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Structural mitigation of a deep-seated slow moving landslide along a major national road in Sri Lanka

Atténuation structurelle d'un glissement de terrain lent profond le long d'une grande route nationale au Sri Lanka

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ABSTRACT: The government has implemented large-scale landslide mitigation works along the National roads in highland areas to avoid the frequent disturbance of the transport system due to the occurrence of landslides. The stabilization of Kahagolla landslide is one of the largest mitigation works carried out under the "Landslide Disaster Protection Project". This landslide was first identified in 1957 and creep movements have followed thereafter at different times affecting the road structure. Detailed field and laboratory investigations, instrumentation and monitoring were performed to investigate the characteristics and the possible causes of the landslide. Stability analysis were carried out on the established landslide profile based on the above information and results indicate that some parts of the landslide are in a highly active stage. Also, analysis indicates that the main reason for landslide activation is the increase of ground water level and subsequent loss of slip surface strength. Based on the results of investigations and stability analysis, suitable combinations of countermeasures were selected by considering both the economic efficiency and the design requirements. The monitoring results up to date after implementing the mitigation measures, show acceptable stabilization of terrain.

RÉSUMÉ : Le gouvernement a mis en œuvre des travaux d'atténuation des glissements de terrain à grande échelle le long des routes nationales dans les zones montagneuses pour éviter les perturbations fréquentes du système de transport en raison de la survenue de glissements de terrain. La stabilisation du glissement de terrain de Kahagolla est l'un des plus grands travaux d'atténuation réalisés dans le cadre du « Projet de protection contre les glissements de terrain ». Ce glissement de terrain a été identifié pour la première fois en 1957 et des mouvements de fluage ont suivi par la suite à différents moments affectant la structure de la route. Des investigations détaillées sur le terrain et en laboratoire, l'instrumentation et la surveillance ont été effectuées pour étudier les caractéristiques et les causes possibles du glissement de terrain. Une analyse de stabilité a été effectuée sur le profil de glissement de terrain établi sur la base des informations ci-dessus et les résultats indiquent que certaines parties du glissement de terrain sont dans une phase très active. De plus, l'analyse indique que la principale raison de l'activation des glissements de terrain est l'augmentation du niveau des eaux souterraines et la perte subséquente de la résistance de la surface de glissement. Sur la base des résultats des investigations et de l'analyse de stabilité, des combinaisons appropriées de contre-mesures ont été sélectionnées en tenant compte à la fois de l'efficacité économique et des exigences de conception. Les résultats de surveillance à jour après la mise en œuvre des mesures d'atténuation, montrent une stabilisation acceptable du terrain

KEYWORDS: Landside, Site Investigation, Ground water level, Monitoring, Countermeasures.

1 INTRODUCTION

Rainfall-induced landslides are one of the most frequent natural hazards in Sri Lanka and it frequently disturbs the life, property and constructed facilities, infrastructures and natural environments in central highlands and hilly areas of Sri Lanka that cover nearly 20% of the total land area of the country, where 30% of the total population live (Karunawardena 2021).

The central region of Sri Lanka is mountainous, with highly fractured and folded basement rock overlain by residual soil and colluvium. Topographically steep slopes and geologically weak strata are the main natural contributors to landslides, with severe, intense rainfall, exacerbated by climate change, as a known trigger. Increased human activities and development in areas at risk, which lack appropriate or adequate regulations, together with the lack of national standards for climate resilient infrastructure, also contribute to the more frequent occurrence of landslide disasters.

As the mandatory agency of the landslide disaster management in the country, National Building Research Organisation (NBRO) took many initiatives such as conducting awareness programs and preparedness drills, giving early warning, and carrying out landslide related research work in order to manage the landslide hazard. Awareness programs have been conducted from the grassroots levels to the national level in order to develop and enhance public and government awareness on the causes of landslides, and their effects through all means possible and thereby reduce disaster risk through hazard awareness. Issuing of early warning messages for landslide threat based on the calculated rainfall threshold limit has been introduced to reduce the possibility of personal injury, loss of life, damage to property, and loss of livelihood. Obtaining Landslide Risk Assessment Report (LRAR) for any construction and development activity in landslide prone areas have become a prerequisite for a building permit issued by local authorities. The above described approaches are generally considered as nonstructural countermeasures for land risk reduction and with the help of these, it was possible to reduce the number of fatalities. However, the records indicate that the extent of damages due to landslides has been increasing, causing loss of life, damage to infrastructure, destruction of property and impacts on livelihoods and local economy. Specially, landslides along the highland roads are a serious problem for the lives of people and the economy in the highland areas.

On the other hand, it is predicted that climate change is likely to increase both the frequency and intensity of extreme rainfall events. Therefore, the importance of application of appropriate structural mitigation measures to reduce the potential for land sliding due to extreme weather events has been well understood and the Road Development Authority (RDA) and the National Building Research Organisation (NBRO) recently implemented a Landslide Disaster Prevention Project (LDPP) along major roads with the Financial and Technical assistance of Japan International Cooperation Agency (JICA). The objective of the Project is to mitigate landslide disaster targeting for major national roads as basic infrastructure through implementing appropriate countermeasures in highland areas, and thereby contributing to enhance the security of the road network and save the lives of residents. This paper presents details of one of the major landslide mitigation works carried out under the LDPP project.

2 DETAILS OF LANDSLIDE

Kahagolla landslide is a well-known massive landslide in the lower central hills of Sri Lanka, which is located at the 10 km post of A016 road in Badulla district. The site area experiences an annual average rainfall of around 2000 mm, which mostly falls during the north-east monsoon from October to January, triggering its movement. The main landslide body extends over 4.5 hectares in an abandoned tea estate with an approximate length and width of 600m and 150m respectively. The road runs across the toe of the landslide, towards the North-Eastern direction. The landslide was first identified in 1957 and gradual movements have occurred thereafter, during periods of heavy rain. The continuing movement of this soil mass pushed the road section as shown in Figure 1 and as a result of that, the road connecting Haputale and Bandarawela towns was sporadically damaged while threatening many lives and community properties located just below the landslide area.

Figure 1. Kahagolla Landslide.

The landslide mass of this site is composed of a colluvium of sand, silt, and boulders. The topographic condition of the site showed features of multiple landslides, gentle but disturbed slopes with a couple of steps formed by smaller scarps, ponds and wet lands scattered in the landslide area. Further, a significant number of open cracks were observed throughout the landslide. According to the topography of the landslide area, the rainfall to the surrounding area flowed into the site in the form of both surface and ground water and was accumulated within the landslide mass and they act as the main triggering factors of landslide. Upsurge of ground water level soon after intense or prolonged rain period destabilized the slope, along with severe erosion by surface water runoff, thus creating instability in landslide mass and gradual movement of the landslide, damaging the main road located at the toe of the landslide.

3 SITE INVESIGATION AND MONITORING PROGRAM

A detailed site investigation and monitoring program was planned based on the preliminary investigation studies which consisted of collection of documents, data, maps, reports and literature related to the landslide and interviewing people at relevant organizations and local people. Since landslides often occur at specific locations under certain landform and geological conditions, studies were done with the existing data (history of events and records of restoration work) in order to understand the geomorphological condition, geology, and properties of similar landslides. Also, efforts were made to understand their relationship with meteorological factors, period of activity, existence of any warning signs, groundwater conditions, chronologic topographic change or erosion of boundaries, and other factors which may relate to the slope deformation surrounding the investigation site area, prior to performing a detailed investigation.

Based on the review of existing reports and the result of the preparatory field surveys, the main investigation and monitoring locations were planned and these are shown in Figure 2.

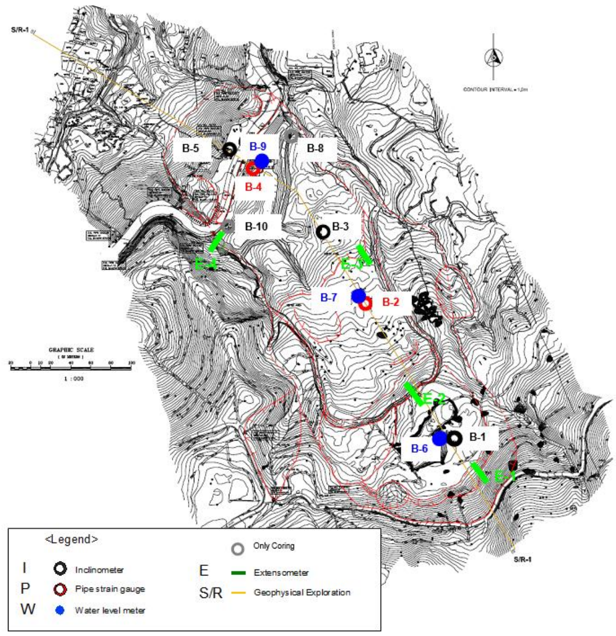

Figure 2. Map of main investigation and instrumentation points

The topographical survey was carried out to prepare the detailed topo maps and cross sections. Topo maps and detailed cross sections were prepared with the scale of 1:1000 or larger and 1:200 respectively. The area of the topographical survey was decided based on the aerial photographs and site reconnaissance survey.

The site investigation comprised of geological field survey, drilling investigation, field and laboratory tests. Geological Field Investigation was conducted based on the analysis of existing walk over survey data and interpreting of aerial photographs. The results of aerial photograph interpretation clearly identified Kahagolla site as a landslide, located in a rolling slope of colluviums formed by a huge collapse of mountain slope. In the lower slope, several small size divided landslides were identified. Several landslides were identified in the upper slope. The morphology of the catchment area also causes a huge amount of water supply to gather inside the landslide, and therefore waterlogged areas appear frequently. Minor folds of geological structures are also weakened by the past landslide occurrences.

A significant number of tension cracks, minor scarps and bulge have been found on the landslide surface. The boundary, main axis of the landslide and its moving direction together with different land moving blocks were identified through the field survey and accordingly geological maps were prepared.

Based on the geological field survey, boreholes using core drilling technique with SPT and geophysical exploration consisting of seismic exploration and electric exploration (Resistivity Survey) were planned and carried out to investigate the geological structure and the potential sliding surface of the landslide. Ten boreholes were carried out at the site as shown in Figure 2 and out of that three boreholes were done along the main traverse of the landslide area. A drilling investigation was conducted by extracting direct core from the ground in order to ascertain the slip plane surface, geological features, and geological structure. Standard penetration test was conducted to seek the N value in order to determine the hardness, firmness, and soil layer structure of the ground in situ during the drilling work. The laboratory tests were conducted from the disturbed soil samples from the boreholes and undisturbed soil samples collected from the site in accordance with the ASTM standards. Shear strength of soft part of the colluvial deposit was tested using undrained Triaxial tests and the direct shear tests conducted from the block samples collected.

According to the lithological data observed from the borehole logs, the rock level was encountered at intermediate depths and varying from 12.55 m to 29.4 m depth within the borehole locations. The major rock types of Charnockitic gneiss, Biotite gneiss, Hornblende biotite gneiss were identified through samples collected from core drilling. The uppermost layers of soil overburden consist of both colluvium and residual soils. These subsoil layers consist of clay, silt, sand, and gravel in different combinations such as clayey silt, silty sand, silty clay, clayey sand, silty gravel, sandy silt, and gravelly silty sand. It was also observed that the boulders were found at different depths in different sizes. The thickness of overburden varies between 21m to 25m just above the road level whereas it decreases gradually towards the downhill.

Two types of geophysical explorations, namely seismic and electric explorations (resistivity survey) were carried out at the site. The Two-dimensional electrical resistivity survey was carried out to understand about the weathering state of each layer, depth to the bedrock, aquifers and their continuity, which was very useful in the design of sub-surface drainage. The sub soil profile obtained from the resistivity survey clearly indicated the high water content area inside the landslide. The resistivity profile obtained along the main axis of the landslide is shown in Figure 3.

Field monitoring instrumentation, namely pipe strain gauges, inclinometers, extensometer, water level meters and rain-gauge were installed at identified locations to monitor the behavior of the landslide as indicated in Figure 2. Monitoring was carried out for about a year covering the monsoon periods before the detailed design was carried out and thereafter it was continued during the construction period too. Monitoring was done once a month during the dry period and twice a month during the rainy period. The response of monitoring devices of water level meter and extensometer for the rainfall received is shown in Figure 4. Main observations of the landslide monitoring were made to reveal the relationship with rainfall patterns and slip occurrence.

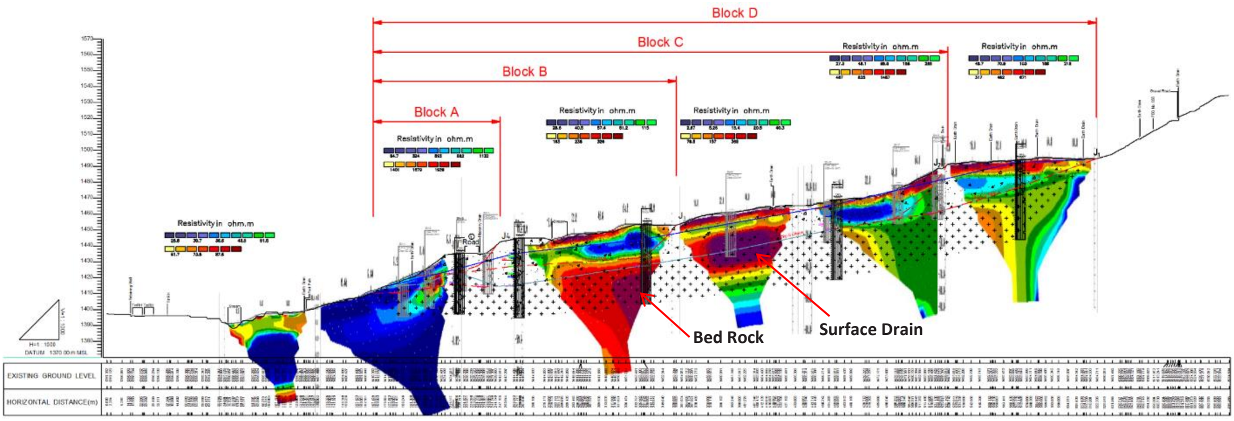

Figure 3. Resistivity profile along the main axis of the landslide

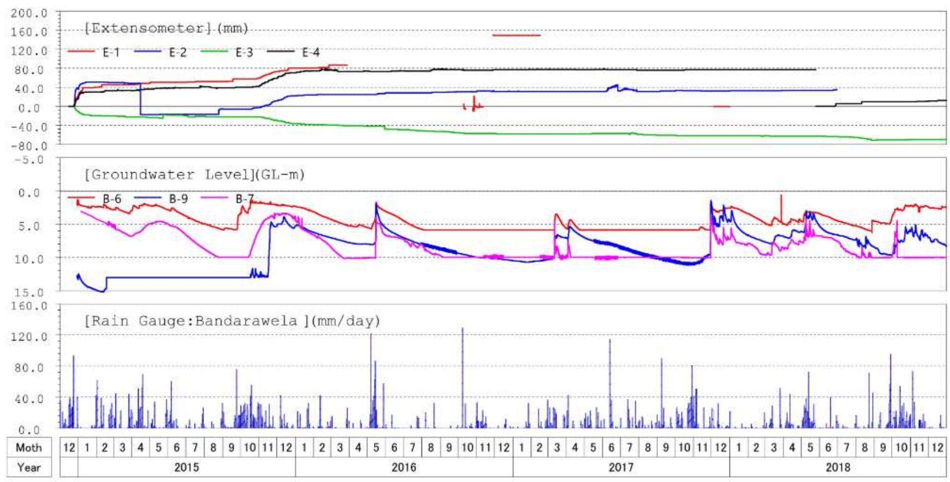

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Figure 4. The response of water level meter and extensometer for the rainfall received

Based on the field reconnaissance and the topographic survey result, the landslide of the site area is divided into four blocks as shown in Figure 5. Block A is located at the toe of the landslide across the road and appeared to be highly active. In block B, height of the scarp was about 3m, however the extension of the scarp towards the side of the landslide was not clear. The main part of the block was gentle but had disturbed the slope. Block C had a 5m high scarp and bare ground was observed around the scarp. Extension of scarp was clearly observed as a form of minor scarp. The main part of the block had a disturbed slope. In the area identified as Block D, the steep slope was located along the estate road and identified as the head scarp. Heavy water seepage and surface water flow were observed in this block during the rainy period. Monitoring results indicated that some parts of the landslide moved actively in rainy seasons. The landslide itself moved repeatedly every year and caused frequent damages to the road. Based on the results of monitoring, it was understood that the landslide area of this site moved intermittently during rainy seasons by various degrees; Block A was the most active but Block B, C and D were still active more or less. This means the countermeasures for the site needed to cope with all blocks. As for the relation of the blocks, it was likely that Block A became activated first then other blocks followed in order of Block B, C and D. It was a rational observation that the blocks moved mutually dependently, and that activity of one block affected the other block consequently.

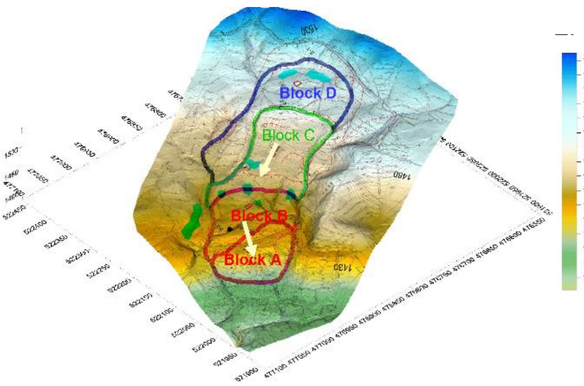

Figure 5. Identified Landslide blocks and movement direction

The direction of the landslide movement was assumed to head straight to block D and the main traverse line of this landslide was presumed at the center of landslide body delineated by the mountain stream on both sides. The direction of the landslide movement was, however, controlled by the stable ridge located at either side of the landslide body at the middle to lower slope. At the middle of the body, the landslide changed its movement counterclockwise and Bock B, and subsequently Block A, moves straight to the main road.

4.1 *Slip surface*

The estimation of the slip surface was mainly done using the core samples collected through the drilling investigation. Typical characteristics of the slip surface such as a thin layer of clay with high water content which is deposit at boundary of stratum were investigated. An effort was made to identify the slip surface on the drilling core sample, based on the above features. In addition, results of the monitoring of inclinometer and pipe strain gauge were considered in the identification of slip surface. However, due to limitations in the quality of core sampling available for the site, the slip surface of the site was assumed mainly based on the boundary between bed rock and overlying colluvium and assumed depth of the slip surface in boreholes is shown in Figure 6. For some sections, the slip surfaces were considered as running through the weathered rock strata. The landslide map and the landslide profile with assumed slip surfaces based on the above data is shown in Figure 7 and Figure 8.

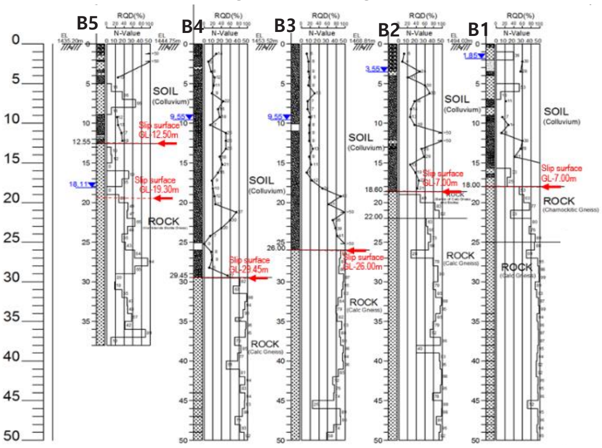

Figure 6. Identified slip surface using output of borehole investigation

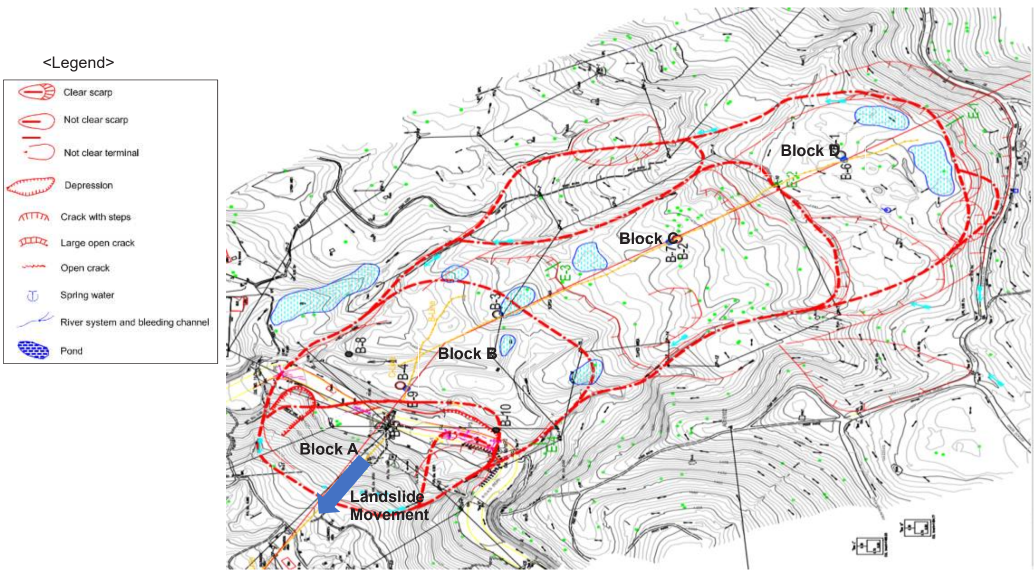

Figure 7. Landslide map showing landslide features

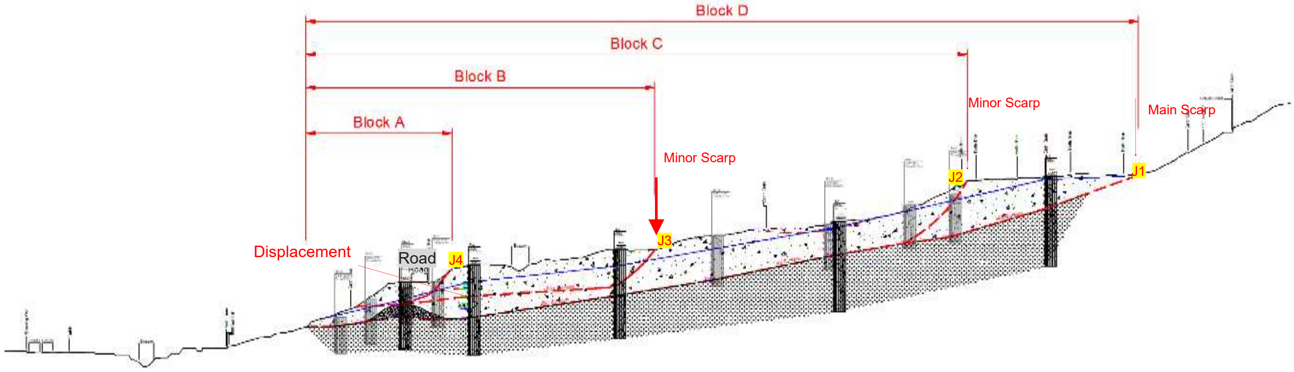

Figure 8. Landslide profile with assumed slip surfaces (J1, J2, J3, J4)

The depth of slip occurrence, slide direction and its velocity, groundwater level fluctuation and its relation to slip occurring were used to model the actual site conditions at the analysis.

4.2 *Analysis*

Stability analysis was carried out for the assumed landslide profile and slip surfaces. The analysis was carried out using GeoStudio 2016 from Geo Slope. The Morgenstern Price method was utilized in the analysis as the assumed slip surface geometry of the failure was irregular in shape. The unit weight (γ), cohesion (c'), and the friction anlage (φ') of 18 kN/m^3, 10 kN/m^2 and 32^0 respectively was used in the analysis. These parameters were obtained from the laboratory tests conducted from the shear undisturbed samples collected from shear surface of the soil. The ground water level required for the analysis was estimated from the field monitoring results. The performance was verified at critical water level, i.e ground water level when landslide starts to slide. This situation is considered a critical state and the factor of safety at the time of landslide is considered as the critical safety factor and its value was taken as 1.0. However, the factor of safety obtained was considerably higher than 1 and indicated that the shear strength parameters obtained from the laboratory test results were not representative of the properties of the slip surface. This may be due to the heterogeneity of soil characteristics, the disturbance to the soil samples in the process of extraction and testing, sample location not representing the whole area etc. Therefore, selection of appropriate shear strength parameters for the analysis were done by simulating the critical state (FOS=1) of the landslide. Shear strength parameters obtained from the laboratory were used as reference for the trial simulation. Trial analysis were done for different shear strength parameters. Previous studies done for Watawala landslide in Sri Lanka shows that cohesion value of the slip surface was relatively small (Rajaratnam and Bandari 1994). Analysis indicated that when c' = 5.25 kN/m^2 and φ'= 17^0, stability model reasonably simulates the observed field deformation condition. Stability analysis results of existing condition of Block A under critical water level is presented in Figure 9.

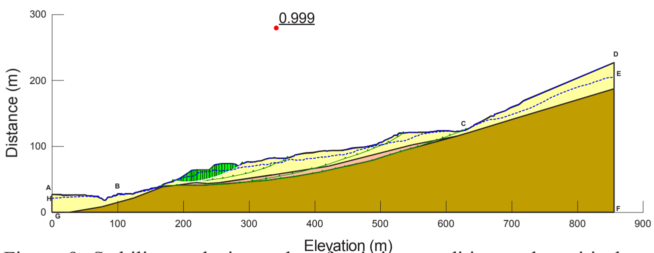

Figure 9. Stability analysis results of existing condition under critical water level _Block A

4.3 *Design of Countermeasures*

Stability analysis had been conducted to determine the scale and quantity of landslide countermeasure works required to maintain the stability of the landslide and so ensure the target safety factor. The design safety factor of 1.2 was targeted by considering infrastructure such as main transport road, some houses, tea cultivation and stream that could be affected in the event of a landslide occurrence. In the selection of design safety factor, both technical and financial aspects were considered. The effectiveness of application of countermeasures were analyzed by GeoStudio 2016 using the Morgenstern Price which is widely used for simple landslide stability analysis. In the selection of countermeasures both control type and preventive type works were examined. Control works were designed to mitigate the landslide by changing natural conditions such as topographic and ground water conditions. Preventive works were designed to stop part or all landslide activity using restrain forces by artificial structures such as retaining wall, soil anchors, piles etc. Stability analysis results with mitigation option of using ground anchors for Block A is presented in Figure 10.

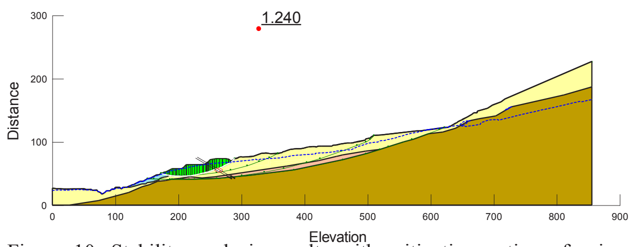

Figure 10. Stability analysis results with mitigation option of using ground anchors for Block A

Counterweight embankment plays a huge role in stabilizing the slip surface J1 and J2 while other most critical slip surfaces are stabilizing with groundwater control works. However, in order to achieve desirable safety margin in slip surface J4, ground anchors are also included in the design.

Based on the results of investigation and stability analysis, several suitable combinations of countermeasures were considered, and examined to decide a couple or more appropriate combinations of countermeasures in terms of both economic efficiency and design requirements. From the more appropriate combinations of countermeasures, an optimum combination of countermeasures was selected by careful examinations and comparison among them. The improvement of safety factor with application of each counter measures are given in Figure 11. The plan and cross section of proposed countermeasures for the landslide mitigation are given in Figure 12.

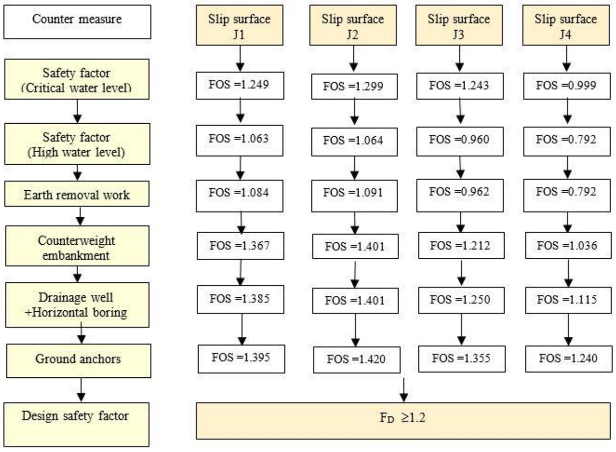

Figure 11. Flow of the safety factor

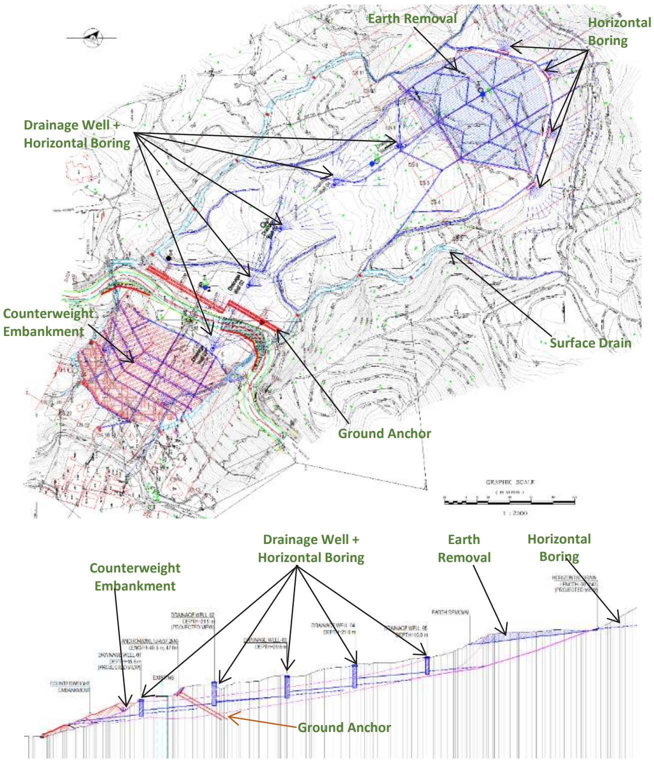

Figure 12. Plan view and cross section of proposed countermeasures

5 CONSTRUCTION OF COUNTERMEASURES

The designed countermeasures were constructed at the site using the Japanese technology and in accordance with Japanese Standards in order to stabilize the landslide. Work was carried out under the full supervision of a Japanese expert and transfer of the technology to the local construction industry was expected. Stabilization involved the construction of surface and subsurface drains and drainage wells to lower the ground water levels. Surface drains were constructed to intercept and divert the surface runoff reducing infiltration and divert the surface water away from the landslide. The drainage wells with horizontal drains were constructed at identified locations to control the ground water level below the design level. Earth removal at the head of the landslide and counter embankment construction at the toe area of the landslide was done with the aim of balancing the force and improving the overall stability of the landslide. Ground anchors were installed just above the road which was located at the toe region of the landslide to prevent the shallow landslide which caused the frequent damages to the road.

Figure 13 shows the photographs of construction of some of the mitigation measures at the site.

Figure 13. Photographs of implemented countermeasures

6 CONCLUSIONS

The Kahagolla landslide had been active for a long period and was a typical slow-moving landslide which caused frequent disturbance to the road transport system in Badulla district, Sri Lanka. Landslide features, landslide profile, slip surface and possible triggering factors were identified based on the field investigations, instrumentations, and monitoring results. Then the stability and countermeasures required to prevent landslide movement were analyzed with sufficient safety factors. Results indicated that the slip surface of the landslide was mainly along the interface between bedrock and overlying deposits and Kahagolla landslide could be divided into four distinguished moving blocks. Based on the detailed field survey and stability analysis, landslide protection works were carried out using the Japanese technology which included the construction of drainage wells, ground anchors, surface and subsurface drainage improvement, soil removing and counter weight embankment etc. Field monitoring carried out after construction of mitigation measures has not shown any movement of the landslide and therefore it can be concluded that the applied mitigation measures are effective and the stabilized landslide is behaving satisfactorily to date.

7 ACKNOWLEDGEMENTS

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