The Use of Lidar Data and VHR Imagery to Estimate the Effects of Tree Roots on Shallow Landslides Assessment

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Abstract. The study of geo-hazards has been benefited from the technological advances in the field of Remote Sensing (RS) techniques as the ALS (Airborne Laser Scanners) Systems with Very High Resolution (VHR) cameras. Recently, the LiDAR (Light Detection and Ranging) is an active sensor technique used for a variety of geoscientific applications including slope monitoring to retrieve ground surface displacements at high spatial resolution. Additionally, LiDAR has been widely used in order to collect high-resolution information on forests structure for the determination and characterization of vegetation cover due its ability to capture multiple returns and to reach the ground, even in forested areas, allowing the generation of Digital Terrain Models (DTMs) for the estimation of forest variables. In this paper, a LiDAR dataset and VHR imagery from aerial survey was used in the southwest zone of Medellin City-Colombia where the most frequent landslides are shallow and triggered by rainfall. Slopes with gradients up to 30% on residual soils characterize the study area, having about of 30% of forest cover consisting predominantly of Eucalyptus and Coniferous forests. For the estimation of the tree roots effects on the shallow landslides assessment on a natural slope, interpolation processes were developed from the LiDAR 3D point cloud, obtaining DTMs of 1 m-pixel. Additionally, orthophotos with the same spatial resolution were acquired in the aerial campaign. The proposed workflow was implemented on a GIS platform, and considers the extraction of the tree heights by generating a Canopy Height Model (CHM), while for the delineation of the tree crown a process of image segmentation was developed. Once the vegetation has been characterized using LiDAR products and dendrometric relationships, the Limit Equilibrium Method (LEM) was used to evaluate slope stability considering the effect of vegetation (trees). The results indicate that the proposed workflow allows to obtain adequate stability indicators for the estimation of tree roots contribution and additionally, this RS technique allows saving resources in this kind of analysis.

1. Introduction
Shallow landslides are the most widespread natural hazards in the world, with an important economic impact and sometimes with tragic results in terms of fatalities. Different models have been proposed over the years to predict landslide hazard in terms of slope stability. A widely used approach is the Limit Equilibrium Method (LEM), where an estimation of the Factor of Safety (FOS) is based on physical and hydraulic data of soil and vegetation properties [1].

Several studies have shown that a switch from land use, land clearing (removal of vegetation) or deforestation processes joined to intensive rainfall events can increase landslides frequency making an area prone to landslides formation, especially in mountainous regions. For these reasons, vegetation has
been recognized to play a major role in the reinforcement and the protection of slopes against shallow landslides [2] decreasing the risk by mechanically reinforcing of soil.

LiDAR (Light Detection and Ranging) is one of the active optical Remote Sensing Technologies (RST) to collect topographic data, which emit laser light pulses to provide highly accurate measures of forest canopy and ground surface. A recent view of the literature shows the potential of LiDAR to monitor slope stability and detecting landslides [3–5] due the possibility to detect small deformations. Additionally, nowadays, this kind of RST provide rapid and Very High Resolution (VHR) geospatial data products for monitoring and characterization of vegetation. In the context of 3D mapping of vegetation, the emitted laser pulses by a LiDAR system can penetrate below the canopy [6] generating models of understory terrain elevations and top canopy surface heights [7].

The detection and extraction of features from VHR imagery is a fundamental operation in digital image processing, but few studies have explored the application of automatic approaches for the mapping of vegetation relevant features and its dendrometric relationships for slope stability assessment. Despite many studies have reported a positive contribution of tree roots on the shear strength of soil, the question of what is the best way to evaluate this influence is remaining [8]. For these reasons, this paper proposes a LiDAR-assisted methodology to evaluate the tree roots contribution in the stability of a natural slope through a GIS environment. Indirect computation of the contribution to soil strength exerted by roots using data of root characteristics (strength, length, distribution, spatial variability and morphology) reported in the literature were considered and, dendrometric relationships were established for developing numerical slope stability analyses using the Limit Equilibrium Method (LEM).

2. Materials and methods

2.1. Site Description

The study area is located in the humid tropic of the northwest zone of Colombia, on the south-western slope of the Aburrá Valley (AV), in the city of Medellin where the most frequent landslides are shallow and triggered by rainfall. Specifically, the area is centered on the coordinates 6° 13′ 48” N, 75° 36′ 52” W as shown in Figure 1. Generally, AV is an area influenced by the Intertropical Convergence Zone generating abundant precipitation with a bimodal distribution with a mean annual value of 1943 mm/year. Slopes with gradients up to 30% on residual soils characterize the study area. This area lies on a bedrock that consists of intrusive igneous rocks and gravitational deposits. Geomechanical properties of soils in study area were adopted from suggested values by [9]. Strength parameters and unit weight were assumed for each soil developed over aforementioned geologic units, independently of water table level, and they are shown in Table 1.

The vegetation in study area corresponds to a fragment of a forest planted mainly with large Eucalyptus (Eucalyptus grandis), and some species with lower abundance such as cypress (Cupressus lusitanica), yarumo (Cecropia angustifolia) and mango (Mangifera indica).

Table 1. Geomechanical properties of soils.

| Geologic Unit | Description         | Unit Weight (kN/m³) | Friction Angle (°) | Cohesion (kPa) |
|---------------|---------------------|---------------------|-------------------|---------------|
| Qll           | Filled Anthropic    | 19.0                | 17.0              | 10.0          |
| NFI           | Debris Flow Deposits| 14.8                | 32.0              | 28.4          |
| KdA           | Stock Altavista     | 15.9                | 34.4              | 27.4          |
2.2. Acquisition and processing of remote sensing data from study area

2.2.1. LiDAR dataset

A LiDAR survey of the study area was used. This survey was acquired on middle of 2013 using a Reigl sensor. The system uses discrete return near infrared laser pulses recording first and last returns per pulse. A flying height of 550 m above the ground, resulted in a mean nominal point density of 8 points per square meter (points/m²).

The raw LiDAR data for the study area was obtained in LAS format, containing a discrete point cloud of ground features with X, Y and Z coordinates. In the raw file, the elevation data corresponds to height above mean sea level, and it is contained in the Z values. The classification values were standardised by data provider according to ASPRS (American Society of Photogrammetry and Remote Sensing) as ground, low vegetation, high vegetation and building. This process involved an initial automated classification using software, which attained accuracies between 60 and 80% depending on terrain variation. A manual editing process aided by 0.5 m resolution orthophoto image acquired at the same time of aforementioned aerial survey followed this process.

Before generating LiDAR derived DTM, the spatial resolution was estimated according to [10] using average point density for the LiDAR dataset, obtaining a grid size of 0.35 m, but this size is not practical to use because long processing time and it is not suitable for infinite slope method for stability analysis. Therefore, in this research for rasterizing 3D point cloud data, a 1 m-pixel size was adopted.

2.2.2. Digital Terrain Models (DTM)

A stand level digital terrain model was created from the LiDAR ‘ground’ return layer. Filtering is used to generate DTM, assuming that terrain changes gradually and not abruptly. Since original LiDAR points were irregularly spaced, a continuous and hydrologically correct surface was created by estimating values for non-sampled areas using an interpolation method specifically designed for the creation of hydrologically coherent DTM. This method is based on the ANUDEM program, incorporated in ArcGIS software version 10.5 (ESRI, California, USA). At most one point used for generating a pixel height value. Whenever two or more points occurred within a pixel, the minimum point was utilized for the interpolation. A pixel size of 0.15 m was used in the interpolation process.

2.2.3. Digital Surface Models (DSM)

The DSM model is a raster image obtained from the elevation attribute of the first return of LiDAR point cloud, and the intermediate pixel are interpolated. The DSM was generated using a general process...
of interpolation in ArcGIS using a triangulated irregular network (TIN) from a LAS dataset and then, a
1 m-pixel size grid was exported by interpolating its cell values from the elevation of the input TIN.

2.2.4. Canopy Height Models (CHM)

CHM are the most common remotely sensed 3D vegetation measurements. The CHM represents the
height of the trees, it means, the distance between the ground and the top of the trees. Tree height models
can be produced using stereo-pair and multiple-stereo photogrammetry applied to images acquired from
aircraft and satellites, but now are most commonly produced using ALS systems, specifically LiDAR
remote sensing [7]. Surface heights can be derived by the subtraction of the DSM from the DTM,
resulting in normalized aboveground object heights. Stand-level CHM was generated at 1 m spatial
resolution.

2.3. Estimation of tree parameters using image segmentation, local maxima algorithm and
dendrometrical relationships

The tree parameters on the study area were extracted from LiDAR derived layers. They were
characterized using dendrometric characteristics considering the adjacent forest stand as reference. The
species of *Eucalyptus grandis* was considered as the reference species due to its abundance in the area.
The methodology for obtaining the variables from the remotely sensed data and by dendrometric
relationships is described below.

2.3.1. Tree Crown (TC)

TC delineation was done by using a technique known as segmentation. This technique was designed for
identifying the edges of a finite set of non-overlapping objects that subdivide an image into tessellated
regions. During this process, adjacent objects can be merged or divided based on specified criteria of
homogeneity. This research used the object-oriented classification method based on the mean-shift
algorithm provided in the open source software Orfeo Toolbox/Monteverdi (French Space Agency –
CNES, Paris, France), considering as input-parameter settings a spatial radius of 20, a minimum object
of 12, and a minimum region size of 100. Both the CHM and the image were resampled to a coarse
resolution to facilitate the segmentation process and reduce processing time. Therefore, 1 m-pixel CHM
model and 0.5 m-pixel RGB orthorectified image from the aerial
survey were used to improve the quality
of object-based image analysis for delineation process in the study area by using the spectral information
from the RGB bands and the TC edge information from the CHM.

2.3.2. Tree Height (TH)

Commonly, TH is remotely sensed and three-dimensionally captured in the form of a CHM. The CHM
was used to locate potential tree locations by identifying a pixel with maximum height within a
neighborhood using fixed size search windows. Some studies have shown that the application of a
smoothing filter to the CHM, prior to local maxima filtering, improves the distinctiveness of trees. In
order to estimate tree heights, individual tree crowns were first delineated using local maxima as
reference points of crowns. From each crown polygon, maximum height was extracted as estimates of
individual tree heights [13]. Values of these heights were calculated and compared with field-measured
height for some reference trees.

2.3.3. Diameter at Breast Height (DBH)

*DBH* refers to the tree diameter measured at 4.5 ft (approximately 1.3 m) above the ground. The *DBH*
(cm) was evaluated by means of Equation 1, modified of [14,15], once *TH* (m) was obtained using the
local maxima algorithm over CHM.

\[
DBH = \frac{1.4959 - \sqrt{1.4959^2 - 0.04767TH}}{0.0238}
\]  
(1)
2.3.4. Tree-Root System (TRS)
Tree root plates are modelled according to the root system morphology (heart-, tap- or plate-like root systems), using simple geometrical patterns (half-sphere, cone and cylinder) [16,17]. Eucalypt root systems are commonly ‘heart-rooted’ according to the classification used and reported by [18]. This TRS was adopted for this study. To define the radial zone of enhanced soil by roots reinforcement, it is necessary to establish the Critical Root Zone (CRZ). This zone is related to the minimum area of tapering roots supporting the vertical tree weight guaranteeing its healthy condition. CRZ was estimated according to the relationship for CRZ Radius (CRZR) that indicates an increment of 1.3 ft (0.39624 m) radius per 1 in (2.54 cm) of DBH [19].

2.4. Estimation of slope stability using Limit Equilibrium Method (LEM)
Hillslope stability can be evaluated schematically by applying limit equilibrium theory [20]. ‘Limit equilibrium’ means that a relationship is established between the shear strength of a material available to resist failure and some condition of shear forces which are present to cause failure [21].

Mohr–Coulomb’s theory of failure states that while failure is essentially by shear, the critical shear stress, \( \tau \), is a function of the normal stress as a combination of cohesion and frictional resistance acting on a potential surface of failure [21]. Mohr–Coulomb failure criterion can be modified to include the contribution of roots to soil shear strength of soils via an additional cohesion to the effective soil cohesion [22]. In this case, Equation 2 represents the shear strength of forest soil considering tree roots effects:

\[
\tau = (c' + c_R) + (\sigma_n - u_w)\tan\phi'
\]  

(2)

where: \( \sigma_n \) is the normal stress, \( u_w \) is the pore water pressure, \( c' \) is the intercept of the failure envelope with the \( \tau \), \( c_R \) is the additional cohesion component by tree roots, and \( \tan\phi' \) is the slope of the failure envelope. The term \( c' \) is often called the effective cohesion, and the angle \( \phi' \) is called the effective angle of internal friction.

2.4.1. Factor of Safety (FOS) considering vegetation effects, ground acceleration and soil saturation
The Mohr–Coulomb relationship is commonly expressed in the form of a ‘Factor of safety (FOS)’, a global indicator that enables to measure the degree of stability of a given slope [17]. The factor is expressed by the ratio of the fully mobilized soil shear strength. The nature of the defining ratio of FOS calculations means that unstable situations are represented by a number between 0 and 1 whereas stable considerations are represented by a number between 1 and infinity [23].

- **Effect of apparent cohesion (\( c_R \)) by tree roots**
Root reinforcement ranges from 1 to 12 kPa [2]. [24,25] demonstrated that Eucalypt roots potentially generate a reinforcement effect within the soil that is equivalent to an apparent cohesion of greater than 20 kPa for strongly root reinforced soil [23]. This study used a combined method of additional reinforcement in soils due to root effects based in Wu and Waldron Model [26], and according to suggested values of root reinforcement model for hillslopes by [27] and [23]. Hence, a value of 10 kPa for additional cohesion provided by roots (\( c_R \)) was applied in critical root zone (CRZ) of each tree (Figure 2). Additionally, a transitional \( c_R \) zone of 5 kPa was proposed to consider the woody transport roots [28]. The transitional \( c_R \) zone was assumed as the zone between the horizontal projection of tree crown area (dipline projection) and CRZ.

- **Effect of roots tensile strength (\( T_R \))**
\( T_R \) is a characteristic dependent on the tree species, root diameter and, the environmental and edaphic factors where trees grow. In this subject is extremely important to consider roots size which cross slip surface to stabilize a slope against landslides [29], because there is a relationship between \( T_R \) and root diameter, usually referred to a simple power function. Hence, \( T_R \) was estimated from the \( T_R \) power
regression equation suggested by [28] for Eucalyptus (Figure 2), obtaining a $T_R$ value of 8.9 MPa (8900 kPa) considering 10 mm of effective root diameter ($d_R$) suggested by [20] because provide a better contribution to slope stability. An angle $\theta$ between roots and slip surface of 90° (according to the suggested in [26]). This assumes the consideration of the maximum effect of $T_R$ value in stabilizing forces acting on the slope.

- **Effect of tree surcharge ($w_T$)**
  $w_T$ resists the tapering and affects the shear strength of a soil. $w_T$ might increases or decreases the overall slope stability depending on the type of soil and the slope parameters. The reference value used for tree surcharge in these calculations was 250 kg of vegetation per square meter (2.5 kPa) [21,30]. The tree load was assumed to be uniformly distributed throughout the calculated CRZ according to [31], taking into account the crown area of each tree (Figure 2).

- **Consideration of ground acceleration ($a_h$)**
  In this case, it was considered a distribution of accelerations determined by the Colombian Building Code NSR-10 [32] for the city of Medellín, located in a medium seismic hazard prone area because of its geographical position. For this reason, the effect of $a_h$ (fractions of $g$) on slope stability of the study area was evaluated adopting a value of $a_h = 0.2g$, taking into account the horizontal force ($F_h$) provided by an earthquake.

- **Consideration of soil saturation by rainfall**
  The condition of eventual soil saturation by rainfall is a random process that must be considered to assess the slope stability. For this reason, in this study two scenarios were considered for $h_w$: the first one was the presence of the water level (piezometric surface) in the most critical condition (saturated condition), i.e. $h_w = z$, and the second one was the most favorable condition (wet condition) where $h_w = 0$.

Finally, the expression for $FOS$ considering vegetation effects, ground acceleration and soil saturation is:

$$FOS = \frac{c' + c_R + [(yw - y_w h_w) \cos^2 \beta + w_T \cos \beta + T_R \sin \theta] \tan \phi' + T_R \cos \theta}{(yw \cos \beta + w_T \sin \beta + a_h y_w \cos \beta)} \quad (3)$$

where: $c'$ is the effective soil cohesion (kPa), $c_R$ is the soil cohesion due to the reinforcement of root matrix of vegetation along the slip surface (kPa), $y$ is the unit weight of soil (kN/m$^3$), $z$ is the vertical height of soil above the slip plane (m), $y_w$ is the unit weight of water (kN/m$^3$), $h_w$ is the vertical height of groundwater table above the slip plane (m), $\beta$ is the slope angle (°), $\phi'$ is the effective angle of internal friction (°), $T_R$ is the root tensile strength (kPa), $\theta$ is the cross angle of roots with respect to slip surface (°), $w_T$ is the vegetation surcharge (kPa), $a_h$ is the ground acceleration (fractions of $g$).

2.4.2. **Slip surface depth definition**

Plant height can give a rough estimate of root penetration [33]. An adult tree of Eucalyptus grandis can reach between 25 and 50 m in height with trunk diameters greater than 40 cm. Root reinforcement is effective if the shear plane of the landslide lies within the rooting zone. The effect of mechanical reinforcement by roots under a forest canopy is often limited to surface soil layers (90% of the roots in the first 50 cm of soil depth) [34].

Species such as Eucalyptus grandis concentrate the 80% of root volume in the first 60 cm of the soil [35]. Nevertheless, this root growth is influenced by the conditions of soil compaction. On the other hand, there is no conclusive evidence that the Eucalyptus populations exceed the water table [36]. Hence, considering the aforementioned explanations, a failure surface at 1 m-depth ($z$) was assumed to guarantee an assumed situation which at least a percent of roots crosses the margins of slip surface, and
that each root element be subjected to tension during the slope sliding process. This value of $z$ adopted is consistent with the values reported by [37] for instability phenomena that mainly affect surface deposits of reduced thickness, generally less than 2 m, i.e., shallow landslides.

![Diagram](image)

**Figure 2.** Schematic model for mechanical analysis

### 3. Results and discussions

Several scenarios (Figure 3) were evaluated to consider the vegetation effect in slope stability under wet and saturated condition of soil. In addition, static and dynamic conditions were taken into account for comparison of $FOS$ results. The first evaluated scenario was the consideration of bare soil without any additional contribution to stability. In this scenario, the results indicate that the majority of cells ($\sim 50\%$) have a $FOS$ value higher than 10 (stability condition), and the inclusion of the apparent cohesion of the tree roots (scenario two) provides a slight improvement in approximately 8% of the study area in both wet and saturated conditions. This proves that small increases in the order of up to 5 kPa in shear strength are sufficient to provide great improvements in slope stability [38].

The results of scenario three, considering tree surcharge ($w_T$), indicate a neutral to slightly negative effect ($\sim 1\%$) in both wet and saturated conditions. Overall, consideration of $w_T$ as a negative impact may be neglected in most cases because it is not significant. [22] and [21] found that tree surcharge have a very limited role on slope stability. $FOS$ calculated by the infinite slope equation is fairly insensitive to the values of $w_T$, particularly in soil depths greater than 5 ft ($\sim 1.5$ m). Moreover, the positive influence of root reinforcement ($c_R$) is more important than any adverse tree surcharge effects related to bank stability [8].

Scenario four raises the consideration of the tensile strength ($T_R$) of the tree roots that cross the slip surface, but this condition only occurs if the assumed planar failure occurs. Commonly, the trees have a
considerably high tensile strength than grass [31]; therefore, trees have stronger soil reinforcement and they will be more productive in terms of stability. This can be seen in Figure 3, where areas with presence of trees have higher FOS values due to the high influence of roots tensile strength in both evaluated conditions. It is notice an increase in FOS values (higher than 10) in approximately 10% of study area. It is important to highlight that root reinforcement decreased with increasing distance from trees. In addition, the results show certain influence of forest structure on root reinforcement and landslide susceptibility.

The results of scenario five indicate a general decay of the FOS values due to the action of the horizontal force ($F_h$) induced by an earthquake of $a_h = 0.2g$ in both wet and saturated conditions. Nevertheless, the morphometric characteristics of the slope, the geotechnical parameters of the soil and the contribution of the vegetation maintain the stability of the slope. Figure 3 shows a decrease in FOS values in approximately 35% of the study area, mainly in areas of vegetation clearings. Significant effects were found for the distance between trees (intergap zone) for root reinforcement in dynamic conditions. Gaps longer than 20 m critically increase the susceptibility to shallow landslides [39]. The position of trees on a slope, as well as their size and density, influences FOS more than root tensile strength [29] and as consequence, a large inter-tree distance leads to lower soil reinforcement in the slope direction [17].

**Figure 3.** Evaluated scenarios for Factor of Safety (FOS). *Static condition ($a_h = 0$):* A) Bare soil, B) Bare soil + Roots apparent cohesion ($c_R$), C) Bare soil + Roots apparent cohesion ($c_R$) + Tree surcharge ($w_T$), D) Bare soil + Roots apparent cohesion ($c_R$) + Tree surcharge ($w_T$) + Root tensile strength ($T_R$). *Dynamic condition ($a_h = 0.2g$):* E) Bare soil + Roots apparent cohesion ($c_R$) + Tree surcharge ($w_T$) + Root tensile strength ($T_R$)

### 4. Conclusions

The contribution of vegetation to slope stability has been determined by calculation of FOS of slope with and without plant roots present in the soil, under two hydrological scenarios (wet and saturated condition). A monospecific *Eucalyptus grandis* was used as a reference species in this study due to its abundance in the area. Nevertheless, it is important to consider the contribution in the shear strength of
soils and apparent cohesion by roots, the use of real root architecture for each species, it means, a diversity of root system shapes (each with different rooting strategies) and the hydrological influence of vegetation.

Despite the results (Figure 3) of the stability indicator of the natural slope of the study area do not indicate the occurrence of a potential shallow landslide (FOS < 1), these results indicate a contribution of the tree roots on the slope stability. Therefore, the proposed methodology becomes a reasonable alternative for the evaluation of shallow landslides using LiDAR technique and VHR geospatial data products from remote sensing technologies. Moreover, the observation and interpretation of RST products can contribute to a better understanding of the controlling physical processes and help in the assessment of hazards as shallow landslides.

The inclusion of values of apparent cohesion due to root reinforcement ($c_R$) and root tensile strength ($T_R$) in slope stability analyses have a visible influence on the decrease of factors of safety (favorable outcome) in both wet and saturated condition, even under a dynamic scenario. With regard to the effect of the tree surcharge ($w_T$), an almost neutral effect in terms of stability could be verified in the evaluated scenarios. It is important to highlight that the presence of vegetation reduces the likelihood of mass failure due to reinforcement of slope soils by tree roots.

Laser systems such as LiDAR offer possibilities to fulfill the needs of forest inventories and joint with VHR imagery can allow the characterization of vegetation in terms of species discrimination and the detection of forest structural attributes such as dominant tree height and crown size. LiDAR is useful for the generation of cartographic products that allows the assessment of shallow landslide considering the tree roots effects.

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