineering laboratory samples were prepared for the direct shear test. The samples were not sheared along already formed residual shear surfaces as the peak shear strength of slip surface soil materials were to be determined together with the residual shear strength. The direct shear strength tests were carried out on each undisturbed box sample using a slow rate of strain which facilitate drainage (drained condition).

RESULTS & DISCUSSION

FIELD OBSERVATIONS

The Kahagolla slope failure is found on the mid–slope region of the North East – South West trending ridge extending from Haputale area (Figure 1). The slope is covered with a colluvial soil layer of variable thickness. The low-lying layer is found to be completely weathered bed rock. It was found that the IC horizon of the residual weathering profile of the Kahagolla landslide had formed through three different rock types, marble/calc gneiss, quartzite, and garnet hornblende biotite gneiss under scarp slope condition (Figure 2). These three rock types have different weathering resistance and as a result of that the slip surface has become undulatory with culminations and troughs. This has caused the sliding material and the surface to experience both land subsidence and upheaval. Subsided upper depression is underlain by the marble bed rock. There is a pool of surface water in the upper mid slope part of the landslide. This area is underlain by marble/calc gneiss bed rock mass with solution cavities. This rock layer is highly permeable and a constant groundwater flow takes place towards the lower slope from this surface water body.

Figure 2: *The mid slope bench slope with marshy condition in the Kahagolla Landslide*

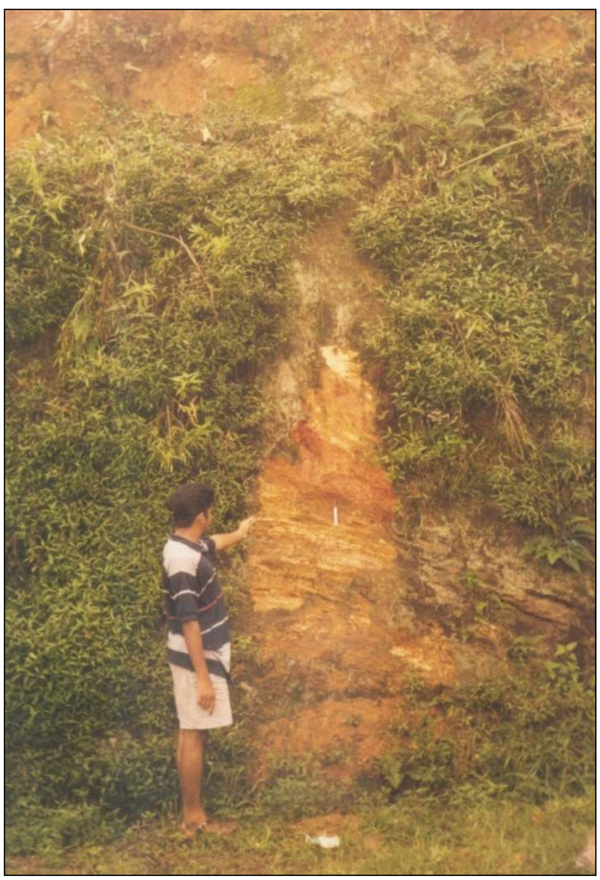


Figure 2: *The head/back scarp of the Kahagolla landslide showing the residual weathering profile*

GEOLOGICAL MAPPING

Scarp slope condition is exposed, garnet hornblende gneiss, quartzite and calc gneiss/ impure marble and garnet granulitic gneiss are found as the bed rock layers as shown in the Figure 3.

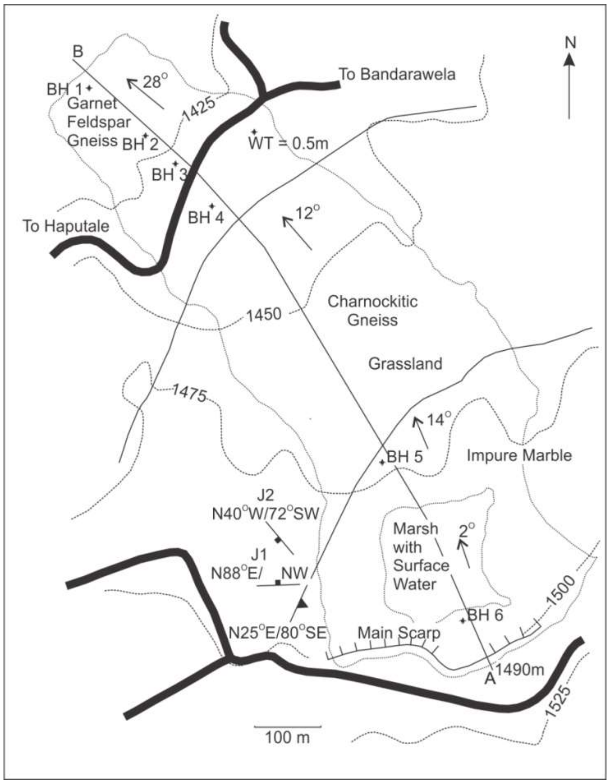


Figure 3: The Engineering Geological Map of the Kahagolla Landslide area

The general strike and dip of foliation layering are found to be 25o NE and 23o SE respectively. There are two main joint discontinuities in the bed rock structure. The strike and dip of first joint discontinuity (J1) are found to be 88o NE and 80o NW respectively. The strike and dip of the second joint discontinuity (J2) are found to be 40o NW and 72o SW respectively. As shown in the Figures 3 and.4, the water table exists at about 0 to 0.5 m depth with pools of stagnated water on the mid slope bench. The axis of the slope failure runs North West – South East and two streams also found to run parallel to the axis of the sliding mass and adjoining to the sliding mass. The slip surface was encountered in the three trial/test pits TP1, TP2, and TP 3. It is interesting to note that the slip surface was detected in the IC horizon of the residual weathering profile. It has well-polished and slickensided planes indicating reactivation of the Kahagolla landslide a number of times in the past.

It is observed that there are three main discontinuities in the underlying bed rock (Figure 3). They include the foliation plane, first joint set (J-1), and the second joint set (J-2). The strike and dip of the J-1 plane is 6 o NE and 68o NW respectively. The J-1 discontinuity is very prominent and runs through the completely weathered soil mass as a weak relict structure, which is parallel to the head/back scarp of the sliding mass. The J-2 discontinuity is parallel to the lateral boundary/minor scarp of the slide and its strike and dip were found to be 10 NE and 80 SE respectively.

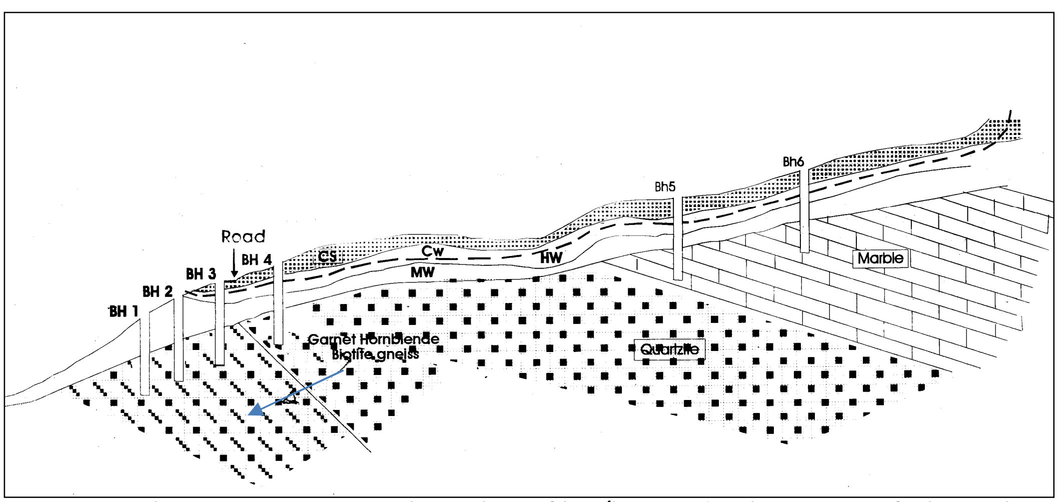
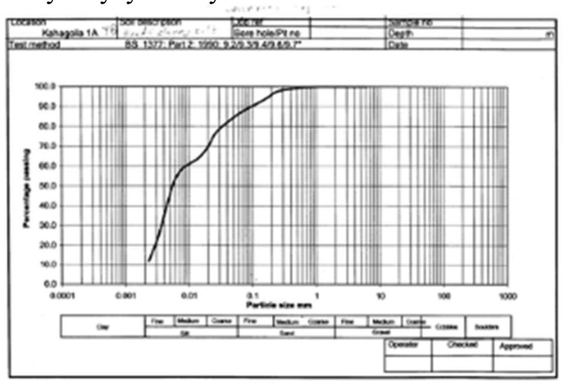
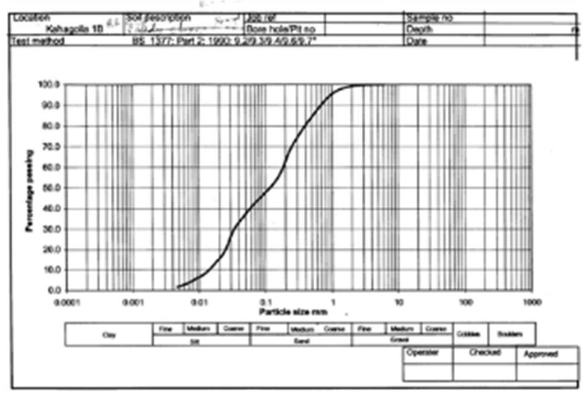


***Figure 4:** The Engineering Geological Profile /longitudinal section of the Kahagolla Landslide based on rotary core drilling (Scale: 1: 200)*

GRAIN SIZE DISTRIBUTION OF SOIL PROFILE

On the basis of two test pits two weathering profile sections were studied. The test pit 1 (TP1) shows that the slope soil overburden consists of four different layers as shown in the soil profile, Figure 5. The top layer is the 1 A and the soil is yellowish brown sandy clayey silt. The top layer is found with embedded boulders and it is The soil profile of the second test pit was also studied. The first layer, 2 A is the Brownish sandy clayey silt and which is the colluvium. The second layer, 2 B is the Brownish to reddish brown sandy clayey silt and which is recognized as the residual soil layer. The third layer, 2 C is the yellowish sandy clayey silt layer and which is found as the upper layer of the completely weathered bed rock. The fourth layer, 2 D is the yellowish sandy clayey silt layer and which is recognized as the lower layer of the completely weathered bed rock. The fourth layer is recognized as the slip surface material.
recognized as the colluvium. The second layer, 1 B is the reddish brown to Yellowish brown sandy clayey silt and which is found as the residual soil layer. The third layer,1 C is the Yellowish-brown silty sand is found as the upper layer of the completely weathered bed rock as indicated by relict structural features. The fourth layer, 1 D is the Yellowish sandy clayey silt and which is found as the lower layer of the completely weathered bed rock. The fourth layer is recognized as the slip surface material with polished and slickensided surfaces.





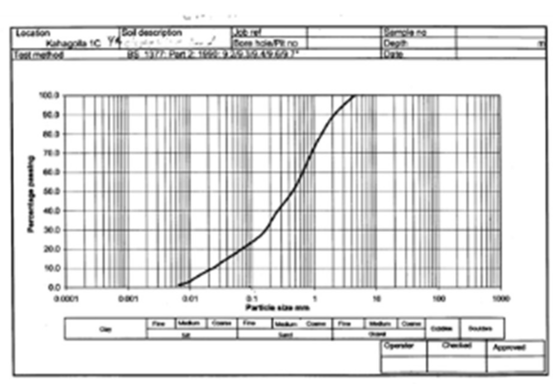
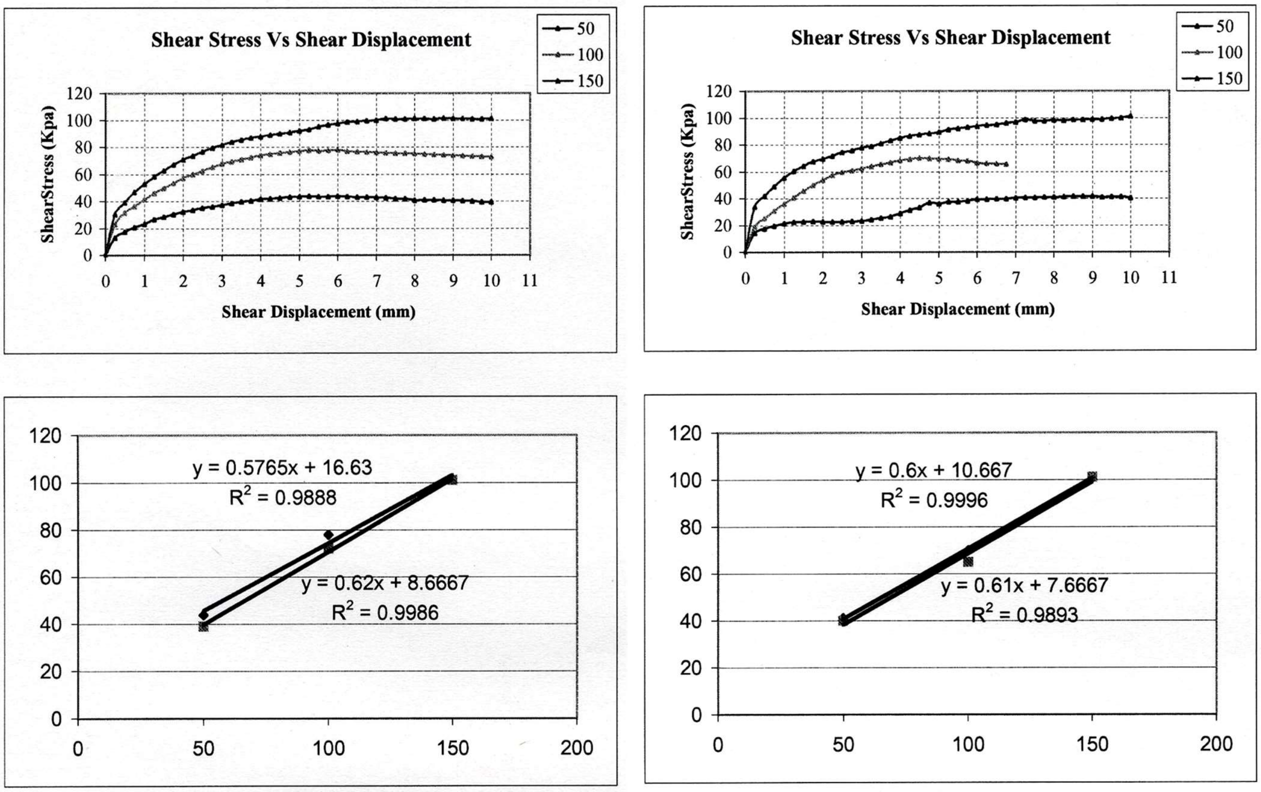


Figure 5: *The grain size distribution of different horizons of Kahagalla landslide (a) IA, (b) 1B, (c) 1C*

DIRECT SHEAR TESTS OF SLIP SURFACE MATERIAL



	Peak Shear Properties	Residual Shear Properties
Equation	y = 0.5765x + 16.63 R^2 = 0.9888	y = 0.62x + 8.6667 R^2 = 0.9986
Cohesion	16.6	8.7
Friction	30	32

	Peak Shear Properties	Residual Shear Properties
Equation	y = 0.6x + 10.667 R^2 = 0.9996	y = 0.61x + 7.6667 R^2 = 0.9893
Cohesion	11	7.6
Friction	31	31

Figure 6: *Shear strength of slip surface material encountered at the test pit-1 and test pit -2*

The sample BSI from the test pit-1 shows cohesion and angle of friction under peak shear strength condition 16.6 and 30 Kpa respectively. The same sample shows the cohesion and the angle of friction under residual strength condition 8.7 and 32 Kpa respectively. The sample BS2 from the test pit-2 shows cohesion and angle of friction under peak shear strength condition 11 and 31 Kpa respectively. The same sample shows the cohesion and the angle of friction under residual strength condition 7.6 and 31 Kpa respectively. Undisturbed box samples of slip surface materials were obtained from two test pits, TP1 and TP2 as shown in the Figure 6 for laboratory direct shear testing.

The peak shear strength values of the Box sample 2 (BS2) were found to be C=16.6 kpa and O = 30 respectively. The residual shear strength values of the Box sample 2 (BS2) were found to be C=8.7 and O=32 respectively. The peak shear strength values of the box sample 3 (BS3) were found to be C=11 kpa and O =31 respectively. The residual shear strength values of the Box sample 3 (BS3) were found to be C=7.6 kpa and O=31 respectively. The low cohesion values are attributed to high silt content in the slip surface material and the angle of friction value of 31 is attributed to sand particles in the slip surface material. The completely weathered rock as the slip surface material exhibits low shear strength values under saturated condition. So subsequent to a tensional failure of the surface materials, a slow shear movement is understood to have occurred through the weakest completely weathered rock material to form the slip surface.

It is noted that the I A horizon (colluvium) and the I B horizon (residual soil) are ruptured first due to tensional failure. The strength of colluvium (I A) is generally higher due to the effect of coarser pebble, cobble and boulder content. The strength of residual soil (I B) is generally higher due to chemical leachents serving as cements. The slip surface material is found to be the yellowish to whitish I C horizon of the soil profile which consists of variable amounts of kaolin clay, weathered mica and small amount of sand particles. The lower cohesive value is attributed to the high silt size particles and the O value of 30.5 is attributed to the sand size particle content. In the scarp slope condition at the Kahagalla site the shear failure plane has not found along a pre-existing relict discontinuity plane but instead ran and ruptured through the I C horizon material as the relatively weakest soil layer from the surface. Residual shear planes were noted in the slip surface material indicating past periodic horizontal movements but direct shear testing was freshly carried out on same soil material of the undisturbed box samples not along pre-existing natural shear surfaces.

SEISMIC REFRACTION SURVEY

As shown in the Figure 7, the seismic refraction profile which was carried out along the longitudinal direction is very well matches with the engineering geological surface and sub – surface profiles. Both the investigation methods confirms the existence of two soil layers above the bed rock hard surface. The layers were well identified as colluvial soil with scattered boulders and the residual soil layer including the I C horizon as the second layer overlying the hard bed rock surface. According to the seismic refraction investigation, the thickness of the colluvial layer varies from 3.3 m to 5.3 m and the thickness of the residual soil layer varies from 0 to 12.3 m. This shows that the thickness of the residual soil layer varies in a very wide range due to different weathering resistance of three bed rock layers in the bed rock structure under scarp slope condition. It seems that the calc gneiss rock layer exists at a greater depth up to 12.3 m.

ABC depth computation (KG1)

Receiver number	1	2	3	4	5	6	7	8
Receiver elevation	0	0.5	1.2	2.2	3	3.7	4.2	4.2
Receiver distances	2.5	7.5	12.5	17.5	22.5	27.5	32.5	37.5
Layer 1 thickness	5.3	4.9	4.6	4.3	3.8	3.6	3.4	3.3
Layer 2 thickness	-0.2	2.3	2.4	3.8	2.8	5.3	5.7	3.9
Bed Rock depth	5.1	7.2	7	8.1	6.6	8.9	9.1	7.2

ABC depth computation (KG2)

Receiver number	1	2	3	4	5	6	7	8	9
Receiver elevation	0	0	0	0	0	0	0	0	0
Receiver distances	2.5	7.5	12.5	17.5	22.5	27.5	32.5	37.5	42.5
Layer 1 thickness	0	0	0	0	0	0	0	0	0
Layer 2 thickness	10.9	11.5	11.8	12	12.3	11.6	10.8	9.6	8.3
Bed Rock depth	10.9	11.5	11.8	12	12.3	11.6	10.8	9.6	8.3

Figure 7: *Results of the seismic refraction profiles with depth to the hard bed rock surface*

DISCUSSION

The field research studies show that the slip surface had developed in the Kahagalla slope failure mainly in the completely weathered rock or I C horizon of the soil profile. The IC horizon had formed through more than one lithological layer under scarp slope condition. This zone of weathered material was found to show relatively weaker shear strength properties with respect to laboratory testing due to considerably high weathering state of the primary mineral grains and also the tendency to fail with lower shear stresses through the weakest soil horizon. The mid area of the slope is found to be underlain by soluble marble/calc gneiss rock having solution cavities. So that it is found that higher permeable highly weathered bed rock zone II A influences rapid rise of water table infiltrating the softer I C horizon resulting in complete saturation. The higher silt content with mica flakes as characteristic soil particles in the I C horizon become lower shear strength material under saturated condition. This understanding based on the research on slip surface materials helps to identify the probable earth material which is viable as the slip surface material is clearly the I C horizon in a weathering profile. This is very determinative in slow moving creep type slope failures. As far as soil particle mineralogy is concerned, I C horizon is the fresh conversion of the rock material into softer soil with weathered feldspar and mica. When compared, I B horizon is found to be relatively higher in strength due to the enrichment of residue of secondary minerals while soluble softer matter had leached away. The lowerlying II A horizon is naturally higher in strength as the highest tendency for the formation of slip surface plane is found along the relatively weakest I C horizon.

Subsurface exploration based on digging three test/trial pits up to the slip surface had revealed that the slope subsurface consists of the top layer of old landslide deposits/colluviums consisting of heterogeneous soils containing erratic boulders, cobbles, pebbles, gravel, sand, silt, and clay size particles, the underlying layer of IA horizon of the residual weathering profile consisting of more oxidized and chemically leached layer of residue particles of relatively higher shear strength, the next underlying layer of IB horizon of the residual soil weathering profile consisting of soils of more enrichment of leached chemical compounds which act as bonding material of the solid soil particles, the underlying layer of IC horizon of the residual soil weathering profile consisting of completely weathered bed rock layer. The IC horizon has saprolite structure with relict mineral bands, relict joint discontinuity planes. The minerals of the IC horizon are not entirely secondary minerals as the chemical weathering processes have not yet completely transformed primary minerals to secondary minerals. This was clearly noticed in Kahagolla landslide. For example, feldspar primary mineral of the parent bed rock has not yet been completely transformed to kaolinite clay particles. The completely weathered bed rock/IC horizon does have whitish silt size particles derived from feldspar which are not as cohesive as normal kaolinite clays as shown by plastic and liquid limit values. The next underlying layer is the highly weathered bed rock or IIA horizon. Which has got rock like nature. Digging of test//trial pits has helped to physically detect the slip/shear surface. The slip surface was clearly detected in the test pits at Kahagolla, the slip surface was found to run mainly through the IC horizon but they run partly through the IB horizon and IIA horizons. When it was carefully examined the slip surfaces are generally well polished or slightly striated planes. IN Kahagolla, landslide, which occurred as reactivated old landslides as evidenced by well-polished slip surfaces in this study.

The study of soil horizons on the main and two lateral minor scarps also has shown that the slip/shear surface is formed at the beginning through colluviums, IA, IB, and IC horizons in vertical to subvertical angles but subsequently becomes flatter toward the foot of the landslide. The test pits and main and minor lateral scarp soil exposures had helped to classify the subsurface soil horizons up to the highly weathered bed rock mass. It can be concluded that from the top to bottom the succession of soil horizons which can be identified are colluviums layer, IA horizon, IB horizon and IC horizon.

The shear strength parameters indicate that the actual slip surface soil materials are found to be low in shear strength with low cohesion which is attributed to the silt like properties that is found in partly transformed feldspar grains into kaolinite clay particles. The internal atomic structures of these primary feldspar mineral grains may have not yet completely transformed to hydrous aluminosilicate clay mineral particles. The moderate angle of friction values was detected in most of the soils in all the landslide sites and these values are due to presence of quartz and heavy mineral residue grains which have survived the chemical weathering process. These quartz grains have come from Garnet gneisses, quartz feldspar gneisses, and charnockitic gneisses.The subsurface engineering geological exploration and direct shear soil strength tests reveal that IC horizon of a residual weathering profile can be recognized as the main slip surface material while the IB horizon is recognized as the other slip surface material.. These slip surface materials were physically discovered in the test pits as well as in the main and minor scarp exposures. The IC horizon is found as the main slip surface material in all the seven sites and it is found that low shear strength properties of IC horizon under saturated condition is the main cause for the formation of the rupture surface through the IC horizon. The soil particles of IC horizon are of silt size (more than 50% generally) and sand size. The silt size partly transformed feldspar to kaoline soil particles are low in cohesive strength while fine to medium sand particles tend to impose moderate frictional strength to the IC horizon soil layers. It can be concluded that IC and IB horizons play a role as weak soil layers to form the slip surface.

The surface engineering geological mapping in Kahagolla landslide site clearly indicates that the slide geometry is well controlled by relict joint discontinuity planes in the residual weathering profile. It is found as a general condition that the first joint set J1 is parallel to the main scarp surface while the second joint discontinuity set is parallel to the minor/lateral scarp surfaces. It is also found that in scarp slope condition, it is common to find two joint sets which are normal to each other and one set is parallel to the escarpment cliff. A head scarp is geologically developed perpendicular to the escarpment cliff. Then one steep or near vertical joint set exists in scarp slope condition and which becomes the relict discontinuity playing a role to easily form the main/head scarp surface. It is also common to see the second joint set in the bed rock structure to have direction approximately perpendicular to the first joint set. This second joint discontinuity plane tends to form the minor/lateral scarps of the landslide. The shear strength is lower always along a joint discontinuity plane compared to shearing through the intact rock area of the bed rock mass. So, in the completely weathered to highly weathered bed rock layers the shear strength becomes lowest along the planes of relict discontinuity planes. So, it can be concluded that relict joint discontinuity planes play a role in controlling slide geometry and the directions of main and minor scarps of a landslide.

Based on this research it can be formulated guide lines to predict the depth to a possible slip surface in a given slope. The first fact is Sri Lankan slopes are underlain by residual weathering profiles. Then during site investigation, it is recommended to dig several test/trial pits and unearth the subsurface residual weathering profile. Then classify the weathering profile into IA, IB, IC and IIA horizons. Then measure the depth to IB and IC horizons. This would give the depth to the possible slip surface of the slope. This research also shows that the shape of the slip surface can also be predicted as follows. If the engineering geological mapping will reveal that the slope is in scarp slope condition then the bed rock mass may consist of more than one lithological rock layer from the top to the bottom of the slope. This study reveals based on the engineering geological studies at Kahagolla, landslide site as a scarp slope due to difference in strength and competencies of different lithological layers along which the rupture/slip surface would develop, an undulatory slip surface can be predicted under the scarp slope conditions. Under the scarp slope condition more than one lithological layer is responsible for the formation of the slip surface soil material. Because different lithological layers have got different weathering resistance and this will form the completely weathered layer to form as an undulatory surface with protrusions and depressions. 9/ This research concludes that old landslides are reactivated only by re-shearing along pre-existing shear planes of the subsurface soil weathering profile which were formed in the past landslide movements. These pre-existing shear planes naturally possesses residual shear strength values after shearing and re-shearing several times and polished preexisting shear surfaces are likely to exist in the subsurface. On the other hand, an old landslide has got an upper layer of colluviums and which is a rather heterogeneous with boulders, cobbles, pebbles, gravel like coarse fraction with silt and clay in a mixed state. So that a weaker slip surface material may not form through coluvium with a hard coarse content of soil particles. It can be concluded that old landslides like Kahagolla, a re-activated only after re-shearing along the weakest slip surface materials pre-existing in the underlying residual weathering profile. So old landslides reactivate by not shearing through the colluvial soils but also by re- shearing through underlying residual soils.

CONCLUSIONS

The study concludes that a landslide movement takes place in two stages. The first stage is the tensional failure stage and the second stage is the shear failure stage. The research on the Kahagolla landslide site has shown that during a heavy rainy period the increasing shear stresses will cause a tensional failure to occur first. The tension, which develops along the longitudinal direction will form transverse tension cracks. If the rain will continue further rain water will infiltrate through the tension cracks to raise the water table above the weaker slip surface soil layer and the soil layer will be saturated in water with reduction of effective stress and increase of pore water pressure. This condition will initiate the second stage of slope failure which is to be referred to as the shear failure stage. In this stage the shear stress will cause a shear displacement to take place and a rupture place is formed and it will become the sip/sliding surface. In this study at Kahagolla the discovery of impure marble as one of the bed rock types with solution cavities with high permeability and storage capacity contributed to form the increasing pore water pressure to bring the slope to the limit equilibrium condition,

ACKNOWLEDGEMENTS

The research study on the landslide at Kahagolla was funded by the Postgraduate Institute of Science (PGIS), University of Peradeniya, and the National Science Foundation (NSF). I wish to extend my gratitude to Head of Department of Civil Engineering, University of Peradeniya for providing laboratory facilities to carry out soil tests at the soils engineering laboratory. I also thank Mr. W.M. Nishantha Weerakoon, the technical officer of the Department of Geology, University of Peradeniya for helping in formatting the manuscript in the computer.

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