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Modelling the Effect of Wind Forces on Landslide Occurrence in Bududa District, Uganda

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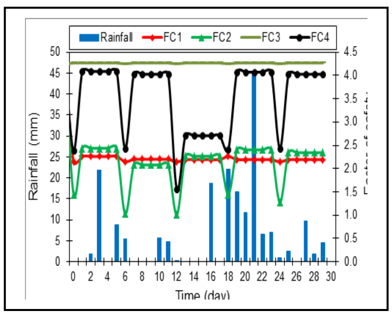
Graphical abstract



Abstract

The hilly area of Bududa District, in Eastern Uganda has suffered heavily from landslide occurrence, making the local populace unsafe. Although the area is well covered by vegetation, a catastrophic landslide occurred on the 26th June, 2012 and killed more than 18 people and wiped out the nearby community. The fallen trees due wind effect prior to the landslide coupled with intense rainfall are believed to trigger that landslide. Therefore, the effect of commonly known causative factor of rainfall and an uncommon landslide causal factor of wind forces on landslide occurrence were investigated in this study. The geometry of the modelled slope consists of 111 m height, 480 m length, and an inclination of 21°. Finite element seepage software, Seep/W and limit equilibrium software, Slope/W were used for modelling the landslide occurrence using five (5) slope models with and without additional shear strength in form of tree root cohesion. Each of the slope models was subjected to four failure criteria (FC). The first two failure criteria (FC1 and FC2) are assigned for group of tree along the slope (FC1) and a single tree at the middle (FC2) of the modelled slope. The other two failure criteria (FC3 and FC4) are assigned for the modelled slope with rainfall infiltration alone and rainfall plus several tree weights, respectively. The wind speed during which the landslide occurred was depicted using Beaufort wind scale 11 and was applied to the appropriate models. The results obtained show that with eucalyptus trees of Diameters at Breast Heights (*DBH*) of 25 cm, a minimum factor of safety (*FOS*) of 1.012 and 1.273 were recorded for FC2 in Slope model 1 and slope model 4 with and without increased cohesion, respectively. This shows an increase in the *FOS* of 23.81%. However, when the *DBH* was increased to a maximum of 60 cm (i.e. in slope model 3), the safety of the modelled slope diminishes and the *FOS* reduces to 0.601 for FC2 on the 25th day, without cohesion, just some hours before the fateful day of the 26th June 2012. This *FOS* remained below 1.0 (0.800 to 0.601) for FC2 with roots cohesion, although a gain in the *FOS* of 33.11% was realized. Hence, it can be concluded that the uncommon natural causative factors of wind have a great influence on landslide occurrence in the hilly areas of Bududa district.

Keywords: Wind force, beaufort wind scale 11, diameters at breast heights, root cohesion, factor of safety

Abstrak

Kawasan berbukit di daerah Bududa, Timur Uganda telah mengalami banyak kejadian tanah runtuh dan membuat penduduk tempatan berasa tidak selamat. Walaupun kawasan ini diliputi oleh tumbuh-tumbuhan, bencana tanah runtuh telah berlaku pada 26 Jun 2012 dan mengorbankan lebih 18 nyawa dan memusnahkan penempatan penduduk yang berhampiran. Pokok-pokok yang tumbang kesan daripada angin kencang sebelum kejadian tanah runtuh itu ditambah pula dengan hujan lebat dipercayai menyebabkan berlakunya tanah runtuh tersebut. Oleh sebab itu, kajian ini bertujuan untuk mengkaji kesan faktor penyebab iaitu hujan dan faktor daya angin yang luar biasa. Geometri cerun yang dimodelkan dengan ketinggian cerun, panjang dan sudut cerun, masing-masing 111 m, 480 m, dan 21°. Perisian kaedah unsur terhingga resapan, Seep / W dan perisian keseimbangan had, Slope / W digunakan bagi memodelkan kejadian tanah runtuh tersebut dengan menggunakan lima model cerun yang berbeza tanpa dan dengan kekuatan ricih tambahan daripada kejelikitan akar pokok. Setiap satu model cerun, adalah tertakluk kepada empat kriteria kegagalan yang berbeza (FC). Dua kriteria kegagalan yang pertama (FC1 dan FC2) bagi mewakili kumpulan pokok di lereng bukit (FC1) dan sebatang pokok dil tengah bukit (FC2) bagi pemodelan cerun. Manakala dua lagi kriteria kegagalan (iaitu FC3 dan FC4) pula mewakili model cerun dengan penyusupan hujan semata-mata dan hujan beserta dengan berat pokok. Kelajuan angin di mana kejadian tanah runtuh itu berlaku digambarkan menggunakan skala angin Beaufort 11 dan telah diaplikasikan pada model yang sesuai. Keputusan yang diperolehi menunjukkan bahawa Cerun model 1 dengan pokok-pokok kayu putih yang mempunyai Diamter Pada Aras Dada (DBH) sebanyak 25 cm menghasilkan faktor minimum keselamatan (FOS) daripada 1.012 dan 1.273 direkodkan bagi FC2 untuk Model Cerun 1 dan Model Cerun 4 iaitu dengan dan tanpa penambahan kejelikatan. Ini menunjukkan pertambahan FOS sebanyak 23.81%. Walau bagaimanapun, apabila DBH ditingkatkan kepada 60 cm maksimum (model cerun 3), FOS dikurangkan kepada 0.601 untuk FC2 pada hari ke-25, tanpa kejelikitan, hanya satu jam sebelum hari kejadian pada 26 Jun 2012. Nilai FOS kekal di bawah 1.0 (0.601-0.800) untuk FC2 dengan kehadiran kejelikitan akar, walaupun peningkatan dalam FOS sebanyak 33.11% telah dicapai. Oleh itu, faktor penyebab semula jadi iaitu angin yang luar biasa mempunyai pengaruh besar dalam kejadian tanah runtuh di kawasan berbukit Bududa, Uganda.

Kata kunci: Daya angin, skala angin Beaufort 11, diamter pada aras dada, kejelikitan akar, faktor keselamatan

1.0 INTRODUCTION

Landslide is among the most important landform shaping processes that may lead to minor or major economic consequences worldwide [1, 2]. In the United States of America alone, Lepore *et al.* [3], reported an economic loss of one to two billion dollar per year due to landslide disaster. It is a major geological phenomenon that includes a wide range of ground movements such as rock falls; deep-seated failures of slope and shallow debris flows that can bury a settled community in just a matter of seconds [4], and its occurrence accounts for thousands of sudden global deaths every year [5, 6].

Several tropical countries experiencing periods of intense and prolong rainfall events are vulnerable to rainfall-induced landslides. In the East African countries; Uganda and Kenya have suffered majorly from the tragic of landslides since the twentieth century [7]. In Kenya for example, Ngecu and Mathu [7] reported a severe landslide that occurred at Gatara village in Murang'a District in central Kenya in 1997. The landslide was facilitated by heavy rainfall which saturated the tertiary Basalt agglomerates and tuffs. In the same year, Ngecu and Mathu [8] reported another landslide along the Thika – Murang'a highway, which also washed away more than 1 km section of that highway.

In Uganda, International Disaster Response Law (IDRL) [9] reported that more than 31 % of the total population in Uganda lives in mountainous areas, and are therefore potentially vulnerable to landslides, which are more frequent in the mountainous regions of Mbale, Kabale, Kisoro, Sironko, Kapchorwa and the districts in the Rwenzori region. For instance, according to Ngecu and Mathu [7], one of the most destructive and largest landslide occurred in Bugobero village of Eastern Uganda in 1997. This landslide moved more than 100,000 m^3 of earth material over 2.5 km down slope. It completely destroyed houses and plantations along its course. It similarly killed seven people and injured several others.

According to report by Uganda Red Cross Society [10], severe landslide buried more than 385 people in a densely populated Bukalasi Sub County, Nametsi parish in Nametsi village in 2010. The landslide was triggered by rainfall and it occurred after it rained heavily and continuously for six days. Similarly, Uganda Red Cross Society [11], reported another landslide in Bulucheke Sub County, Bumwalukani Parish. This landslide occurred in 2012 and it buried the whole villages of Namanga and Bunakasala in Bududa District. Surprisingly, most of the slopes in these areas were covered by eucalyptus trees which were nearing maturity but all were swept down the slope with a huge soil mass. Therefore, this landslide is believed to be triggered by continuous rainfall coupled with windy storm elements.

The Mountainous region of Bududa District has records of heavy rainfall, with cases of strong winds reported in some areas, and landslide occurrence has never dwindled. Scores of people have perished year in year out but detailed systematic geotechnical studies has remained a main concern, specifically to the people of Bududa as well the government of Uganda.

Therefore, this study was selected to systematically study the effect of wind forces on landslide occurrence on slope with eucalyptus trees. A particular period (i.e. June 2012) where a catastrophic landslides occurred in Baduda district was considered in this study. Soil properties and climatic condition from the area were employed in the modelling process. Similarly, the wind forces determined from the wind speed recorded during the event were as well used. A numerical analysis using Seep/W [12] and Slope/W [13] was employed for modelling the landslide occurrence.

2.0 MATERIAL AND METHODS

2.1 Site Description

The study area is located in Bududa district, Eastern Uganda. The area is located at latitude 01° 01'51"N and Longitude 34° 25'19"E. It stretches from an altitude of 1643 m down to an elevation of 1532 m above mean sea level and is characterized by steep slopes with V-shaped valleys indicating river incisions [14]. The slope is typically inclined at about 21°. There has been a little disparity in the level of annual precipitation from 2010 to 2012 [15], with the minimum annual precipitation of 2113.2 mm recorded in 2011 and the highest value of 2218 mm recorded in 2012. However, the annual average rainfall in the area is above 1500 mm. The area is densely populated with about 952 persons per square kilometer in some areas [14].

2.2 Laboratory Experiments

The study commenced by determining the relevant soil properties which would be used and characterized the soil from the study area. Similarly, the input soil parameters required in the numerical analysis were also determined. These soil properties include, particle size distribution, Atterberg limits, specific gravity, shear strength and saturated hydraulic conductivity functions (k_{sat}). These properties are determined using recommended procedure outlined in the British Standard [16]. The relevant soil properties used in the numerical analysis include, Soil Water Characteristic Curve (*SWCC*), suction-dependent hydraulic conductivity function, rainfall data and wind force. The *SWCC* was determined using pressure plate equipment based on recommended procedure outline in ASTM [17]. The suction-dependent hydraulic conductivity curve was estimated from various *SWCCs* and soil k_{sat}s using van Genutchen method [18]. The rainfall data of the study area was obtained from Uganda Meteorological Department [18]. Wind forces corresponding to various *DBH* values were determined based on Beaufort wind scale 11. The summary of the soil properties is tabulated in Table 1.

2.3 Numerical Modelling

The numerical analysis commences by running several steady state analysis to establish the soil initial condition which is estimated as 50 kPa (i.e. matric suction at the residual water content). Upon achieving the initial condition, the transient seepage analysis were then performed with the actual rainfall condition from the study area. The generated pore-water pressure distribution from the seepage analysis was exported to Slope/W for the slope stability analysis. An infinite slope model was adopted because the depth of failure at the site was much less than the length of the failure. Four failure criteria were considered for the numerical modelling.

Table 1 Summary of the soil properties for the modelled slope used in the study

Property	Silty clay	Sandy silt	Silty gravel
Liquid limit, (%)	46.4	59.3	53.2
Plastic limit (%)	19.4	31.9	35.5
Plasticity index (%)	27	27.4	17.7
Moisture content (%)	29.9	32	32
Specific gravity, G_s	2.67	2.65	2.63
Effective cohesion, c (kPa)	7.07	7.6	3.3
Effective frictional angle, ϕ' (°)	33.4	32.1	39.5
Coefficient of permeability, k_{sat} (m/s)	8.0×10^{-7}	5.0×10^{-7}	2.81×10^{-6}
Saturated unit weight, γ_{sat} (kN/m^3)	17.91	18.54	18.05
Dry density, γ_{dry} (kN/m^3)	13.79	14.15	13.66

The first two failure criteria (i.e. FC1 and FC2) were assigned for group of trees on the slope (FC1), and for single tree at the point of the slope (FC2) of the modelled slope. The other two failure criteria (i.e. FC3 and FC4) were assigned for slope models with rainfall infiltration alone and rainfall infiltration plus several tree weights, respectively.

Other parameters required in the numerical modelling, include the root cohesion, wind forces and the weight of the tree. A pull out test to determine the root tensile strength (Δc) is beyond the scope of this work, therefore it was not conducted in this study. However, a value of 5 kPa was assumed for the root tensile strength. This value of 5 kPa is in accordance with root cohesion values recommended by other researchers such as Chiaradia *et al*. [19] who conducted a study on tree root strength in Italy and found that the maximum available rooted soil cohesion was 5 kPa. Similarly, Lateh and Ramadhansyah [20], found the roots cohesion value to range between 5 kPa and 10 kPa in a gullied slope along East-West highway in Malaysia.

The tree weight was calculated from an empirical formula that relates the *DBH* and the height of the tree (*H*). This formula (Equation 1) was given by Michelle *et al*, [21] and was initially derived by Myers *et al*. [22].

$$W_T = (1.6402)\ DBH^{2.199} H^{0.406} \quad (1)$$

Where; W_T is the weight of tree in pounds (lbs), *DBH* is the Diameter at Breast Height in inches (in) and *H* is the Height of the tree in meters (m).

However, the height (*H*) of the tree, was calculated from the Tree Crown Area (C_a) which in turn depends on the height of crown base (H_{CB})and the Tree Crown Width (C_w). The H_{CB} was calculated from an empirical formula (Equation 2) reported by Nutto *et al*. [23]. This empirical formula also relates *DBH* and *H*.

$$H_{CB} = -5.12 - 0.407DBH + 1.193H \quad (2)$$

The C_w of the tree was determined using equation 3 which is also reported by [23] and the C_a of the tree is obtained by multiplying H_{CB} by C_w by the shape coefficients [24]. The shape coefficient ranges from 0.25 to 1.0 depending on the shape description.

$$C_w = e^{0.504+0.0307*DBH} \quad (3)$$

According to Uganda Red Cross Society (URCS) Report [25], a representative sample of the eucalyptus trees brought down by the landslides was realized to have an average tree height (*H*) of 25 m. Therefore, DBH of 25, 30 and 60 cm were used in this study for assumed eucalyptus tree height of 25 m.

3.0 RESULTS AND DISCUSSION

3.1 Constant Wind Load and Various Tree Weights

The determined wind load and the tree weight using Equations 1-3 are presented in Table 2. These loads are restricted to Beaufort scale 11 which relates to the situation in study area and are determined for eucalyptus trees with *DBH* values of 25, 30 and 60 cm, respectively.

In all the five slope models, both the wind load and the self-weight of the eucalyptus trees with different *DBH* values are used and they are represented as point load or line load.

Table 2 Summary of the tree weight and the wind load for the eucalyptus tree for various DBHs

DBH (cm)	Height (m)	Crown width C_w (m)	Crown area C_a (m²)	Tree weight, W_T (kN)	Wind load (kN)
25	25	3.57	18.67	6.8	10.35
30	25	4.16	26.01	10.15	14.42
60	25	10.44	129.06	45.58	71.57

3.2 Influence of Tree Distribution and Tree *DBH* on Landslide Occurrence

The results of the numerical analysis obtained for the four failure criteria on the influence of the tree distribution and *DBH* values on landslide occurrence are discussed under this sub-section.

3.2.1 Model Slope 1 (DBH of 25 cm)

The results obtained from the slope model 1 with eucalyptus trees with *DBH* of 25 cm based on the assumed failure criteria is presented in Figure 1. Tree distribution was pivotal to the realization of the result of the landslide occurrence after running a coupled seepage and limit equilibrium analysis of Seep/W and Slope/W [12,13]. The modelling result from the model slope 1 shows FC2 as the critical failure criteria with a tremendous decline in the factor of safety from the initial value of 4.25 to 1.012, just after the thirteenth day. However, the factor of safety increases to a value of 2.263 before it decreases to 1.444 again on the eighteenth day and finally to a factor of safety of 2.341 even up to the fateful day. With the tree of *DBH* 25cm, all the failure criteria (FC1, FC2, FC3 and FC4) registered factors of safety greater than 1.0, hence giving the minimum stability condition of the slope to landslide occurrence when subjected to different environmental conditions. Less fluctuation of factor of safety was observed due to FC1, this may be attributed to the distribution of the trees along the slope.

3.2.2 Model Slope 2 (DBH of 30 cm)

The results obtained from the slope model 2 with eucalyptus trees with *DBH* of 30 cm based on the four failure criteria is presented in Figure 2. These results indicate FC1 and FC2 as the most critical failure criteria, showing the beginning of failure with the minimum factor of safety of 0.826 on the seventh day in FC2. The modelling result from the model slope 2 also shows that FC1 registered a tremendous decline in the factor of safety from the initial value of 4.25 up to 0845, just after thirteenth day.

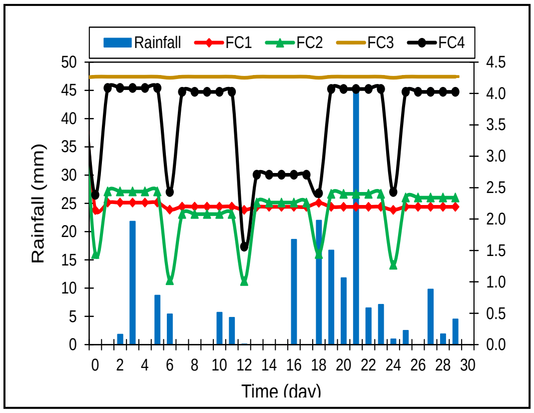


Figure 1 Failure trend of slope model 1 with various FC criteria for *DBH* of 25 cm

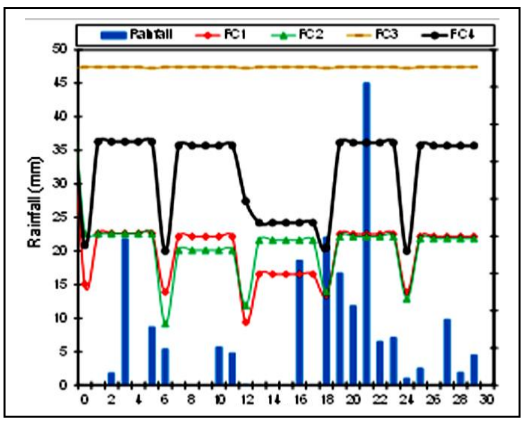


Figure 2 Slope model 2, with failure beginning in FC1 and FC2 with *DBH* of 30 cm

With the tree of *DBH* 30 cm, the remaining failure criteria (i.e. FC3 and FC4) registered factors of safety greater than 1.0, but since the slope has shown a sign of failure, there is a possibility of landslide occurrence on model slope 2 any time when subjected to different environmental conditions. Lower factor of safety were observed in this slope model compared to slope model 2. This shows that an increase in DBH to 30 cm has resulted in decrease of factor of safety.

3.2.3 Model Slope 3 (DBH of 60 cm)

The result of the stability analysis for the model slope 3 is presented in Figure 3. The factor of safety for model slope 1 dropped significantly from the initial condition value of 4.25 to a stable value of 1.012 with FC2. However, the factor of safety for the model slope 3 registered failures in other three failure criteria (i.e. FC1, FC2 and FC4) after including the first rainfall set of day one in the modelling. The model slope continued to regain strength and at the same time declining in stability at the end of a rainfall set after every six days and the trend of failure is seen even with a minimum factor of safety of 0.562 (FC1) on the 25th day before the landslide eventually happened on the 25th June 2012. This shows signs of total slope failure which triggers the landslide. The slope remained stable only with FC3 (bare slope). It shows that *DBH* of 60 cm produces very large weight for the over turning moment in the slope stability analysis.

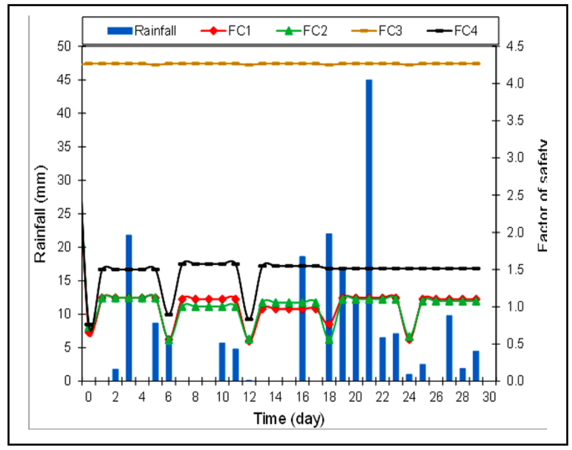


Figure 3 Failure trend of slope model 3 with FC1, FC2 and FC4 showing failure for *DBH* of 60 cm

3.3 Influence of Tree Distribution, Tree *DBH* and Root Cohesion on Landslide Occurrence

The results of the numerical analysis obtained for the four failure criteria on the influence of the tree distributions, *DBH* and root cohesion on the landslide occurrence are discussed in the following sub-section.

3.3.1 Model Slope 4 (DBH of 25 cm plus Root Strength)

The results obtained from the slope model 4 with eucalyptus trees and *DBH* of 25 cm based on the assumed failure criteria is presented in Figure 4. From the results of the analysis, the factor of safety increases with failure criteria. FC1 realized a minimum increase in the factor of safety of about 12 .99% on the first day of the analysis and the maximum increase in the factor of safety of 106.63% on the13th day due additional cohesion of 5 kPa on the top layer of silty clay soil. For FC2, the minimum increase in the factor of safety 19.32% (from 1.273 to 1.519) on the 25th day, with a maximum increase in the safety factor being 32.6% obtained from 2nd to the 6th day. The factor of safety of the initial slope condition also increased by 3.98% (from 4.250 to 4.419) as a result of root cohesion on the top layer of the silty clay material and such increase in the factor of safety also manifested in FC3 and FC4 as well. Hence, the slope showed great improvement in the resisting force due to additional cohesion from tree roots.

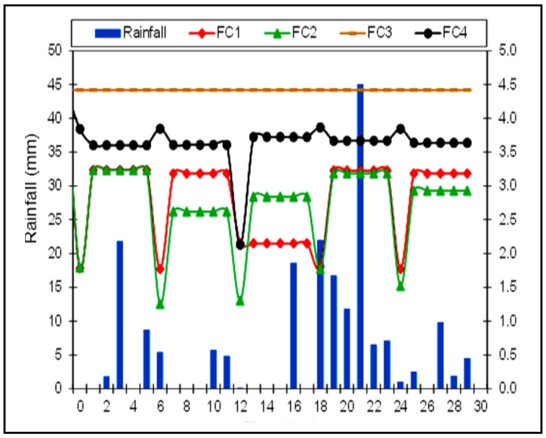


Figure 4 Increment in the factor of safety of slope model 4 due to increased cohesion for *DBH* of 25 cm

3.3.2 Model Slope 5 (DBH of 60 cm plus Root Strength)

The results obtained from the slope models 5 with eucalyptus trees with *DBH* of 60 cm based on the assumed failure criteria is presented in Figure 5.

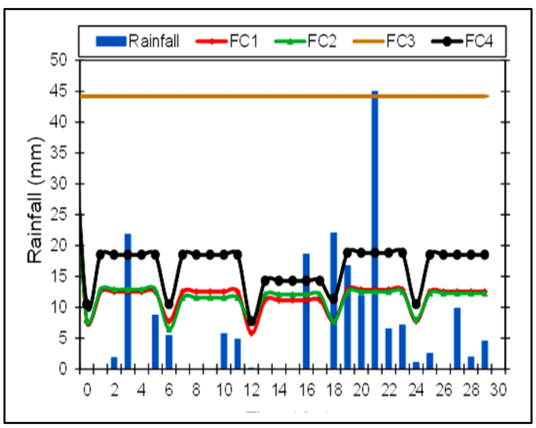


Figure 5 Improvement in the factor of safety for slope model 5 after additional cohesion from the roots *DBH* of 60 cm

These results also shows that factor of safety increases with failure criteria and the minimum increase in the factor of safety was 0.009% (i.e. from 0.767 to 0.774) on the 19th day and the Maximum was 37.54% between the 2nd to the 6th day which is obtained from FC1. For FC2, the minimum increment in the factor of safety was 8.37% realized on the 1st day (i.e. from 0.729 to 0.790) and the maximum was 37.54%, obtained on the 19th day with all other increments in the factors of safety of more than 13% for FC2. The factor of safety of the initial slope condition also increased by 3.8% (i.e. from 4.250 to 4.419) as a result of root cohesion on the top layer of the silty clay material and such increase in the factor of safety also manifested in FC3 and FC4. Hence, the slope showed great improvement in the resisting force.

3.4 Influence of Additional Tree Cohesion on Factor of Safety of the Slope

The effect of additional cohesion from tree roots on the factor of safety of the slope due to the four failure criteria is presented in Figure 6. The additional cohesion results in an increase in the factor of safety of the slope due to an increase in the resisting forces along the potential slip surface. The variations in the factor of safety follow similar pattern in both cases.

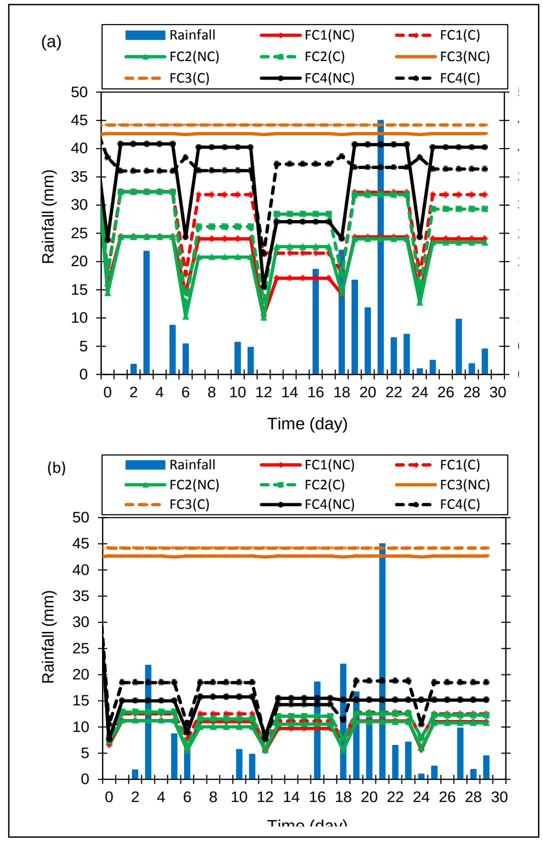


Figure 6 Comparison of factor of safety due to root cohesion (a) *DBH* of 25 cm (b) *DBH* of 60 cm (NC- with no cohesion and C-with cohesion)

3.5 Influence of Rainfall on Landslide Occurrence

Although the tree distribution varies in the five slope models analysed in this study, the failure criteria with rainfall infiltration alone (i.e., FC3) produced insignificant changes in the factor of safety when compared to other failure criteria. The factor of safety remained at the initial condition value of 4.25 for all the five slope models even though the *DBH* values were varied. This is because the area is well covered by vegetation which in turn intercepts the rainfall and facilitate run off generation compared to infiltration. However, FC4 shows cyclical trend in the factor of safety after modelling the slope with rainfall and tree weight of various *DBH* values. This signifies the significance of the tree in the stability analysis.

3.6 Summary of Results and Discussion

Five model slopes were used to model landslide occurrence in the hilly areas of Bududa District, with four different failure criteria (FC1, FC2, FC3 and FC4). The summary of the findings have been discussed in chronological order beginning with the model slope 1 as described below.

The modeling result from the model slope 1 shows FC2 recorded a tremendous decline in the factor of safety from the initial value of 4.25 up to 1.012, just after the thirteenth day. All other failure criteria registered factors of safety greater than 1.012.

From the assumed four failure criteria, the result of the Model slope 2 analysis shows the beginning of failure with the minimum factor of safety of 0.826 (FC2) on the seventh day and also in FC1 on the 13th day.

The model slope 3 continued to regain strength and at the same time declining in stability at the end of a rainfall set after every six days and the trend of failure was observed even with a minimum factor of safety of 0.562 (FC1) on the 25th day before landslide eventually happened on the 25th June 2012. This shows signs of total slope failure within FC1, FC2 and FC4 to trigger landslides.

Slope model 4 had its factor of safety generally increased with all failure criteria and the minimum increase in the factor of safety 12 .99% on the first day of the analysis and the maximum increase in the factor of safety of 106.63% on 13th day due additional cohesion of 5kPa on the top layer of silty clay soil.

The result of the analysis from slope model 5 shows that the factor of safety increases generally with all failure criteria and the minimum increase in the factor of safety was 0.009% (i.e. from 0.767 to 0.774) on 19th day and the maximum was 37.54% between the 2nd to the 6th day, observed from FC1.

Finally, from all the model slopes, FC3 indicate a full stability after considering the effect of rainfall infiltration only on the occurrence of landslide in the study area, implying that rainfall alone cannot trigger landslides in the hilly areas of Bududa.

4.0 CONCLUSION

Based on the outcome of this study, the following conclusions can be stated:

1. Slope model 1 with eucalyptus trees of *DBH* 25 cm, without consideration of additional shear strength from the roots yielded a minimum factor of safety of 1.012 for FC2, and when additional shear strength inform of root cohesion ($\Delta c = 5\,\text{kPa}$) was considered on the top layer of silty clay, the factor of safety increases to a minimum value of 1.253 for FC2. Looking at other failure criteria for Slope models 1 and 4, with eucalyptus trees of *DBH* 25 cm, with and without increase in cohesion respectively, all have factors of safety greater than 1.0, signifying high degree of stability and safety from landslide occurrence.
2. With *DBH* of 60 cm, the factor of safety reduced to 0.601 with FC2 on the 25th day, just some hours before the fateful day on the 26th June 2012 (Model 3) but an increase in the factor of safety by 33.11% (from 0.601 to 0.800) with FC2 as seen from slope model 4 due to an increased cohesion from the roots. The safety factors for critical failure criteria still less than the recommended threshold value of 1.0. Therefore for the maximum tree *DBH* of 60 cm, the stability of the slope was not fully guaranteed and this was considered to trigger the landslide on 26th June 2012.
3. The uncommon natural causative factors of wind have great influence on landslide occurrence in the hilly areas of Bududa.
4. Rainfall alone has less significant role in the landslide occurrence in Baduda. The landslides in the area occurred due to the combined effect of rainfall infiltration and wind effects.

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