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EFFECT OF LAND USE ON SLOPE STABILITY

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ABSTRACT: Forest cover in Thailand had been decreased from 53 to 28 percent in 1961 to 1989. Thai government issued logging ban policy from 1989 until present, then forest loss is significantly decreased. Forest land had been changed to plantation and community areas. Consequently, Thailand loss more than 534 lives and 73 million USD of casualties on landslide from 1970 to 2007. This study is aiming for analysis the effects of root reinforcement on the watershed area for slope stability. Three different types of land use on the Mae Phrong–Mae Phun watershed were selected for comparison. This area was suffered by landslide in 2006 causing the loss of 75 lives. The area loss more than 63% of the forest to orchards and residential areas from 2000 to 2016. Three areas of land uses; original forest (F201), orchard (A401), and an old landslide area (F201–M103) are selected. Soil strengths with root reinforcements and the factors of safety (F.S.) of each land use were calculated. The root spreads and root densities on 1×1m area with 0.1m soil thickness on slope are considered in the models. The severe condition of prolong and heavy rainfall as occurred in 2006 with the saturated soil condition was assumed. The forest area (F201) had the highest average F.S. of 1.730. The F.S. on F201–M103 and A401 areas are not significant different of 0.976 and 0.982, respectively. Using the small grid size in the model could help to identify locations for potential landslides in the study area.

Keywords: Slope stability, Land use, Root reinforcement

1. INTRODUCTION

Landslides are a devastating natural hazard in mountainous areas and usually occur during heavy rain when water seeps into the soil, causing an increase in the soil unit weight and moisture content but a decrease in the soil strength. The causes of landslides are not only heavy rainfall. Changes in land use occur primarily due to increasing population causing the needs for more agricultural area. The natural forest in many watershed areas had been converted to cultivated mono-cropping land. Such deforestation and land use change removes deep–rooted forest tree to relatively shallower- and weaker-rooted trees [1-4]. The Mae Phrong–Mae Phun watershed (MPMP) was 105.65 km^2 in 2000, with forest area of 93.35 km^2 and plantation area of 6.87 km^2. In 2016, the forest area had reduced by 34.26 km^2 from 2000 to 59.09 km^2, while the plantation area had increased by 61.22 km^2 to 68.09 km^2 [5]. In 2000, Southeast Asia (including Indonesia, Malaysia, Laos, Thailand, and Myanmar) had a total tree cover loss of 13,070 km^2. Which was predicted to increase by 7.853% annually. In 2020, there was 24,350 km^2 of forest loss. The global percentage change of forest to plantation area is 19.86% [6, 7]. The landslide susceptibility will be higher when forest area is transformed into bare slopes, human buildings, or plantation. [8, 9].

Protection from landslide damage can be by structural or biological methods. Reforestation and land use improvement are easy and low–cost methods [10-12]. The stability of the slope can be increased using hydrological and mechanical effects [13-16]. The mechanical effects of roots on slope stability include increasing the soil shear strength by providing additional apparent cohesion to the soils [13, 17-20]. Hydrological effects can increase soil suction, resulting in an increase in the effective soil strength [21, 22]. Moisture is extracted by plant roots in the soil, which is known as the evapotranspiration process. The presence of roots in the soil can also increase soil permeability [23]. In general, root reinforcement in soil develops from the root strength, root spread, root density, and root depth in the soil. For mature natural forest, the tree root is dense to the lower depth and wide spreading. Thus, the overall root strength is high compared to cultivated land with mono cropping as shown in Fig.1.

Ever though the complete prevention of forest loss is not possible, but management of land use to reduce potential landslides can be planned and addressed in several ways, such as control cutting to reduce the risk of landslides, or cultivation of crops mixed with forest trees. Therefore, it is necessary to calculate the soil strength (c_s) with root reinforcement (c_r) for overlapping areas of roots. This study aimed to provide a method for calculating the root strength using c_s+c_r to analyze the slope stability with an assumed critical area of each land use.

The current paper attempts to study soil strength with root reinforcement. The combination of tree root spreads in each land use. And the factors of safety of each land use on slope area. The land uses are examined as the calculating of the soil strength with root reinforcement based on a small 1×1m grid area in order to determine the slope stability. Three land uses (old landslide, orchard, and original forest) are investigated the effect of root spread overlapping and slope stability. The results of this study could be further developed into sustainable land use management.

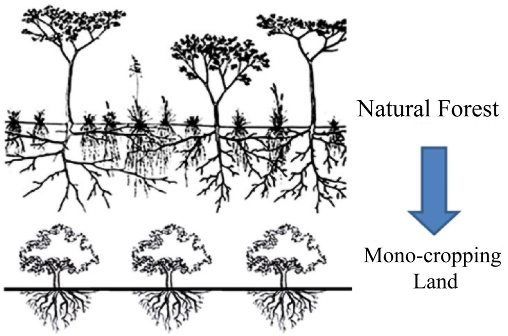

Fig.1 Root pattern for natural forest compared to for cultivated land under mono–cropping

2. MATERIALS AND METHOD

2.1 Study Area

The study area was the Mae Phrong–Mae Phun (MPMP) watershed in Lab–Lae district, Uttaradit province, Northern Thailand. The area consists of mountainous topography with elevations from 100 to 860m MSL covering 106 km^2. In 2006, there was a large amount of landslide damages amounting to more than USD 88 million, with a large loss of lives and many casualties. Most of the watershed's geological features are in the Upper Lab–Lae category (P_{111}, shale, mudstone, chert interspersed with sandstone) interspersed with the Lower Lab–Lae category. (P_{112}, gray sandstone interspersed with shale and black, gray mudstone) In addition, the plains in the southeast are sediments (Q_a), as shown in Fig.2 [5, 24, 25].

The MPMP watershed has several different lands uses. Initially, farming was agroforestry, but when the price of the crops increased, the trees were cut down trees and the area was converted into a monoculture. Land uses have changed in the MPMP watershed since 2000, as shown in Fig.4, with 93.35% as forest area in declining steadily to 34.26% in 2016. In contrast, the 6.87% of agricultural area in 2000 had increased to 68.09% in 2016 [5, 24, 25].

2.2 Topographical Features

The shear strength properties of soil in the MPMP watershed were obtained from shear strength testing of stable soil samples from different areas according to the land use, based on direct shear testing. The average soil cohesion (c_s) was 1.55 t/m^2 and the average angle of internal friction (Ø) was 22.5° [24].

The most common slopes were in the range 21°–40° and landslides were more common on slopes of 31°–40°, accounting for 51.40% of the total landslide area.

The relationship between soil thickness and the degree of slope was investigated to estimate the soil thickness variation with degree of slope, as shown in Fig.3.

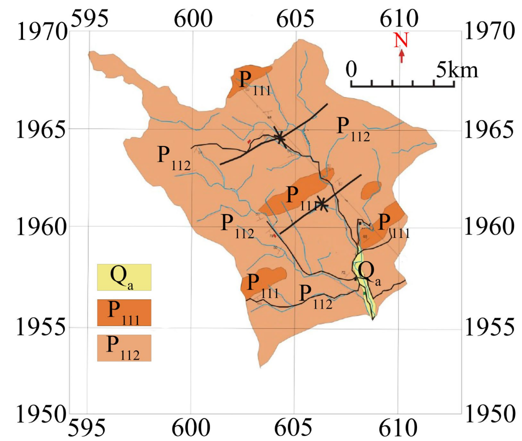

Fig.2 Geological map at Mae Phun subdistrict, Lab–Lae district, Uttaradit province [5]

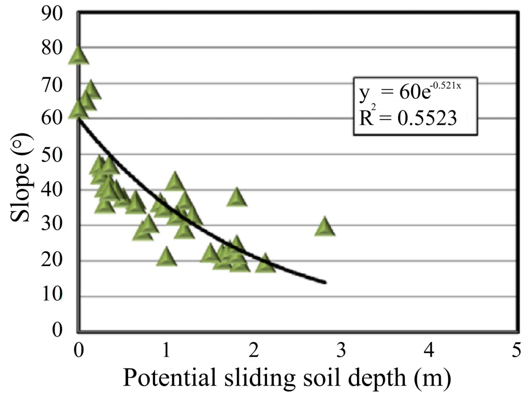

Fig.3 The relationship between soil thickness and degree of slope [5]

The researchers used back analysis based on actual landslides to determine soil depth and strength parameters from the slope data of the most frequent landslides. The *c* value was 0.96 t/m^2, Ø was 21.17°, the slope was 35°, and the depth of the soil layer was 1.8 m.

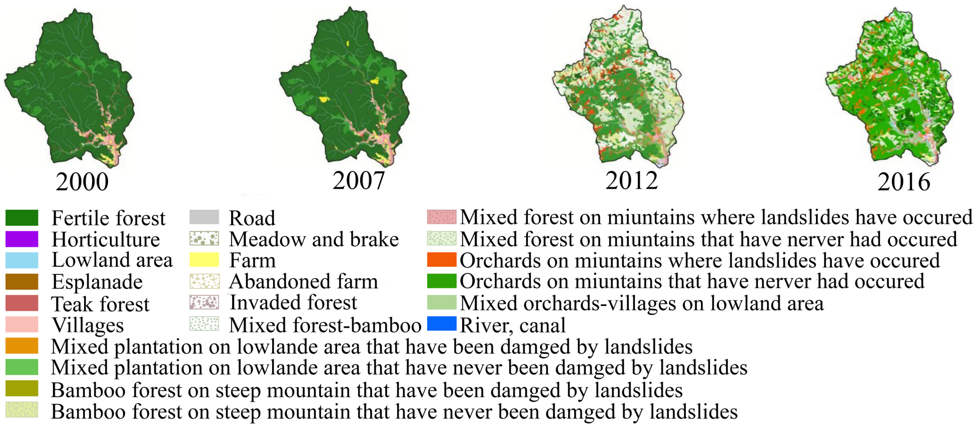

Fig.4 Changes in land use in MPMP watershed [5]

2.3 Root Properties

Tree placement in each land use area was surveyed using a total station camera, as shown in Fig.5, with the plant position and root spread shown in Fig.11. Plant root surveys investigated some plants and divided them into three groups: natural forest trees, orchard trees, and pioneer trees. The relationship was determined from the surveyed roots and the relationship was then used to estimate root spread, root depth, and root cohesion from the canopy radius [25, 26].

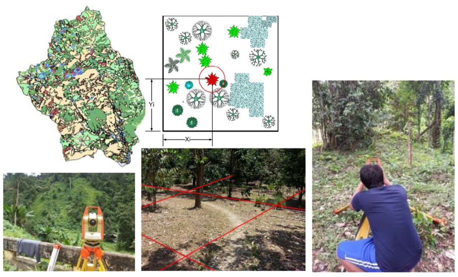

Fig.5 Survey of plant information in representative land use plots [5]

There three study areas were an old landslide, an orchard and original forest. The first area was bamboo-mixed forest (F201–M103), mixed with pioneer plants from the old landslide, having around 25 plants. The old landslide area was approximately 50×20m. In the orchard (A401), there were only 3 types of plants, and arranged at equal spacings between 4m and 8m, with an approximate area of 40×40m. The mixed forest (F201) was the densest forest with large trees without any record of landslides. There were 17 plant species with an approximate area of 40×40m.

2.4 Soil moisture During Rainfall

The seepage analysis in the MPMP area is based on [27]. It was discovered that most rainstorms were 1–7 days long and used 100 years return period of rainfall. The initial average moisture content was 74.7%, and the saturation ratio result is as shown in Fig.6.

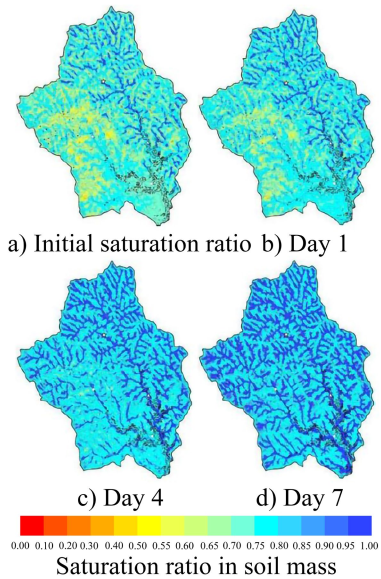

Fig.6 Saturation ratio in soil mass with rainfall (1.00 equal to 100% Saturation) [27]

Divide the boundary of the soil slope from the moisture value into three ranges, namely the lower slope (0–50m from the stream), representing 47.18% of the area. The middle slope (50-100m from the stream) representing 34.60% of the area, and the upper slope (>100m from the stream) representing 18.22% of the area. This research uses a lower slope because the MPMP is mainly a low-lying area with a slope of 0°–35° and is an area where land use changes are permitted [28]. The researchers chose the lower slope that was most susceptible to landslides. It is where the soil mass becomes saturated with rain [27]. Figure 7 shows that the soil on the lower slope area is saturated within 3–4 days of rainfall.

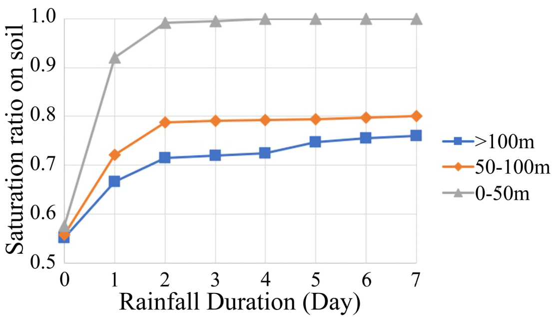

Fig.7 Saturation ratio each slope [27]

2.5 Methodology (Root modeling)

Wu *et al.* [13] suggested the primary influence of root reinforcement on soil shear strength could be expressed as the cohesion term in the Coulomb failure criteria based on the soil-root composite shear strength. Thus, tension is applied to them as the soil is sheared, as illustrated in Fig.8.

The overall shear strength of the soil and roots (τ_{sr}) can be written as Eq. (1), where c_s and c_r are soil cohesion and root cohesion, respectively, σ is the total normal stress, and ∅ is the internal friction angle of the soil. Solving for the shear strength contributed by root strength, the result is shown in Eq. (2). The cosαtan∅+sinα term can be approximated by 1.2 [13, 29]. The maximum root tensile strength, t_r, is the sum of the maximum tensile strength of each root (T_{ri}) with the root area ratio (%RAR) over the unit area of soil, as shown in Eq. (3), when d is the root diameter and A is the cross-sectional area of the soil. Substituting Eq. (3) into Eq. (2), expresses c_r in terms of T_{ri} and %RAR, as shown in Eq. (4).

$$\tau_{sr} = c_s + c_r + \sigma tan\emptyset \quad (1)$$

$$c_r = t_r(cos\alpha tan\emptyset + \sin\alpha) \quad (2)$$

$$When\ \%RAR = \frac{A_r}{A} = \frac{\sum_{i=1}^{n}(\frac{\pi d_i^2}{4})}{A}$$

$$t_r = \sum_{i=1}^{n} T_{ri}(\%RAR) \quad (3)$$

$$c_r = 1.2\sum_{i=1}^{n} T_{ri}(\%RAR) \quad (4)$$

Calculation of the soil strength with root reinforcement can be done by assuming the root spreading as circular discs of thickness z and radius r stacked from top to bottom. The root radius varies with depth, so that the simulation emulates the natural spreading properties of roots. When determining the location of trees in an area, the Land uses were surveyed to determine representative tree locations, as shown in Fig.9. Therefore, the plant position and root spread in each soil layer thickness were established and the average root-soil shear strength of each layer (c_{avg}) was computed, using Eq. (5).

$$c_{ij.avg} = \sum_{k=0}^{n} \frac{c_{ijk} \cdot A_{ijk}}{\sum A_{ijk}} \quad (5)$$

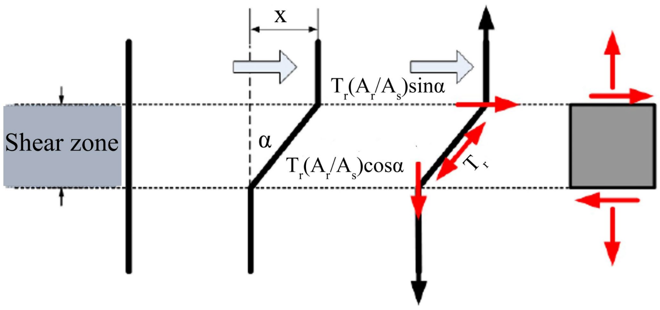

Fig.8 Model of root reinforcement in shear zone [29]

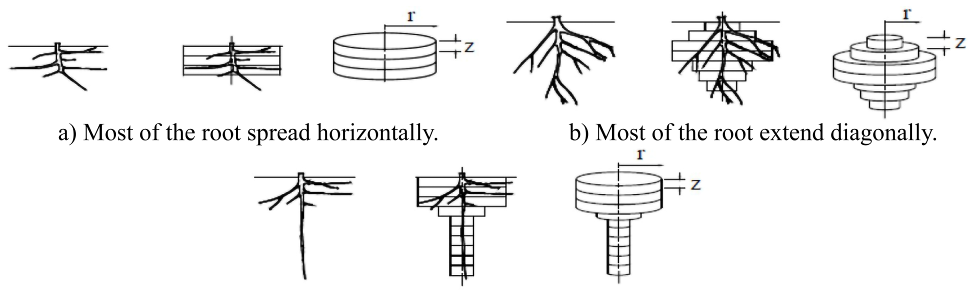

Fig.9 Using a cylinder to simulate root spread [30]

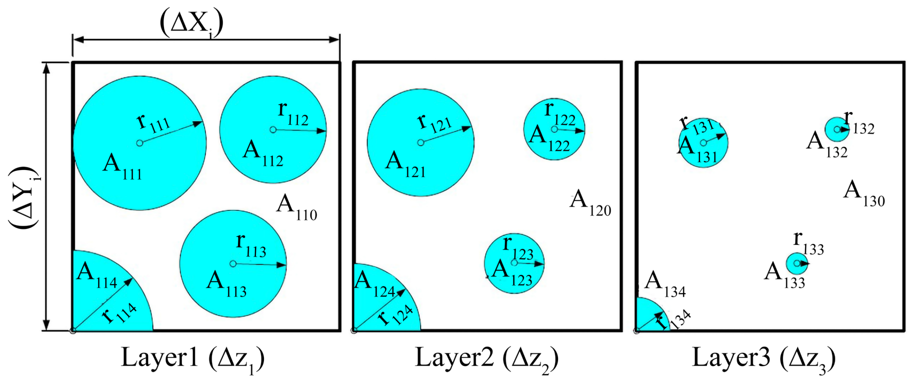

Fig.10 Distribution of roots at different depths on any base area (i)

where i is the number of the base area i with width multiplied by length as $x_i \cdot y_i, j$ is the number of the soil layer where the thickness in each layer is equal to Δz, k is the number of trees in the base area i, the soil outside the root spread was assigned $k = 0$, $c_{ij.avg}$ is the average cohesion on base area i and layer j , c_{ijk} is the soil strength with root reinforcement, A_{ijk} is the area of root spread, and $\sum A_{ijk}$ is area of base area i, as shown in Eq. (6).

$$A_{ijk} = \pi r_{ijk}^2 \quad (6)$$

where r_{ijk} is radius of the root k that extends

The c_s+c_r for each grid (every 0.1m and grid size is 1×1m depth) was calculated using Eq. (5), as shown in Fig.12. When determining c_s+c_r at all depths, the assumed size of the failure plane was 10×20m. Then, the value of the c_s+c_r was used to calculate F.S. moving around the assumed area 1 grid distance, recalculating F.S. in the process, for all areas in the different land uses, as shown in Fig.13.

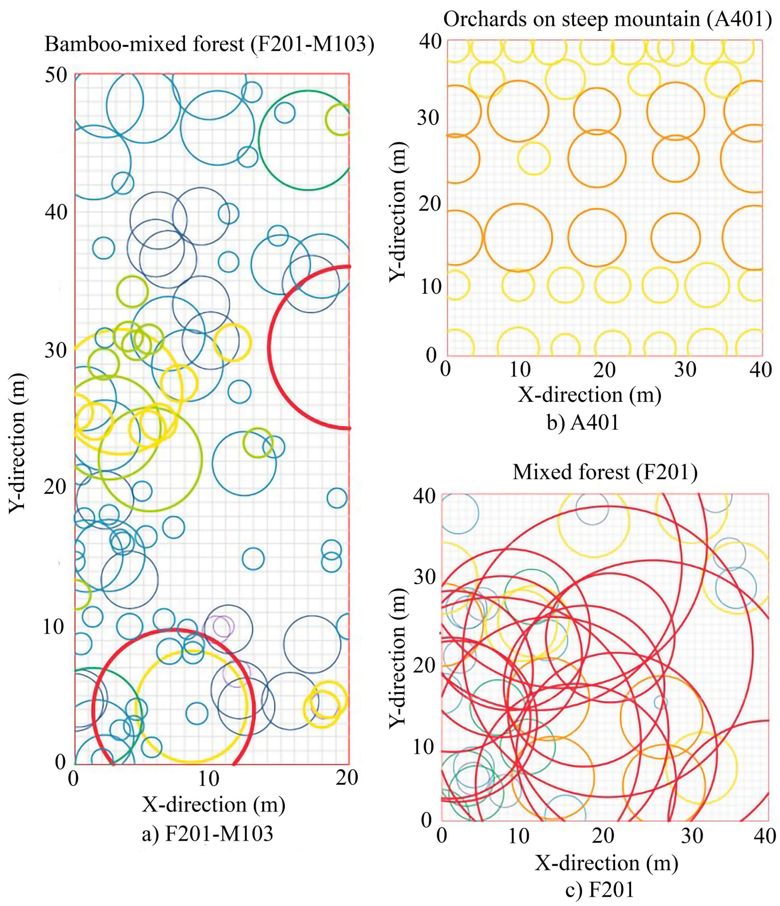

Fig.11 Root spread

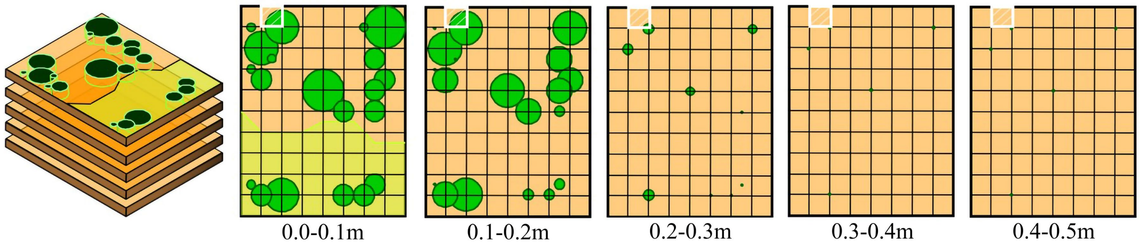

Fig.12 Grid in each layer

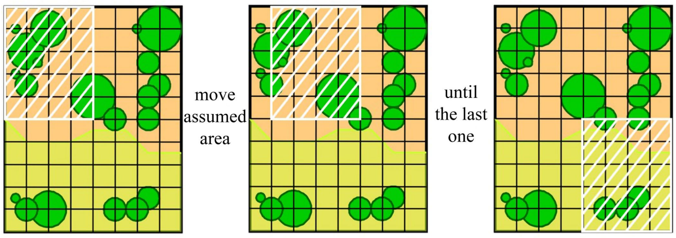

Fig.13 Trial for critical area

The modeling created layers with a thickness of 0.1m from the soil surface with c_r determined for each soil layer, as shown in Fig.14, based on the limit equilibrium method, and determining the failure plane as circular.

In the simulation, 5m of bare land was added to each side of the areas, so the size of F201–M103 was 60×30m, of A401 was 50×50m, and of F201 was 50×50m, with each into a grid of 1×1m. The plant areas overlapped, so the strength of plants was reduced according to the number of plants in that area. For example, if the number of plants was 2, then each type was reduced by 50%, for 3 plants each was 33%, for 4 plants each was 25%, and for 5 or more plants, each was 20%.

3. RESULTS AND DISCUSSION

3.1 Root Strength

The first calculation verified that there were trees in the grid. For each tree had individual values for %RAR (root area ratio) and c_r. where the c_s+c_r of the grid was determined using Eq. (7) and Eq. (8).

$$c_r + c_s = (\,Summation\ of\ root\ strength) + (Remaining\ strength\ of\ soil\,) \quad (7)$$

$$c_r + c_s = (\,\textstyle\sum_{x=1}^{n}(A_{RX}\ \times \%RARX \times F_{re} \times c_{rx})) + (c_s \times (A_G - \textstyle\sum_{x=1}^{n}(A_{RX} \times (1 - \%RARX)))) \quad (8)$$

where A_{RX} is the radius area of root x in the grid, $\%RARX$ is the root area ratio of root x, c_{rx} is the root cohesion of root x in the grid, F_{re} is the c_r reduction factor depending on the number of plants in the overlapping area, A_G is the area of the grid, and n is the number of trees with root spreading into the grid.

The grid on the yellow square in Fig.15 has 3 trees with roots spreading into the grid (Root1, Root2, and Root3). The value of c_s+c_r for the yellow grid was determined using Eq. (9).

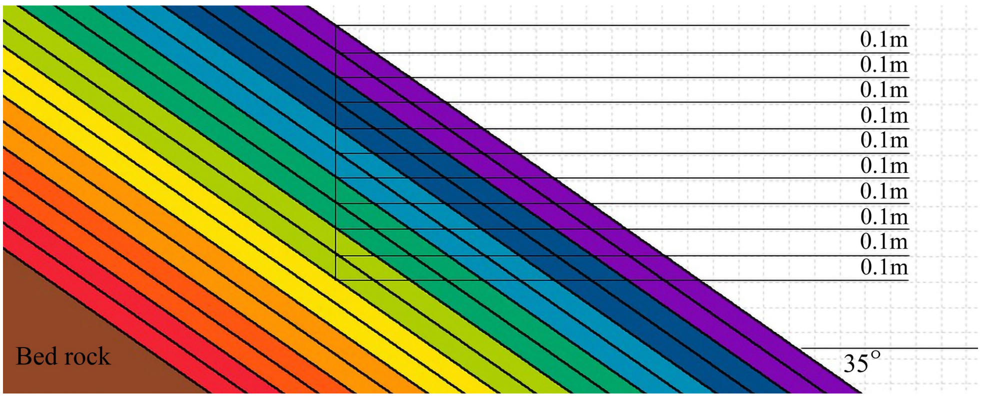

Fig.14 Modeling slope with root reinforcement

$$c_r + c_s = ((A_{z1} \times \%RAR2 \times c_{r2}) + (A_{z2} \times \%RAR1 \times c_{r1} \times 0.5) + (A_{z2} \times \%RAR2 \times c_{r2} \times 0.5) + (A_{z3} \times \%RAR1 \times c_{r1} \times 0.33) + (A_{z3} \times \%RAR2 \times c_{r2} \times 0.33) + (A_{z3} \times \%RAR3 \times c_{r3} \times 0.33)) + ((A_{z1} \times (1 - \%RAR2) \times c_s) + (A_{z2} \times (1 - \%RAR1 - \%RAR2) \times c_s) + (A_{z3} \times (1 - \%RAR1 - \%RAR2 - \%RAR3) \times c_s)) \quad (9)$$

where F_{re} values for 2, 3, 4, and over 5 overlapping root zones are 0.5, 0.33, 0.25, and 0.2, respectively, A_{zx} is the area in zone x, A_{z1} has only Root2, A_{z2} has Root1 and Root2 (2 overlapping roots zone), and A_{z3} has Root1, Root2, and Root3 (3 overlapping roots zone).

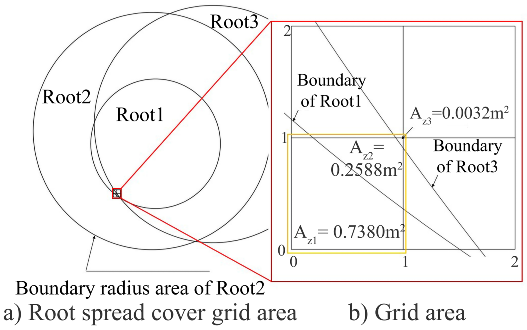

Fig.15 Calculation in each grid size of 1×1m

Calculation for every grid and every layer from the ground surface (Z=0.0–0.1m) to the last soil layer (Z=1.7–1.8m) will yield the combined strength of soil and root. Soil strength with root reinforcement in each grid is shown in Fig.16 as the average, minimum, and maximum of each land use.

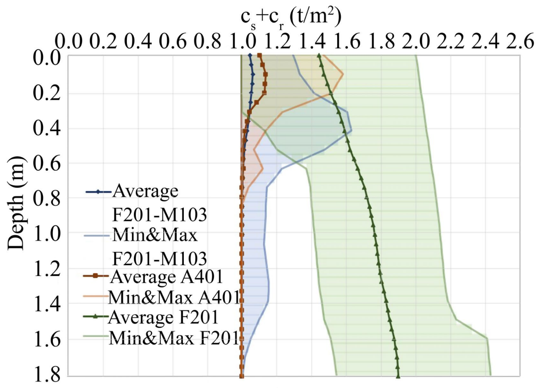

Fig.16 c_s+c_r in each land use

Since the pioneer plants have very low c_r and are very shallow, in some grids, c_s+c_r was less than 0.96 t/m² or less than the soil strength (c_s) due to the root strength (c_r) being less than c_s or the grid areas overlapped. However, for the current study, if c_s+c_r was less than c_s, then c_s was used for the stability analysis.

3.2 Factor of Safety

This case study using the parameters from [5, 24, 25], namely c_s = 0.96 t/m², $\emptyset$ = 21.17°, degree of slope was 35°, depth of soil layer = 1.8m, and soil mass was saturated (heavy rain, saturated condition, unusual critical condition) [27]. The F.S. was calculated from the average value of c_s+c_r for each grid in the assumed area (10×20m). For the bare slope (without root reinforcement) F.S. was 0.9701. The plot contour is a factor of safety for each land use is shown in Fig.17, where the x-axis and y-axis are the centers of the assumed area in each land use. In F201–M103, the F.S. average, minimum, and maximum were 0.9771, 0.9710, and 0.9913, respectively. In A401, the F.S. average, minimum, and maximum were 0.9816, 0.9722, and 0.9912, respectively. In F201, the F.S. average, minimum, and maximum were 1.7301, 1.5118, and 1.8866, respectively.

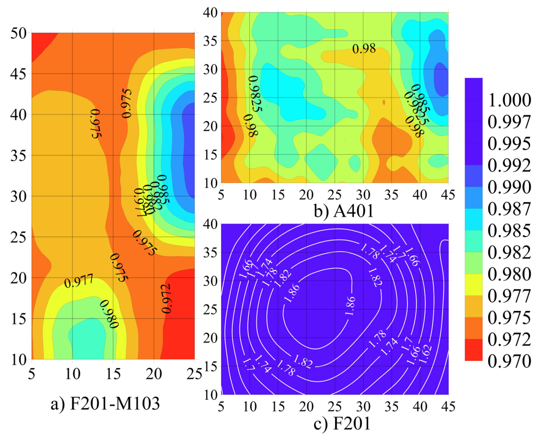

Fig.17 Contours of F.S. in each land use

Table 1. Factor of Safety in each land uses

Land use	Factor of Safety (Saturated condition)		
	Min	Max	Average
Bare slope	0.9701	0.9701	0.9701
F201–M103	0.9710	0.9913	0.9771
A401	0.9722	0.9912	0.9816
F201	1.5118	1.8866	1.7301

The land use F201–M103 consists of many pioneer plants and bamboo; hence, F.S. was close to the value for a bare slope. On land use F201, there were big trees, resulting in a higher F.S. [24, 25].

The land use A401 contained only orchard plants. In the middle, F.S. was higher than in the lateral parts due to the overlapping roots. The part with the highest F.S. had trees planted further apart, which influenced the value [24, 25].

The land use of F201 had the highest F.S of all the land uses because the area was a part of a dense forest area. There were many large forest trees especially the one at the middle of the site [24, 25].

4. CONCLUSIONS

(1) Three study areas (old landslide, orchard, and original forest) in Uttaradit province, Northern Thailand were selected to compare the effects of root reinforcement on the stability of the slopes.

(2) The old landslides area with mixed bamboo forest area (F201–M103) and the orchard area (A401) had similar F.S. values, even though the total number of trees in the F201–M103 area was 100 compared to 43 in A401. However, the c_r value of pioneer plants in the F201–M103 area was less and root depth shallower than those in the orchard (A401).

(3) The average F.S. values in the F201–M103 and A401 areas were 0.9761 and 0.9816, respectively. The trees in land use F201–M103 were concentrated in a small area compared to the well-distributed trees in land use A401.

(4) The root spread overlapping in the model applied reduction factors of 0.5 and 0.33 for 2 and 3 overlapping areas. This needs more study to verify its suitability.

(5) The forest area (F201) had an average F.S. of 1.7301, the highest among all land uses. There were 25 large trees with high c_r values and deep roots.

(6) Calculation of c_s+c_r based on a small 1×1m grid area and 0.1 m thin soil layers was able to simulate the root reinforcement with good correlation to the actual field data.

(7) The trial using a small landslide area in the model could help to identify locations for potential landslides in the study area. Moreover this study could be scaled up to evaluate the landslide risk for large watershed area with known land uses.

5. ACKNOWLEDGMENTS

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