Effectiveness of radial sub-horizontal drainage in improving the landslide stability: A case study on central highlands, Sri Lanka

Efficacité du drainage sous-horizontal radial pour améliorer la stabilité des glissements de terrain: étude de cas sur les hauts plateaux du centre, Sri Lanka

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ABSTRACT: Slope instability, triggered by excessive rainfall is one of the common hazards that geotechnical engineers are challenged within tropical countries such as Sri Lanka. These slope failures are initiated in colluvial layers or planes of low shear strength in differently weathered zones in the thick soil overburden. Improvement of surface and subsurface drainage has proven to be effective in lowering the ground water table as well as preventing perched water table conditions. Badulusirigama Landslide in central highlands of Sri Lanka is an example for a slow moving long rotational slip that activates after heavy rainfall events. The landslide was rectified with more than 45m long individual sub-horizontal drains that are arranged into a network of radial drainage groups at different elevations along the long sliding mass. This site is well equipped with monitoring instruments. The rectification measures were numerically simulated in 2D plane strain conditions to evaluate the improvement of the stability of the slope during the drains construction as well as in response to an actual critical rainfall event. The results indicate that the bottom up sequence of drainage construction is more rapid in improving the stability of a slope when compared to top down sequence of drainage construction. The results of the analysis revealed that with the critical rainfall of total 725 mm that spanned over 30 days with low initial intensities and a peak intensity of 216mm/day after 24 days, an adequate factor of safety was maintained in the rectified slope throughout. There was a sharp reduction of FOS soon after the peak rainfall at 25th day but the slope could recover and the FOS restored as the rainfall intensity reduced.

RÉSUMÉ : L'instabilité des pentes, déclenchée par des précipitations excessives, est l'un des risques courants auxquels les ingénieurs géotechniciens sont confrontés dans les pays tropicaux comme le Sri Lanka. Ces ruptures de pente sont initiées dans des couches colluviales ou des plans de faible résistance au cisaillement dans des zones altérées différemment dans le mort-terrain épais du sol. L'amélioration du drainage de surface et de subsurface s'est avérée efficace pour abaisser la nappe phréatique ainsi que pour prévenir les conditions de la nappe phréatique perchée. Le glissement de terrain de Badulusirigama dans les hauts plateaux du centre du Sri Lanka est un exemple de glissement de rotation long et lent qui s'active après de fortes pluies. Le glissement de terrain a été rectifié avec des drains subhorizontaux individuels de plus de 45 m de long qui sont disposés en un réseau de groupes de drainage radiaux à différentes altitudes le long de la longue masse glissante. Ce site est bien équipé d'instruments de surveillance. Les mesures de rectification ont été simulées numériquement dans des conditions de déformation plane 2D pour évaluer l'amélioration de la stabilité de la pente pendant la construction du drainage ainsi qu'en réponse à un événement pluvieux critique réel. Les résultats indiquent que la conséquence ascendante de la construction de drainage améliore plus rapidement la stabilité d'une pente par rapport à la séquence descendante de construction de drainage. Les résultats de l'analyse ont révélé qu'avec les précipitations critiques de 725 mm au total qui s'étalaient sur 30 jours avec de faibles intensités initiales et une intensité maximale de 216 mm / jour après 24 jours, un facteur de sécurité adéquat était maintenu dans la pente rectifiée. Il y a eu une forte réduction de FOS peu de temps après le pic de pluies au 25ème jour, mais la pente pourrait se rétablir et le FOS a augmenté à mesure que l'intensité des précipitations diminuait.

KEYWORDS: sub-horizontal drainage, slope stability, slow moving landslide, numerical modelling.

1 INTRODUCTION.

Badulusirigama landslide is located in the Badulla administrative district of SriLanka. It is about 4 kilometers away from the city centre of Badulla and towards Batticaloa highway. A part of the landslide is situated within the premises of Uwa–Wellassa University. The landslide is located on a gentle valley type slope. The slope angle is around 10– 15 degrees. Top most soil cover consists of gravelly and sandy soils. The area is covered by a mixed vegetation. Residential buildings are concentrated into the toe area of the slope. Badulusirigama landslide was a slow moving landslide which may get accelerated during heavy rainfall events.

This landslide possessed a considerable risk to residential areas around the lower part of the slope. Rupture surfaces had been formed in layers composed of low strength material. The continuous creep movement of the mass had further decreased the shear capacity of the rupture zone. In addition, presence of deeper cracks have promoted deeper infiltration of water into the mass and water accumulated in those cracks had resulted in generating positive pore water pressures, encouraging the slope instability. Noticeable movements in this landslide were observed after major rainfall events in 2007, 2011 and 2012. Consequently, this was identified as a high-risk landslide which requires immediate rectifications by the government of Sri Lanka.

Improvement of subsurface and surface drainage is a commonly adopted technique to rectify large landslides such as

Badulusirigama landslide, due to the cost efficiency and low maintenance requirements in long run (Cook et al. 2007). The main objective of using the subsurface drainage is lowering the ground water table. Although the concept used in drainage improvement is simple and straightforward, the drainage design should be thorough and should be capable of maintaining suitable ground water levels for a long time, through large number of different whether events. According to literature, there are number of factors which govern the effectiveness of subsurface drains in stabilizing a slope. Location of the subsurface drains, length of subsurface drains, zones of penetration, inclination as well as configuration of the subsurface drains are vital factors in maintaining the slope stability (Kleppe & Denby, 1984, Lau & Kenny, 1984, Conforth 2005). The drains should also be designed to cater for its specific features such as the local climate conditions and land use. Number of numerical studies have been conducted by various researchers to evaluate the performance of subsurface drainage in improving the slope stability in different regions of the world (Nonveiller 1981, Gjetvaj et al. 2009, Rahardjo et al., 2011, Santoso et al., 2011). Badulusirigama landslide in Sri Lanka was improved mainly with long subsurface drains in combination with surface drainage and some bio–engineering measures. Remediation of Badulusirigama landslide is remarkable due to the usage of longer subsurface drains of about 40 - 60 m in length arranged in a radial orientation as opposed to typically applied lengths of 15 to 30 m in parallel orientation. Badulusirigama landslide was also equipped with different monitoring instruments which are functioning since 2014 to date. Thus, this landslide is a resourceful case history to improve the understanding on the behaviour of rain induced landslides in the region. This paper investigates the performance of the subsurface drainage network constructed to mitigate the landslide. Numerical analysis has been carried out under two dimensional plane strain conditions.

2 SITE INVESTIGATION PROGRAMME

Site investigation comprised of a series of surveys to collect information of the landslide. The information is gathered through field visits, geomorphological survey, borehole survey and geophysical survey. Figure 1 shows the site investigation plan with selected locations for borehole survey and section lines, along which the geophysical surveys had been carried out.

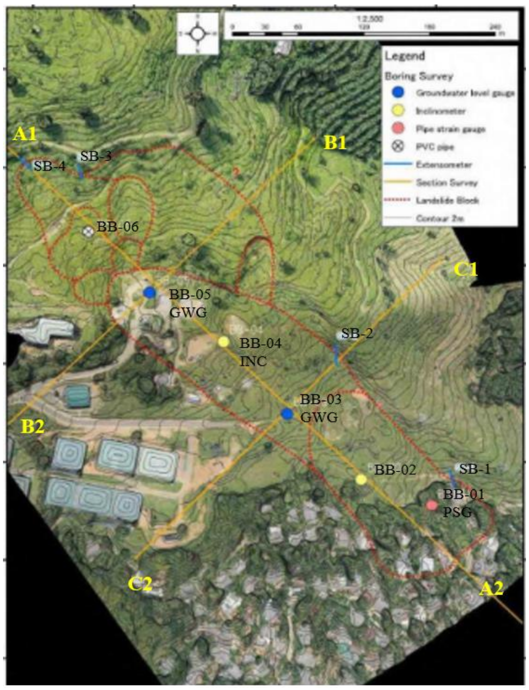

Figure 1. Selected investigation locations and survey lines at Badulusirigama(JICA Report, 2015)

2.1 *Geomorphological Survey*

This comprised of topographic survey, cross sectional survey and an Unmanned Aerial Vehicle (UAV) analysis. The UAV survey data had been used to develop the Digital Elevation Model (DEM) of the site.

2.2 Borehole Survey

Five boreholes had been drilled at selected locations (Figure 1) in order to identify the subsurface conditions as well as to grasp an idea about the location of the slip surface. Standard Penetration Tests (SPT) had been carried out at 1.0m intervals to determine the formation of geological structure and presence of weak planes. These drill-holes were then utilized to install other different monitoring instruments such as inclinometer guide pipes, pipe strain gauges and water level sensors, for further monitoring purposes (Figure 1).

2.3 Geophysical Survey

Seismic Refraction Surveys and Resistivity Surveys had also been conducted along the selected sections of the site. Results of the Resistivity Survey data were mainly utilized to investigate the ground water conditions including the locations of aquifers, and to confirm the information gathered by the geological surveys.

3 INTERPRETATION OF THE INVESTIGATION RESULTS

The geo surveys conducted at the site reveals that the Badulusirigama landslide covers a relatively large land area. The width of the slide is about 120m, length is around 500 – 600 m and the depth to the failure plane varies between 10- 20 m. The whole moving mass was divided in to three distinguished blocks namely; upper slide, middle slide and lower slide, as shown in Figure 2. The slides were identified with the aid of the tension cracks observed at the ground surface and the findings of the geophysical investigations.

According to the investigation results, the site stratigraphy can be divided into three main layers. The topmost soil layer is formed of colluvium and has a thickness of around 10 – 15 m. The colluvium layer is followed by a completely to highly weathered rock layer and the thickness of this layer is around 15 – 25 m. A highly to moderately weathered rock layer is encountered at a depth of around 25 – 30 m. The interpreted sub soil profile based on the geological survey data is shown in Figure2.The ground water table had been encountered at an average depth of around 6 – 7m at the investigated locations and was confirmed by geophysical survey results. However, presence of shallow water table conditions and stagnant ditches have also been observed at some locations. Existence of local unconfined aquifers is perceptible from the results of the resistivity survey. In addition, BB-05 had indicated a ground water level 2.5 m below the ground level during significant precipitation events. Results of the monitoring programme indicate slight movements of the landslide when excessive rainfall events were present. The extensometers installed at the upper slope area (SB-3 and SB-4) had indicated that the slide was actively moving during the heavy rainfall in December 2014 (total cumulative rainfall of 622 mm during 18 days). Meanwhile, extensometers at the toe of the slope (SB-1 andSB-2) had indicated compression displacements which denoted that the slide was rotational in nature. In addition to this, inclinometer and the pipe strain gauge which were installed at BB-04 and BB-01, respectively, had indicated displacements coinciding with rainfall events. The inclinometer data showed some relative displacements at a depth of around 9 – 10 m from the ground surface and strain gauge indicated displacements at a depth of 12 – 13 m from the existing ground level. These evidences confirm the occurrence of active movements of the landslide in response to excessive rainfall events along the potential failure plane.

4 SLOPESTABILITY UNDER EXISITING CONDITIONS

4.1 Geotechnical model of the site

Subsurface information acquired through borehole investigation were compared with the data obtained from geophysical surveys. It enabled the prediction of subsurface profile with a substantial degree of accuracy. Relative thicknesses of the subsurface layers encountered at each drilled location are summarized in Table 1.Subsurface profiles at borehole locations were linked together with geophysical survey data to procure the continuous subsurface profile of the site. Figure 2 presents the subsurface profile of the site along the long section A1 - A2.

Table 1. Interpreted subsurface profile at Badulusirigama landslide

Soil layer		Formation/weathering condition	Thickness (m)
1st layer (top layer)	🟨	Colluvium deposits	Vary from 10 to 20
2nd layer (middle layer)	🟫	Completely to highly weathered rock	Vary from 10 to 20
3rd layer (bottom layer)	⬛	Highly to moderately weathered rock	Not confirmed

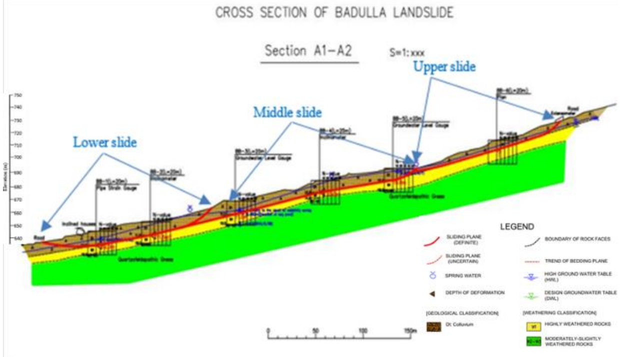

Figure 2. Long section along A1- A2 (JICA Report, 2015)

4.2 Two dimensional plane strain idealization of the site profile

A 2D plain strain analysis of slope stability was conducted using the commercially available software GeoStudio 2012. A cross section along A1- A2 was selected so that the section passes through the centre line of the impending landslide and represents most critical terrain along the slope. Fundamentally, plane strain models are adopted for long geotechnical problems that are uniform along the translational direction. Although this condition is not satisfied by the geometric formation of the current geotechnical problem, selecting the most critical section for the analysis and assuming the plane strain conditions is deemed to yield worst case scenario performance for the landslide. The material parameters adopted in numerical modeling are presented in Table 2. These properties were deduced based on the lithological description of the soils encountered in boreholes, SPT N values, laboratory test results and local experience on similar sites. Figure 3 shows the modeled long section. Analysis was conducted to assess both existing conditions and the behaviour after implementation of the rectification measures. Separate analyses were conducted for modeling the seepage and assessment of slope stability using the different modules available in the software.

Table 2. Summary of parameters adopted for different subsoil layers

Parameter / Layer	γ (kNm^{-3})	γ_{sat}(kNm^{-3})	C' (kPa)	Φ' (deg)
Colluvium	15	16	2	22
Completely to highly weathered rock	16	17	6	32
Moderately weathered rock	20	20	20	40

4.3 Seepage analysis using SEEP/W module

An initial seepage analysis was conducted, using the Geo Studio SEEP/W finite element module, to set up the pore pressure profile of the site. For this analysis ground water table was assumed to be present at a depth of around 1 – 2 m below the existing ground level. The main reasons behind adopting a high ground water table for the analysis are; perched water table conditions observed at the site, indications of high ground water table in boreholes during rainy periods. Table 3 shows the parameters used for seepage analysis. Table 4 summarizes the seepage boundary conditions adopted.

Table 3. Hydraulic conductivity parameters adopted in seepage analysis.

Formation	Saturated Permeability (m/day)	SWCC	Permeability function
1.Colluvium	0.860	Silty Sand*	Estimation based on VG**
2.Completely to highly weathered rock	0.086	Silt*	Estimation based on VG**
3.Highly to moderately weathered rock	8.6E - 10	Saturated only material	

*Built in function available in SEEP/W module

**Based on the estimation method by Van Genuchten 1980 available in SEEP/W module

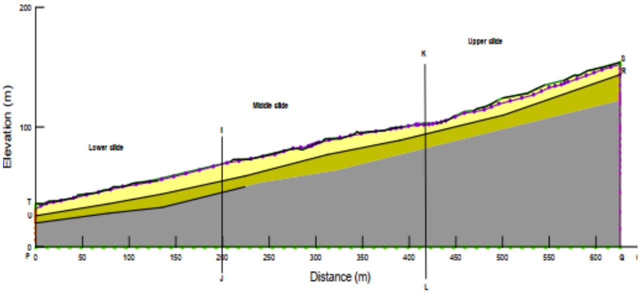

Figure 3. Long section idealized in SLOPE/W and SEEP/W

Table 4. Adopted seepage boundary conditions

Boundary condition	Type	Value
PQ, RS, TU	Total flux	0 m^{3}s^{-1}
PU, QR	Total head	Height of the sides

The steady state pore water pressure profile of the existing slope, derived from the steady state seepage analysis is presented in Figure 4.

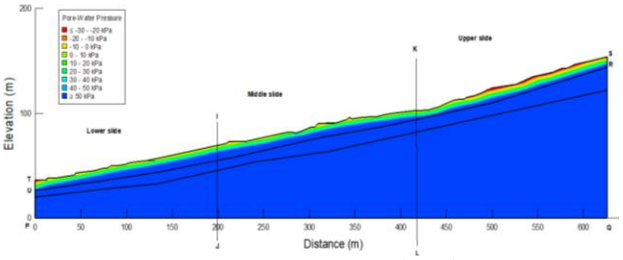

Figure 4. Pore water pressure contours profile of the slope

The blue colour shading indicates the positive pore water pressures below the ground water table. Yellow to orange colour shadings indicate the matric suction profile generated through the seepage analysis. The result from the initial steady state seepage analysis was taken as the input to transient seepage analysis, simulated for different rainfall and groundwater conditions, as described in the succeeding section.

4.4 Stability analysis with high ground water table condition

After establishing the initial pore water pressure profiles, the long section model was used to analyze the stability of the slope. In the case of Badulusirigama landslide, the location and the extent of the slip surfaces were confirmed by means of comprehensive site investigation and monitoring programme. Hence, the slip surfaces identified at the site during the site investigations and monitoring were pre-defined in the SLOPE /W module during stability assessment. The cross section A1 – A2 is reproduced in Figure 5 incorporating the fully specified failure surfaces used for stability analysis.

Another set of analyses were conducted to investigate the safety margins of a possible composite failure surface that combines the three failure surfaces. The three slip surfaces were identified at the site, based on the tension cracks observed at the surface, that separates the slides from one another. However, it is also possible that the three slides moved together through the common rupture surface present at the interface between weak, moderately weathered rock and the relatively strong highly weathered material. This will form one long sliding mass that starts from the upper area of the slope and ends at the toe of the slope.

The slope stability analysis was carried out using Spencer's method, which accounts for both force and moment equilibrium. Table 5 summarizes the safety margins obtained for each slip surface, under existing condition prior to any improvement.

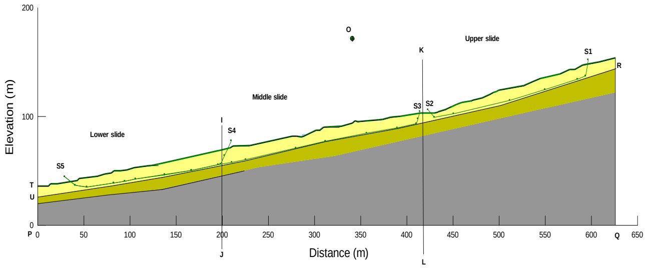

Figure 5. The slip surfaces of each slide are fully defined in SL OPE/W module

Table 5. Factor of safety values for prevailing conditions

Slide	Factor of safety
Upper	1.03
Middle	1.08
Lower	1.10
Composite failure	1.07

5 MODELLING THE EFFECTIVENESS OF RECTIFICATION MEASURES

5.1 proposed rectification measures

According to the information obtained from the field investigation surveys and monitoring programme, it was apparent that the Badulusirigama landslide was a slow moving (creeping) deep seated landslide in which the movements were accelerated during the periods of heavy rainfall. The main triggering factor is the prolonged rainfall and consequent rise of the phreatic surface. Apart from the development of perched water table conditions, increase of loading above the failure surface as a result of stagnant water bodies, were the main causative factors leading to slope movements. Therefore, the foremost focus when designing mitigation measures was to control the rise of ground water table during heavy precipitation events and direct the surface water paths away from the slope.

The main objective of introducing subsurface drainage was to lower the rising ground water table during infiltration events. In this context, altogether fifty one (51) number of subsurface drains have been installed at the site. The drains have been grouped in fans named from A to F (Figure 6). The first three fans (i.e. A, B and C) composed of eight (8) drains and the rest has nine (9) drains each. The drains are 3 to 5 degrees inclined to the horizontal plane. Figure 6gives a plan view of the subsurface drainage arrangement. Figure 7 shows the elevation of each drainage fan in relation to section A1- A2.The lengths of the subsurface drains are being varied in between 45 to 60 m. Drains are designed to outbreak the potential slip surface by 5 to 10 m distance. The tip interval of individual drains of the fan varies from 5 to 10 m. Each fan (drainage group) has a footprint of approximately 1800 m^2.

In combination with sub-surface drainage measures, surface drainage ditches have also been designed aligning with natural channels to eliminate the infiltration and spring flow. The total length of the surface drainage ditches are 861 m.

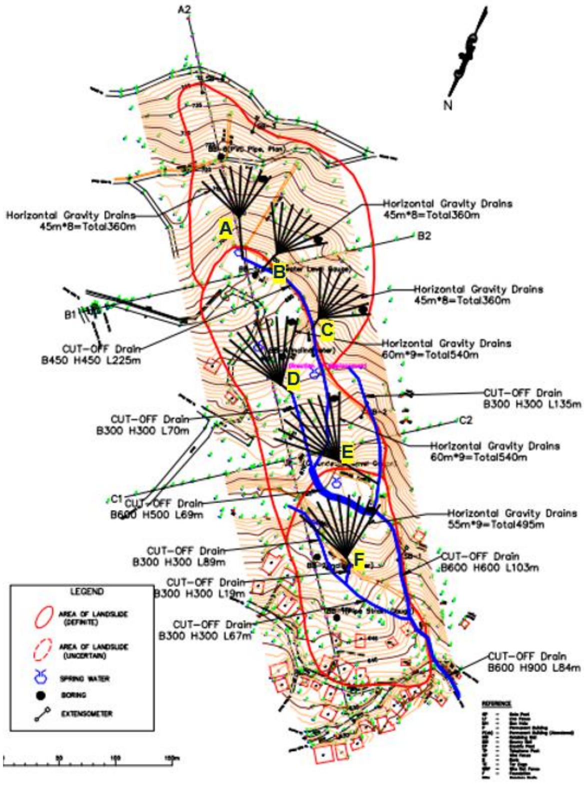

Figure 6. Plan view of the proposed drainage improvement

5.2 Simulation of subsurface drainage

Drains were simulated as lines in the SEEP/W model as shown in Figure 7. The "Seepage boundary condition" option available in SEEP/W module was used for the sub-horizontal drains. When this boundary condition is used, the software initially assigns zero flux boundary condition at each drain and then reviews the boundary condition by the maximum pressure. Thus, if the calculated pressures at the drain nodes are greater than zero, solver automatically sets the nodal pressure values to zero. In other words, the total heads at the nodes are always kept equal to respective elevation head. This type of boundary condition permits the water out from the system if the pressures in the surrounding are positive or zero. Furthermore, this boundary condition does not allow water draining into the soil, in case of negative pore water pressures in the surrounding soil. Therefore, the drain would not become a source of water when the surrounding soil is unsaturated. This allows for the possibility of water table drop below the level of the drains during longer dry periods, representing the condition that would occur naturally.

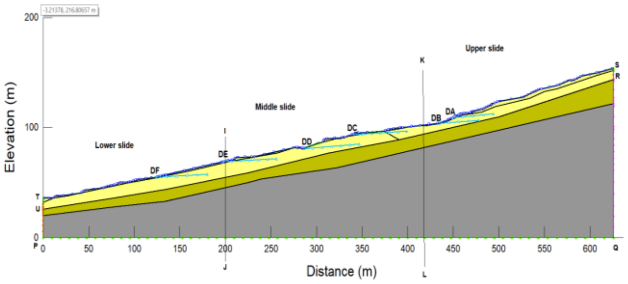

Figure 7. Drains simulated in the section A1 - A2

5.3 Performance of the slope during implementation of rectification measures

After implementing the sub-horizontal drains in the model, the improvement of the slope during the implementation of drains, were investigated. Two construction sequences;

Case 1: Simulating top – down construction of drains

Case 2: Simulating bottom – up construction of drains, were studied to investigate the effect of the drain construction sequence (Table 6) on the stability improvement. Assessing the construction sequence of the drains also provides understanding on the effectiveness of each drain on the overall stability improvement.

Table 6. Summary of drain installation sequence under each case considered

Construction timeline	Installed drains under Case 1	Installed drains under Case 2
At the start	A	F
After 03 days	A,B	F,E
After 06 days	A,B,C	F,E,D
After 09 days	A,B,CD	F,E,D,C
After 12 days	A,B,C,D,E	F,E,D,CB
After 15 days	A,B,C,D,E,F	F,E,D,C,B,A

The transient analysis was set to continue for further 30 days after the completion of drain installation. Accordingly, the total time duration for each case was 48 days. The reason for extending the analysis for further time steps is to observe the temporal variation of the pore pressures, flow rates through drains as well as behaviour of the overall slope in terms of stability. No infiltration conditions were simulated during the period of construction.

Variation of the factor of safety of the three slides as well as the possible composite failure, under the two cases during the construction, are presented in Figure 8.

5.3.1 Case 1: Simulating top-down construction of drains

A noticeable improvement of the FoS of the upper slide (to 1.1) could be observed after the installation of Drain-A (DA). Safety margins have further increased to 1.2 since the installation of Drain-B (DB). Thereafter the installation of successive drains did not have a significant impact on FoS of the upper slide. In contrast, installation of first three drains does not significantly contribute to enhance the FoS values of middle and lower slides. FoS of the middle slide has increased from 1.15 to 1.30 after the installation of DD. Further, increments in the FoS of the middle slide can be seen corresponding to installation of the next two drains (i.e. DE and DF). The FoS of the lower slide has not increased during the installation of the first five drains. With the installation of the final drain DF, factor of safety of the lower slide has gained a significant improvement from around 1.1 to 1.3.

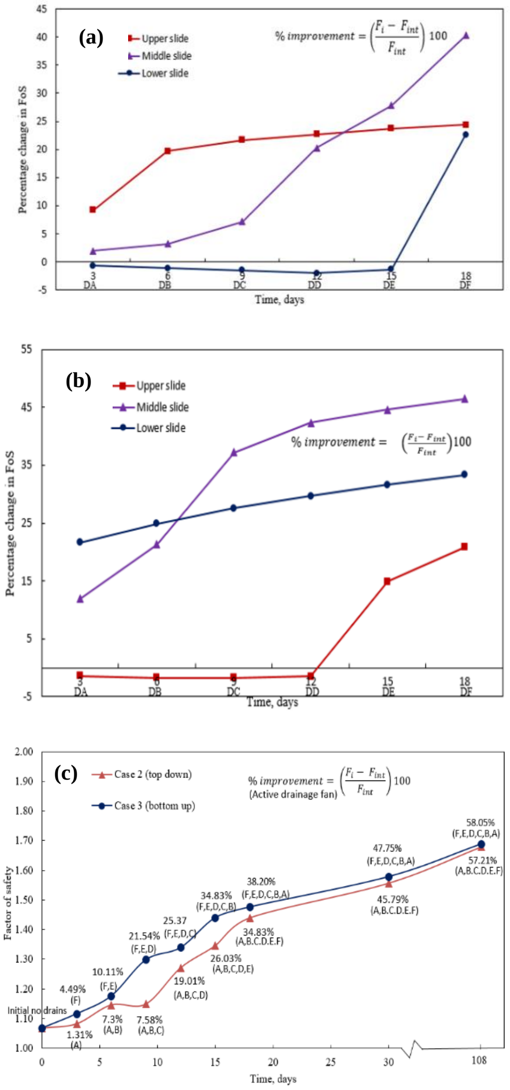

Figure 8. Variation of the factor of safety with drainage improvement (a) Case 1 (b) Case 2 (c) Case 1 and 2 for composite slip surface

5.3.2 Case 2: Simulating bottom–up construction of drains

The lower slide has gained a FoS improvement with installation of DF. Thereon, FoS of the lower slide increases at a uniform rate with the installation of rest of the drains. However, a FoS value of above 1.4 has gained since the installation of DC. Installation of drain DF caused some enhancement of the FoS of middle slide. Rapid improvements of the FoS values are noticeable in the middle slide, soon after the installation of DE and DD. The FoS value of the upper slide has gained a significant improvement only after the installation of DB. During the installation of four previous drains DF, DE and DD, FoS of the upper slide has only increased marginally.

In the composite slope, the rate of FoS improvement is rapid when the drains are constructed in bottom-up sequence. After a period of about 90 days (3 months) since the completion of the construction of drains, FoS achieved under both construction sequences (i.e. Case 1 and Case 2) has become similar.

5.4 Performance of the rectified slope with subsurface drainage system during a typical rainfall event

An actual critical rainfall event (the most critical rainfall event since the installation of the monitoring system) occurred during the period of 01st of December 2014 to 31st of December 2014 was applied on the slope to investigate the performance of the subsurface drainage measures, during a subsequent critical rainfall. Rainfall event was simulated as a unit flux boundary condition, varying with time.

As illustrated in Figure 9(a), the factors of safety of all three slides remain more or less unaltered until the rainfall event on 17th December 2014 occurs. The rate of decrease in factor of safety is almost same for the top two slides and was comparatively high for the lower slide. After the critical rainfall event of 216 mm on 25th December 2014, factor of safety values have significantly decreased. Factor of safety values of all the slides tend to increase after the cessation of the rainfall event on 25th December 2014 despite the occurrence of some minor rainfall events. Figure 9(b) shows the factor of safety variation of the composite slope during the rainfall event. Factor of safety starts to drop after the 50 mm rainfall on 65th day. Minimum factor of safety after the rectification measures has been recorded on the 79th day, which is six days after 215 mm rainfall event on day 73. Nevertheless, the safety margin of the slope is still well above the value of 1.40.

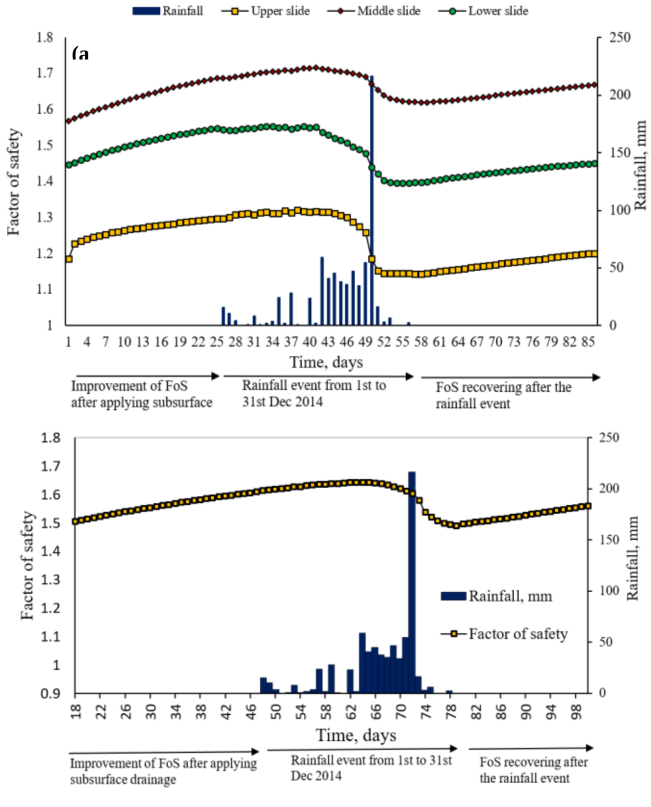

Figure 9. Variation of factor of safety with response to the critical rainfall event simulated :(a) For three individual slides, (b) Composite slide

Further to the study presented in this paper, a real scale three-dimensional analysis was also conducted simulating actual fan type drainage arrangements, using PLAXIS 3D software (Kankanamge 2020). Although there were differences in the numerical values of the safety margins, the response of the slope during drainage improvement and against the actual rainfall were similar.

6. CONCLUSIONS

Badulusirigama landslide located in central highlands of Sri Lanka was identified as a slow moving landslide which is at high risk during rainfall periods. This landslide was improved using long subsurface drains arranged in fan type configuration. The degree of improvement in the stability of the landslide due to the implementation of subsurface drains were investigated in this study.

The numerical analysis conducted in 2D plane strain formulation, considering different internal and external factors that govern the stability of a slope, indicates that the use of subsurface drainage networks in the Badulusirigama landslide has substantially improved the stability of the slope. Improvement of the factor of safety value of the slope is rapid when the subsurface drains are constructed commencing from the toe region of the slope. The sequence of drain installation had an impact on the gradual achievement of factor of safety. It was shown that, with a bottom-up sequence of drain installation, the safety margin as indicated by FoS, increased faster than in the case of a top-down sequence of installation. With the completion of the installation of all the drains, the final factors of safety achieved by the two different construction sequences were similar. The analysis also revealed that the improvement measures can maintain an acceptable margin of safety during rainfall events as high as 216 mm/day.

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