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# Laboratory and modelling investigation of root-reinforced system for slope stabilisation

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## Abstract:

Most natural slope failures are induced by seepage and/or rainfall. Soil bioengineering is an environmentally friendly method which employs vegetation to reinforce the soil in sloping terrain. The vegetation can contribute to slope stability in two ways, mechanical and hydrological. This paper demonstrates the effect of a vegetation root matrix on a soil slope and focuses on mechanical reinforcement using an example of vetiver grass. Vetiver grass (*Vetiveria nemoralis* A. Camus) specimens, grown for under a year, were used in this study. The investigation programme includes root observations, direct shear tests and centrifuge model tests. The growing rate of the vetiver roots and the root area ratios were observed during the tests. The cohesion and angle of internal friction of root-reinforced soils were determined from a standard direct shear apparatus and a large direct shear apparatus. A series of centrifuge tests was carried out to demonstrate the effect of vegetation on seepage- and rainfall-induced slope failures. The results indicate that the vetiver roots showed rapid growth within a year and that the shear strength of the root-reinforced soil was significantly increased by the bundle of roots. The results also reveal that the bundle of root fibres in the centrifuge model tests helped to reduce the deformation of the soil slope due to instability by increasing the shear strength of the slope.

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## 1. Introduction

Landslides are one of the most widespread earth processes which involve the failure of sloping earth material. Landslides are considered to be one of the most important problems in geotechnical engineering. This is because landslides are usually among the most costly natural disasters in terms of human fatalities and economic loss. In recent years, natural slope instability has increased especially in tropical monsoon zones, such as Southeast Asian countries. There are several factors that can cause natural slope failures, such as geological activity, hydrological influence and human interference, but seepage and rainfall are the main factors. The infiltration of rain water can cause a rise in the groundwater level and an increase in pore water pressure or a decrease in the matric suction of the soil. In addition, the physical process of rainfall infiltration into the ground and its seepage through the soil layers have been studied by hydrogeologists, soil scientists and geotechnical engineers (Ng and Shi, 1998).

To increase slope stability, several methods have been used, such as soil nails, retaining structures, geosynthetic reinforcements and shotcrete. However, these methods are costly and may not be suitable for natural slopes. In ancient times, the use of vegetation in soil slopes and earthen covers for landfill was well recognised, and it is still well-known that the effect of vegetation plays an important role in increasing soil slope stability. Soil bioengineering is an environmentally friendly alternative that uses vegetation for improving slope failure. There are two main contributions whereby vegetation can affect slope stability, i.e., hydrological and mechanical processes. Firstly, changing the soil moisture regime and drawing the water from the soil via evapotranspiration (Ali and Osman, 2008) can increase soil suction. Secondly, the roots of vegetation can enhance slope stability by increasing the shear strength of the soil (Gray and Sotir, 1996; Wu et al., 1979). The role of vegetation in slope stability has been defined by Greenway (1978), Coppin and Richards (1990) and Wu (1995). In addition, this method is applied to prevent shallow failure as well as soil surface erosion in natural slopes.

Vetiver grass (*Vetiveria nemoralis* A. Camus), was promoted to help prevent soil erosion and water runoff or infiltration by the World Bank in the 1980s, and is important in soil bioengineering (Greenfield, 1996). Recently, the Chaipattana Foundation and the Office of the Royal Development Projects Board, Thailand, have promoted the use of vetiver grass for soil and water conservation for many royal projects in Thailand. Vetiver grass is fast growing and requires low maintenance. The length of vetiver roots has been seen to grow up to 2–3.5 m

(Chinapan et al., 1997). Vetiver roots can penetrate deep into the ground to form a net-like barrier capable of filtering silt and containing top soil. Normally, shallow failure is a typical failure mode of soil slopes in regions with prolonged and heavy rainfall; it always occurs 1–1.5 m in depth from the surface (Gray and Leiser, 1982). Hence, shallow failure of natural slopes could be prevented by the rooting depth of the vetiver grass which interlocks with the soil particles. Previous research has investigated the tensile root strength properties of vetiver grass for resisting shallow failure and superficial erosion (Hengchaovanich and Nilaweera, 1998).

Recently, the stability of model soil slopes that were reinforced by plant roots has been investigated by Sonnenberg et al. (2010) at 15g using a centrifuge. By continuously raising the groundwater table in model slopes, contributions of mechanical root reinforcement were back-analysed based on observed slip surfaces at failure. Takahashi et al. (2014) studied the effect of vegetation structures on seepage-induced slope failure using a 50g centrifuge model. Eab et al. (2014) continued the study of Takahashi et al. (2014) focusing on a root-reinforced slope subjected to rainfall infiltration using a rainfall simulator in the centrifuge.

The aim of this paper is to present an investigation programme of the vetiver root-reinforced system for slope stabilisation using a laboratory technique. The shear strength parameters of root-reinforced soils were determined using standard direct shear tests for single vetiver and large direct shear tests for a group of vetiver. The growing rate of the vetiver roots and the root-area ratios were observed by direct measurement and an image processing technique, respectively. Finally, a series of centrifuge model tests using a seepage and rainfall simulator to demonstrate the effectiveness of roots in shallow depths against slope instability was also performed.

## **2. Experimental Investigation**

In the soil bioengineering approach, the selection of suitable vegetation is the first important step. Vetiver grasses have been selected based on the type of soil and the type of environment which could help them survive for a long period of time. Thailand's Land Development Department (LDD, 1998) suggested that the roots of vetiver grass can penetrate deep into the ground and that vetiver grass is suitable for arid areas. However, research on the engineering aspects of vetiver grass is still limited and on-going. In this study, observations of vetiver grasses have been performed in both field and laboratory tests. In the field, vetiver grasses were planted

along a slope to observe the rate of growing and to make a comparison with the vetiver specimens grown in the laboratory. In the laboratory, the vetiver specimens were grown under three conditions: (1) vetiver specimens grown under hydroponic conditions; (2) a single vetiver specimen planted in a cylindrical container; and (3) a group of vetiver specimens planted in a cubic box.

## 2.1 Vetiver Specimen Preparation

In this study, the vetiver specimens were grown under three conditions. The first condition is hydroponics. Twelve identical single vetiver specimens were grown in a container with a liquid nutrient (without soil). An air pump was also installed in the container to provide oxygen, as shown in Fig. 1(a). This experiment was used to investigate the growing rate of vetiver roots without destroying the roots. Measurements were taken continuously, for over 6 months, of the length of the root and the radius of the root bundle for each specimen (Fig. 1(b)).

For the second and third conditions, the vetiver grasses were grown in soil. The soil used in this study was collected from a typical slope area. The chemical properties of the soil were tested and are reported in Table 1. The results show that the various nutrients remained relatively high and were similar to those used for planting purposes. In other words, this kind of soil can be used for cultivation on agriculture land. The single vetiver specimens were planted in plastic bags and placed in PVC tubes, having a diameter of 150 mm and a length of 600 mm, in preparation for the standard direct shear tests. Fig. 2(a) shows a schematic of planting vetiver grass for single specimens. Four samples were prepared by cutting at the upper part from the up–down direction with a thickness of 20 mm for each tested sample to fit the direct shear box, as shown in Figs. 2(a) and 3(a).

For the group specimens, the vetiver grasses were grown by planting them in a 300-mm<sup>3</sup> wooden box. Nine vetiver specimens were planted with a spacing of 75 mm, as shown in Fig. 2(b). These group vetiver specimens were prepared for the large direct shear tests. Three samples were prepared for the tests by trimming them to fit the large direct shear mould, 300 mm × 300 mm × 200 mm, as shown in Fig. 3(b). In addition, this group of vetiver grass specimens was prepared for image processing to define the root area ratio as well. It is noted that the group vetiver specimens were planted in the same soil which was used for the single vetiver specimens.

## 2.2 Vetiver Roots Observation

Fig. 4 presents the average values for the root length and the root bundle diameter from the hydroponic vetiver specimens. The results have been observed and measured continuously for 2–6 months. The relationship between the length of the roots and the radius of the root bundle is shown in Fig. 4(a). The growing rate of the roots can be determined from a plot of the length of the roots with respect to time, as shown in Fig. 4(b). According to the results, it is indicated that the roots of the grass have spread the radius of the root bundle up to 1.7 cm (Fig. 4(a)) and that the roots can grow up to 180 cm within 6 months (b). The average growth rate of roots is approximately 30 cm/month. As shown on the plot in Fig. 4(b), the current study has shown a slightly higher growth rate of vetiver compared to that in the data by Kaewsaeng (2000). The difference is probably caused by the planting conditions and the measurement methods. The data by Kaewsaeng (2000) were taken from the specimens planted in soil and measurements of the roots required the removal of the plant.

Moreover, observations of the group vetiver roots can be defined by a root area ratio. The term root area ratio refers to the fraction of the total cross-sectional area of a soil that is occupied by roots (Gary and Sotir, 1996). The root area ratio plays an important role in the contribution of the root fibres to the shear strength when it is directly defined by the cross-sectional area in the shear plane. However, the root area ratio measured in the plane perpendicular to the root-growth direction is really difficult to determine and it varies with depth. The parallel plane measurement of the root area ratio, which is easier to observe and represents an average of the root fibre contribution in the soil, was used in this study. Alsheimer and Hughes (2007) have reported the technique of using image processing to observe root distribution in a large direct shear specimen. Photographs of roots and soil were taken with a digital camera and transferred to binary images via the histogram function of Photoshop software. The black and white pixels of the images could be distinguishably counted between the soil and the roots. The ratio between the pixels of the roots and the total pixels can be loosely defined as the root area ratio. The results show that the average root area ratio of the group vetiver at 4 months and 6 months are 2.44% and 4.37%, respectively. Fig. 5(b) shows the binary image for the method used to estimate the root area ratio based on the colour in the image. For example, the white and black colours represent the soil and the void space, respectively, while the grey colour represents the root area. Hence, the root area ratio can be determined by the total pixels of the roots and the total pixels. The root area ratio for the 6-month group vetiver root was 4.56% (Fig. 5).

### 2.3 Shear Strength of Vetiver Roots

In this study, the reinforcements of the vetiver root system were studied using direct shear tests in the laboratory. Laboratory tests were chosen instead of field tests; hence, the vetiver sample could be simply prepared and the density and the water content of the soil could be controlled between 20% and 25% for the bare soil and vetiver grass specimens. This could minimise the effect of the differences in matric suction during the tests. Two types of specimens were prepared in this study, i.e., single and group vetiver. Four-month-old single vetiver specimens (Fig. 2(a)) were prepared for the standard direct shear tests. On the other hand, six-month-old group vetiver specimens (Fig. 2(b)) were prepared for the large direct shear tests. To observe the increase in shear strength from the vetiver-root reinforcement, bare soil with the same density and water content for the four-month and six-month specimens were prepared for the direct shear tests as well.

Four-month-old single vetiver grass was individually prepared in the cylindrical plastic bags and put into PVC tubes to ensure that the roots of the vetiver could grow vertically into the soil, as shown in Fig. 2(a). A 60-mm-diameter cylindrical mould was used to perform the direct shear tests for the four-month-old single specimens, as shown in Fig. 3(a). The tests were performed by following the ASTM D3080 (1998) (similar to JGS 0561) standard with the shear rate of 1.5 mm/min. Normal stress rates of 10, 20, 50 and 100 kPa were applied for each test. All specimens were sheared until they reached the peak point, started showing fairly constant shear stress or a maximum horizontal displacement of 6 mm. The shear strength of the four-month-old vetiver root reinforced soil and the bare soil was obtained as presented in Fig. 6 (a). The cohesion intercept and the friction angle were determined according to the Mohr–Coulomb failure criterion, as presented in Table 2. The presence of the vetiver roots has improved the strength of the soil. As a result, the vetiver grass was able to increase the cohesion of shear strength by almost 7 kPa. Ali and Osman (2008) reported the increase in cohesion of the shear strength of soil by vetiver roots. The results show that the cohesion of the soil was increased to around 11 kPa from the average values for a rooted zone 1 m in depth.

Six-month-old vetiver grass was prepared as a group specimen in the cubic box, as shown in Fig. 2(b). The large direct shear apparatus was chosen to perform direct shear tests for the group vetiver specimens, as shown in Fig. 3(b). The tests were performed following the ASTM D3080 (1998) standard. Normal stress rates of 30, 50 and 75 kPa were applied by the hydraulic pressure

system. The side friction between the sample and the shear box was minimised by applying some oil. All the data from the displacement transducer and the load cell were acquired by an automatic data logging system. All plotted in Fig. 6(b). The friction angles were determined based on the Mohr–Coulomb failure criterion as presented in Table 2.

According to the results, the increase in cohesion of the soil for the single vetiver specimen was higher than the group specimen (see Table 2). The difference is probably caused by the contribution of the Vetiver root loosely defined by the root area ratio. In addition, another difference is also caused by the scale effect of the tests. Cerato and Lutenecker (2006) have reported the results of tests using three different specimen sizes and the scale effect of direct shear tests on sands. Their results indicate that the friction angle decreases as the specimen size increases.

### **3. Centrifuge Modelling**

Centrifuge modelling is a physical model test that is now widely used in geotechnical research or design. Since slope stability is a gravity-dependent problem, the major advantage of using centrifuge modelling is to enable researchers to test reduced-scale physical models at the correct stress level by increasing the g-level (Taylor, 1995). The centrifuge facility at the Tokyo Institute of Technology was used for this study. The soil slope models were prepared in a steel box. In this study, a 50g centrifugal acceleration was used to model the slope stability problem. Two types of tests were conducted: (1) see- page tests and (2) rainfall tests. A brief summary of the experimental details are given in the following sections.

#### **3.1 Properties of Materials used in the Model**

According to JGS0051 (a Japan Geotechnical Society standard), Edosaki sand is defined as a fine sand and was employed to prepare the slope models. The grain size distribution curve of Edosaki sand is shown in Fig. 7 and its engineering properties are described in Table 3. Two types of fibre were used in this study: (1) a fishing line with a diameter of 0.33 mm and a length of 10 mm and (2) polyester fibre (Teijin RA04FN, size of 17 dtex) with a diameter of 39  $\mu\text{m}$  and a length of 10 mm. In the model tests, the 1% by mass (approximately 3% by volume) of the 20-mm-deep fishing line, mixed with sand in model scale equivalent to 1 m in prototype scale, was able to represent the 4-month-old vetiver grass, as shown in Fig. 4. Similarly, the 2% by mass (around 7% by volume) of the polyester fibre, with a depth of 40 mm and mixed in model scale

equivalent to 2 m in prototype scale, was able to represent the 6-month-old vetiver grass. It is noted that the values of 3–7% by volume are slightly higher than the root area ratio of 4.56% observed from the 6-month-old vetiver group specimen. However, it is still comparable to the typical values for the root area ratio of 3–5% for other small vegetations observed in literatures (Wu, 1995; Gary and Sotir, 1996). Fig. 8 presents photos of the fishing line and the polyester fibre before and after being mixed with the sandy soil. The engineering properties of the soil mixed with 1% fishing line and 2% polyester fibre are also summarised in Table 3.

The shear strength of the soils was examined by standard direct box shear tests. The soil specimen was prepared in a cylindrical shape to have a diameter of 60 mm and a height of 20 mm. The observation after the tests revealed that the fibre was randomly oriented even after the tests. Therefore, the effect of fibre orientation on the shear strength is small compared to the percent of mixing and adhesion mobilised by the fibre with the soil. In the tests, Edosaki sand with a water content of 15% was compacted to achieve a degree of compaction of 80%. In the case with the fishing line, a water content of 15% was needed to mix with 1% fishing line, and in the case with the polyester fibre, a water content of 17% was needed to mix with 2% fibre to reach the final water content of 15%. The direct shear tests were carried out to obtain the angle of shearing resistance ( $\phi$ ) and the cohesion intercept ( $c$ ) of the soils. Fig. 9 compares the results of the direct shear tests for the soils. The results indicate that with 1% fishing line added, the cohesion of the soil increased just around 2 kPa and the friction angle around 8 deg., while with 2% polyester fibre added, the cohesion of the soil increased around 14 kPa and the friction angle around 3 deg. Consequently, the fibre has increased the cohesion of the soil by 1.4 kPa and 14 kPa for fishing line and polyester fibre, respectively. The difference is likely caused by the type and the amounts of materials, as summarised in Table 3. Considering the fact that the increase in the cohesion of the soil reinforced by the real vetiver grass was 6–7 kPa, it can be said that the shear strength of the soil with fishing line and polyester fibre exhibits similar shear behaviour to the soil reinforced with vetiver grass (Fig. 6), which could increase the shear strength of the soil mainly from the cohesion. Thus, both materials can be reasonably selected to model the vetiver grass in centrifuge model tests.

### **3.2 Slope Model and Testing Procedure**

In the centrifuge tests, the slope models were conducted under two conditions: (1) seepage tests – the tests were conducted to define the mechanism of slope failure during the groundwater

flow from the far area where the rain had fallen, and (2) rainfall tests – the tests were conducted to examine the effect of run-off on the slope surface. These two tests were carried out to simulate the mechanism of the slope failure. The model slopes were prepared inside a steel box, 450 mm in width, 150 mm in breadth, and 270 mm in depth, and consisted of two parts, one a bedrock part that was made of aluminium plates and was placed on a 10 mm-thick acrylic plate, as shown in Fig. 10, and the other a soil part which was made of Edosaki sand and consisted of four layers that had a total thickness 80 mm in height in the model scale. Fig. 10 shows the schematic system for both seepage and rainfall model tests. During the tests, pore-water pressure transducers (PWPs) and accelerometers (ACCs) were installed in the soil layers during compaction to measure the pore water pressure and the soil slope displacement, respectively. In the seepage cases, 10 PWP transducers and 4 accelerometers were installed in the model tests and, in rainfall cases, 8 PWP transducers and 6 accelerometers were installed in the model tests. The locations of the PWP transducers and the accelerometers are presented in Fig. 10. The pore water pressure transducers used are SSK Micro Pore Water Pressure Transducers Model P303AV-2 with a diameter of 6 mm and a length of 8.5 mm (diameter of wiring = 1.3 mm). The accelerometers used are SSK Micro Accelerometers Model A5-50 with dimensions of  $5 \times 5 \times 15$  mm<sup>3</sup> (diameter of wiring = 1.6 mm). If the wiring of these sensors had been in the vertical direction, perhaps the wiring could have been rainwater infiltration paths and could have restrained the slope deformation. To avoid such conditions, the wiring was extended in the horizontal direction. The slope displacement was calculated by integrating the inclination of the accelerometers along the depth. A digital camera was installed in front of the transparent window to observe the displacement and/or the deformation of the slope failure during the tests.

### ***3.2.1 Seepage test***

For the seepage tests, a 50-mm-wide water supply tank was installed inside the steel box on the left side to provide seepage flow from the upslope during the tests. A filter was installed between the vertical side wall of the tank and the slope model to make sure that only water could seep through to the slope model. In addition, a laser displacement transducer was installed on the top of the soil slope to measure the slope displacement, and one small digital camera was installed at the middle-top of the steel box to observe the slope surface cracking. Therefore, the deformations of the soil slope were clearly observed by video recording and the laser displacement transducer as well as by the accelerometers. The model slope consisted of two parts,

one bedrock, with a length of 236 mm, a height of 136 mm and an angle of 30 deg., between the slope surface and the bottom plate, and the other the soil part, as shown in Fig. 10(a). During the centrifuge operation, the groundwater level in the model slope was controlled by changing the water level in the water supply tank. In the seepage tests, two cases were conducted, i.e., (1) the case of a soil slope without reinforcement, to be used as reference, and (2) the case of a soil slope reinforced at the surface by a 20-mm fishing line. The purpose of the latter was to simulate the mechanism of shallow roots at the top of surface which are similar to 4-month-old vetiver grass.

### ***3.2.2 Rainfall test***

For the rainfall tests, heavy rainfall conditions were chosen to impose over the slope model. An array of pneumatic spray nozzles (H. Ikeuchi & Co., BIMV45075) was selected to simulate the heavy rainfall in the centrifuge. The rainfall simulator consisted of nine spray nozzles and was placed above the steel box at a distance of 80 mm. On the left side of the steel box, a small tank, 80 mm in width, was installed as a water storage tank and was used as a rain gauge to estimate the precipitation on the slope. In addition, one small digital camera was installed at the top-right side of the steel box to observe the slope failure at the toe. After soil compaction was complete, Japanese noodles were installed between the model slope and the front transparent window so that the deformation of the slope could be clearly observed. Thus, the soil displacements were measured by both the accelerometers and the video recording taken through the front transparent window of the steel box. The bedrock part of this model is 165 mm in length, 76 mm in height and the slope angle of 25 deg., as shown in Fig. 10(b). The surface of the model bedrock was roughened by attaching sand paper to it. During the tests, rainfall intensity of 1000 mm/h (20 mm/h in the prototype) was used by spraying rain drops over the slope surface. Two cases were performed for these rainfall tests, i.e., (1) an unreinforced soil slope used for reference and (2) a soil slope reinforced at the surface by 40-mm polyester fibre. The 40-mm fibre-reinforced model is similar to the case of the six-month-old vetiver grass.

### **3.3 Results of Centrifuge Model Tests**

Fig. 11 shows the variations in phreatic lines within the soil slope. The positions of the phreatic lines are calculated from the pore-water pressure measured by the PWPs at the toe in both seepage and rainfall tests. According to these results, the phreatic lines for the seepage tests (Fig. 11(a) and (b)) were approximately parallel to the slope between the boundary of the soil

and the bedrock. In contrast, the phreatic lines in the rainfall tests (Fig. 11(c) and (d)) were raised at the toe. In addition, the phreatic lines for the rainfall tests in the root-reinforced case decreased. This decrease may have been caused by the polyester fibres which helped prevent the rising up of the groundwater table. Moreover, the results from PWP's in the rainfall case (Fig. 11(c) and (d)) indicate that the soil slope was not fully saturated. The results of the centrifuge model showed that small soil erosions were observed at the near failure stage only in the unreinforced case and that no runoff or soil erosion was observed in the reinforced case. Hence, the effect of runoff and soil erosion could not account for the slope surface in this study.

Fig. 12 shows digital snapshots of the slopes after the tests together with the slip surface formation timing in terms of the pressure head near the toe. In the seepage tests, the slope failure started in the toe area when the pressure head at the toe has approximately reached 30 mm for both the unreinforced and the root-reinforced cases (Fig. 12(a) and (b)). By presenting the 20-mm root-reinforced case in the soil slope, there is no slip surface in the middle of the slope (Fig. 12(b)). Deformation is limited around the toe in the root-reinforced case, while it is extended to the middle in the unreinforced case (Fig. 12 (a)). This is attributed to the effects of the root fibres on the soil surface. In the rainfall tests, the slope started to collapse from the toe and progressively moved upward until the pressure head near the toe reached around 40 mm (Fig. 12(c)). There is no slip surface beside the small deformation at the toe slope in the 40-mm root-reinforced case in the soil slope (Fig. 12(d)). The displacements of the soil slope can be calculated from the accelerometers, as presented in Fig. 13. The plots show the horizontal displacement of each accelerometer, where the values in the legend represent the pressure head near the toe slope. In the seepage tests (Fig. 13(a) and (b)), the slope presents a large displacement around 16 mm once the pressure head near the toe reaches around 50 mm in the unreinforced case, as depicted in Fig. 13(a). For the root-reinforced case in Fig. 13(b), the slope displacement decreases to 8 mm with a high pressure head of 60 mm. On the other hand, the slope collapsed due to the heavy rainfall condition, as shown in Fig. 13(c). The displacement in the rainfall case reached 15 mm when the pressure head near the toe reached 30 mm. By applying fibre reinforcement on the top surface, the deformation of soil was reduced less than 3 mm without collapse as depicted in Fig. 13(d). Table 4 summarises the comparison of slope displacements for each test.

#### **4. Result and Discussions**

According to the root observation results, the growth rate of vetiver roots is relatively high compared to others (Lyr and Hoffmann, 1967). The maximal depth of development of vetiver root systems can go up to 200 cm in the first year and the average daily increment in roots is approximately 10 mm. The direct shear test results indicate that vetiver roots significantly enhance the shear strength of soil especially the cohesion of the soil. These results agree well with the observation by Ali and Osman (2008). However, the increase in cohesion for the single vetiver specimen is higher than that for the group specimen due to the scale effect of the specimen size. The results in Fig. 6 show that the friction angle and cohesion decreased due to the increase in specimen size.

In addition, the centrifuge results indicate that the presence of root fibre on the surface of a soil slope was able to enhance the slope stability in both seepage and rainfall-induced slope failure problems. In the seepage tests, the root reinforcement was able to improve the soil slope by preventing cracks on the slope surface. Moreover, the results for the root-reinforced slope in the rainfall tests show a small deformation of the soil slope at the toe of the slope without collapses.

The results from this study indicate that the length and the radius of the root bundle are important parameters which can help prevent slope instability by increasing the cohesion of the soil. Therefore, vetiver roots are seen to have a great effect on the strengthening of the surface soil where the root length and the radius of root bundle are generally high.

#### **5. Concluding Remarks**

According to the concepts of soil bioengineering and the observation results for vetiver grass, vegetation roots can increase the shear strength of soil by mechanical reinforcement. The present research confirms a significant contribution of the vegetation root to slope stability. A series of centrifuge model tests on a slope whose surface is reinforced by model roots was conducted to understand the mechanism of the vegetation reinforcement against seepage and rainfall-induced shallow failure. The conclusions of this study are as follows:

(1) The results from direct shear tests confirmed that the roots significantly increased the shear strength of the soil. The shear strength of the root-reinforced soil depended on the root length and the root area ratio.

(2) The centrifuge model tests illustrated that slope failure due to seepage and heavy rainfall is triggered by the rising of the water table and starts around the toe of the slope. The rise in the water table causes the effective stress to decrease and results in a decrease in the shear strength of the soil.

(3) It was confirmed from the centrifuge model tests that the presence of root fibres on the slope surface helps prevent cracking on the soil slope.

(4) The centrifuge model with rainfall simulator tests demonstrated an important role of vegetation roots in slope stability, namely, the ability to delay both the infiltration rate into the ground and the rising of the groundwater table.

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**Table 1.** Chemical test result of planted soil

Test	Value	Level
Alkaline-Acidity (pH)	6.7	Medium
Organic (O)	12.13%	High
Phosphorus (P)	61 mg/kg	High
Calcium (Ca)	7,859 mg/kg	High
Magnesium (Mg)	974 mg/kg	High
Potassium (K)	1,996 mg/kg	Very high

**Table 2.** Results of direct shear tests

Test	Specimen	Shear strength parameters	Increase in cohesion (kPa)
Standard direct shear test	Bare soil	$c = 6.8 \text{ kPa}; \phi = 22.8^\circ$	6.8
	4 months old single vetiver	$c = 13.6 \text{ kPa}; \phi = 29.7^\circ$	
Large direct shear test	Bare soil	$c = 2.5 \text{ kPa}; \phi = 21.8^\circ$	6.0
	6 months old group vetiver	$c = 8.5 \text{ kPa}; \phi = 29.2^\circ$	

**Table 3.** Properties of compacted soils used in centrifuge models

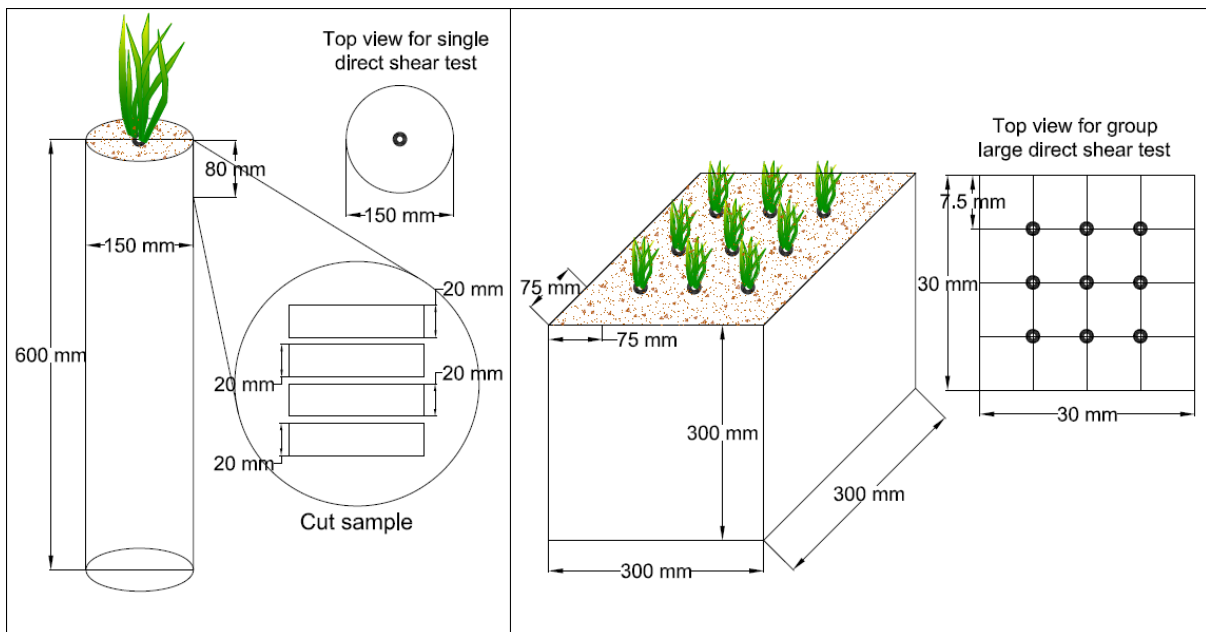
Soil type	Edosaki Sand	Edosaki Sand + 1% by mass of fishing line	Edosaki Sand + 2% by mass of polyester fiber
Specific gravity, $G_s$	2.65	-	-
Maximum dry unit weight, $\gamma_d$ (kN/m <sup>3</sup> )	12.9	13.5	12.9
Optimum water content, $w_{opt}$ (%)	15.2	15.8	17.3
Total unit weight, $\gamma_t$ (kN/m <sup>3</sup> )	14.9	15.4	15.2
Cohesion intercept, $c$ (kPa)	4.8	6.2	18.9
Angle of shearing resistance, $\phi$ (°)	28.6	36.5	31.5

**Table 4.** Summary of centrifuge test

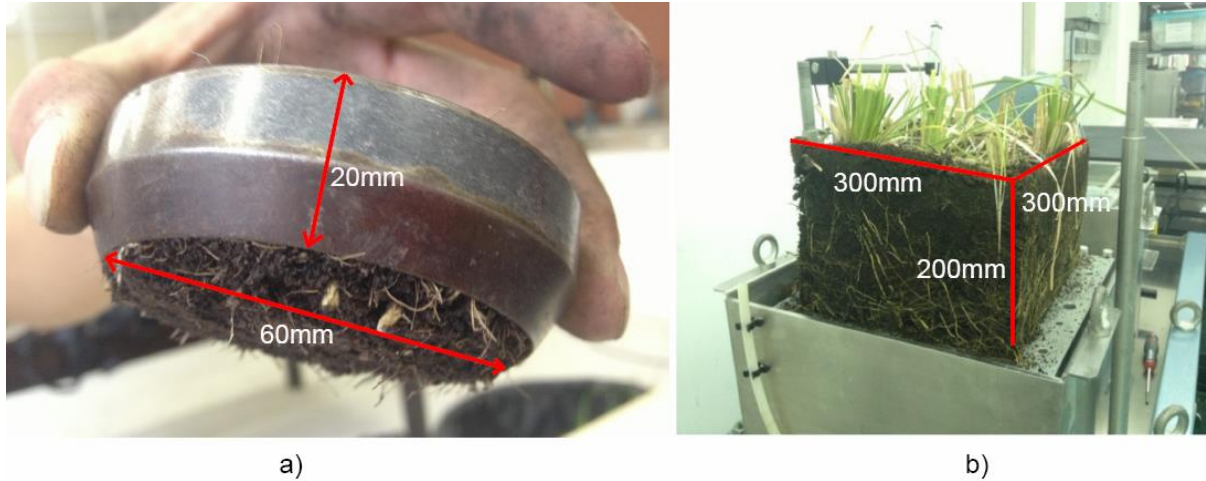
Tests		Model case	Real case	Displacement (mm)	Slope deformation
<b>Seepage</b>	1	Un-reinforced	Bare soil	16	Collapsed
	2	Fishing line with 20 mm depth reinforced zone	1 m depth of vetiver grass (4 months old)	8	Collapsed; less crack on surface
<b>Rainfall</b>	1	Un-reinforced	Bare soil	15	Collapsed
	2	Polyester fibres with 40 mm depth reinforced zone	2 m depth of vetiver grass (6 months old)	3	Small deformation; without collapse



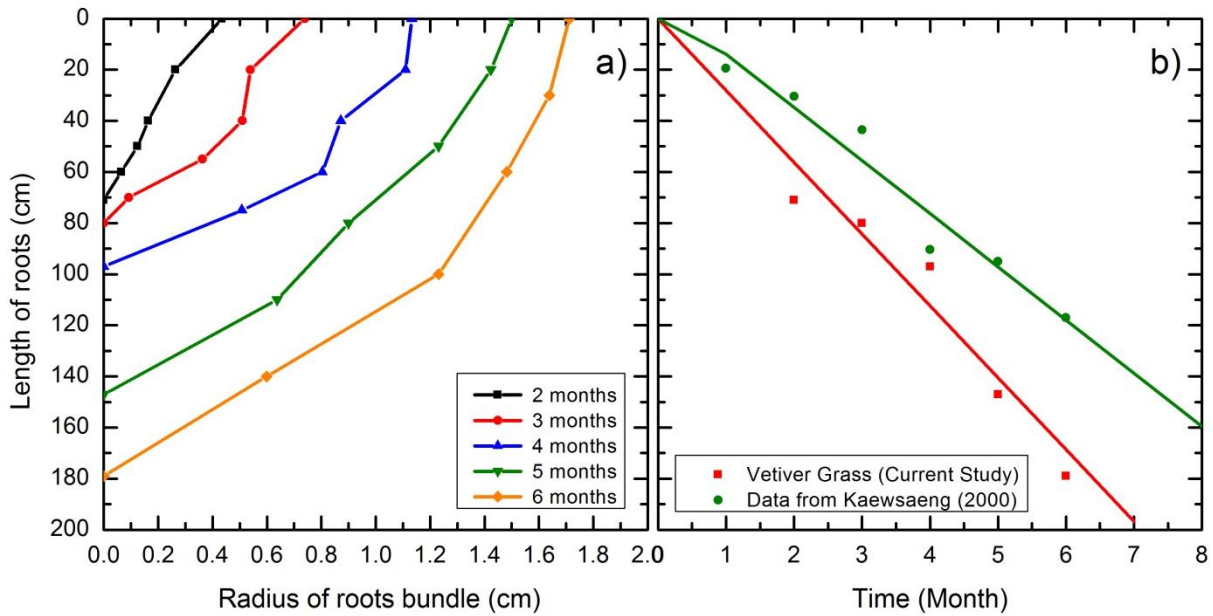
**Figure 1:** a) Vetiver specimens grown in hydroponic condition and b) Root observation



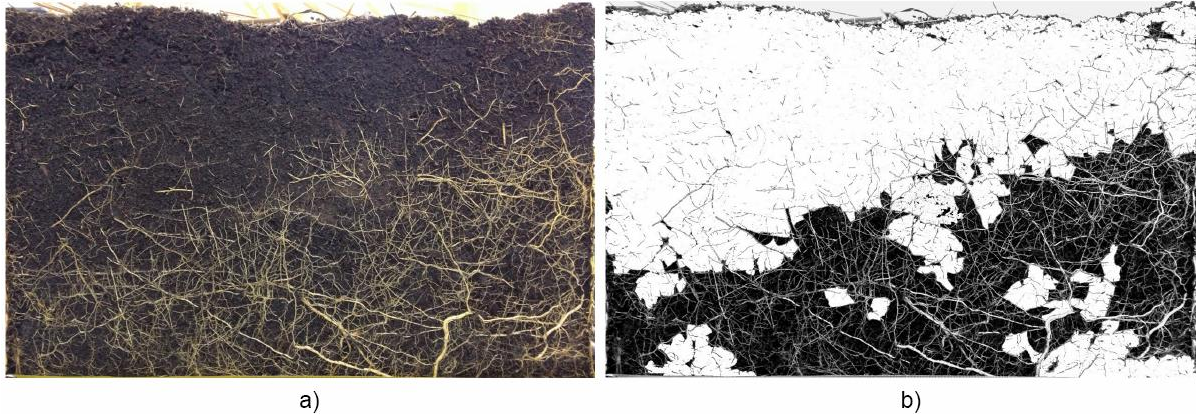
**Figure 2:** Vetiver grass specimens prepared for the shear tests: a) 4 months old single vetiver grass for the standard shear test and b) 6 months old group vetiver grass for the large direct shear test



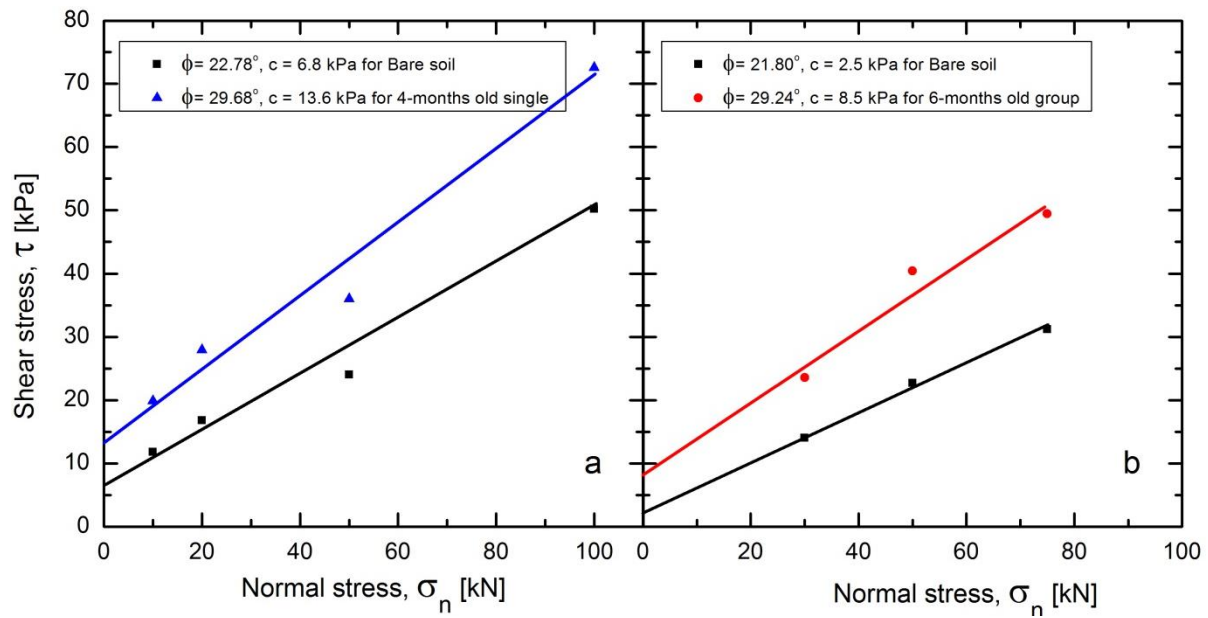
**Figure 3:** Tested samples for direct shear tests: a) a 60 mm diameter direct shear apparatus and b) a 300mm x 300mm large direct shear apparatus



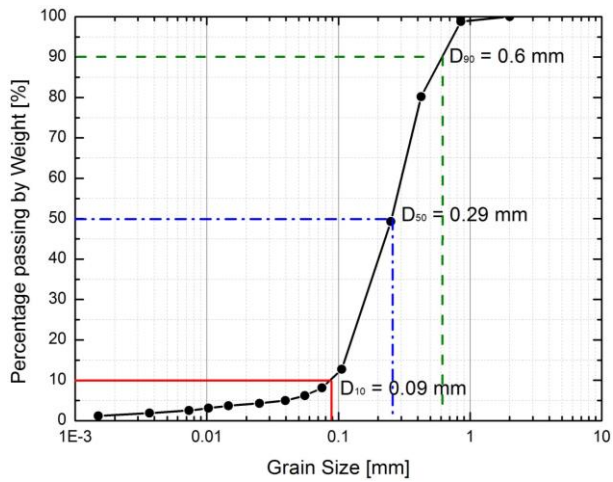
**Figure 4:** Average values of vetiver root measurement: a) Relationship between length of roots and radius of roots bundle and b) Growing rate of roots



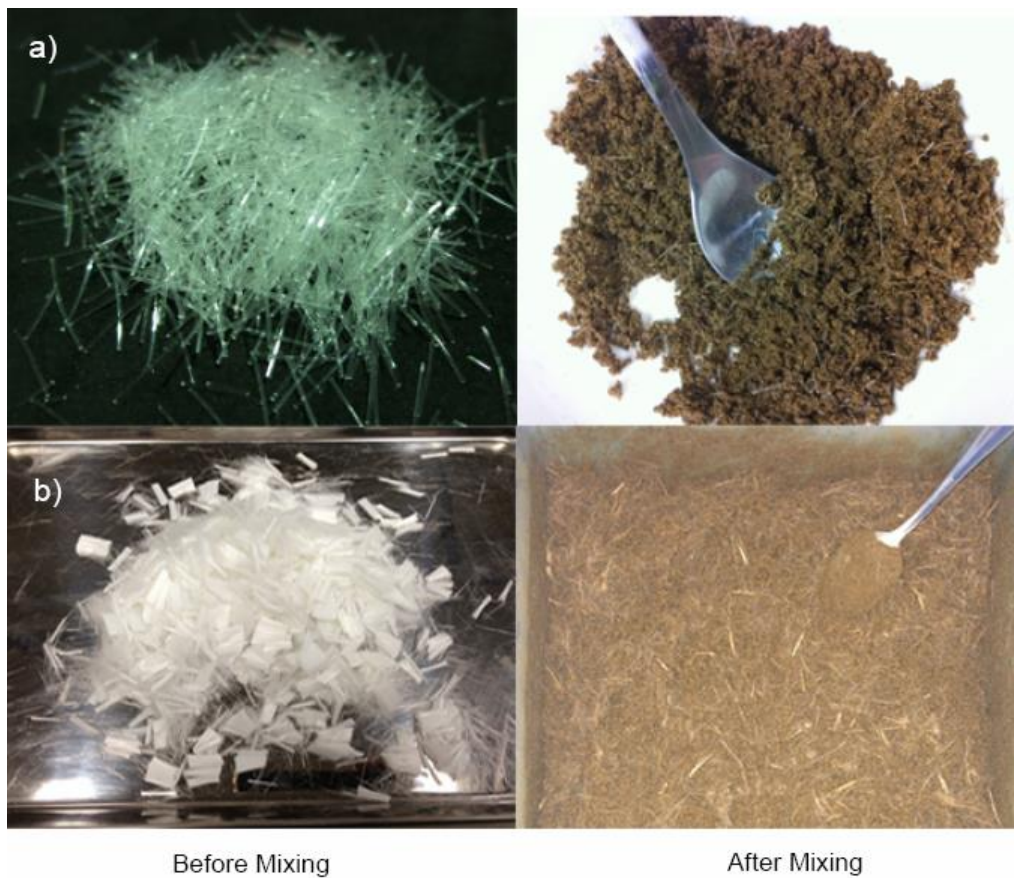
**Figure 5:** Determination of root area ratio: a) Root photograph taken from the 6 months group vetiver and b) Binary image with the result of root area ratio of 4.56%



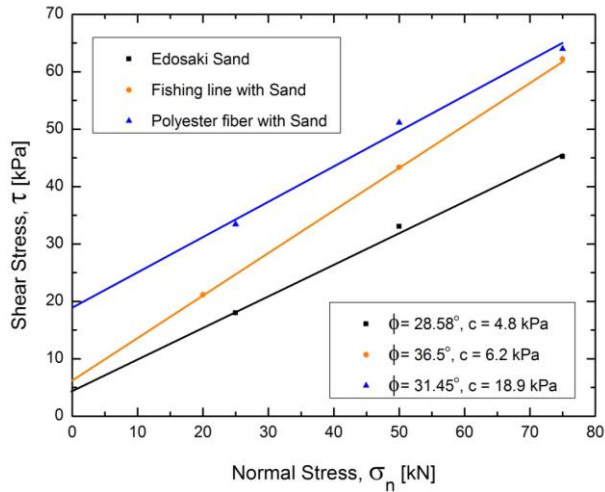
**Figure 6:** Shear strength of roots with soil: a) 4 months old single vetiver from direct shear test and b) 6 months old group vetiver from large direct shear test.



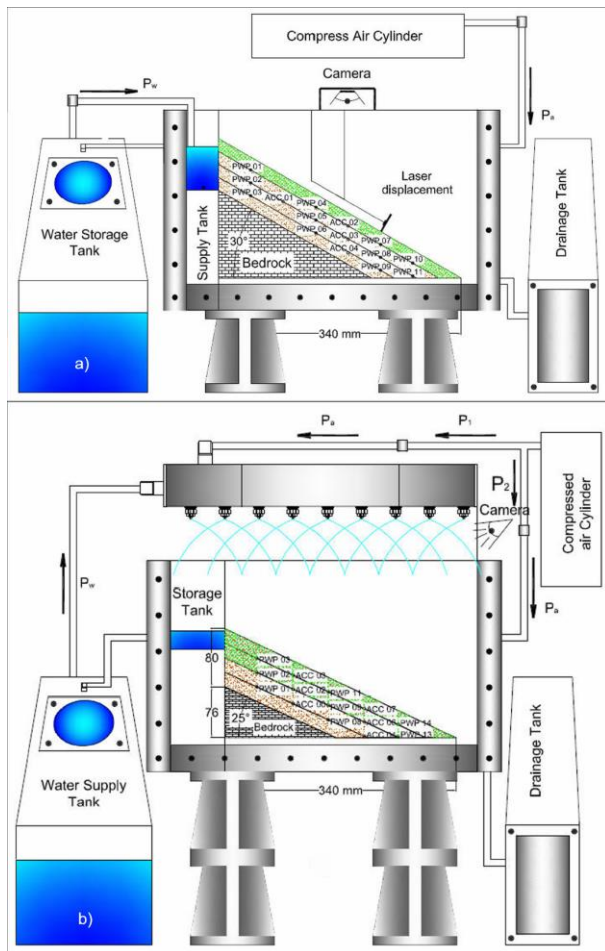
**Figure 7:** Grain size distribution curve of Edosaki Sand



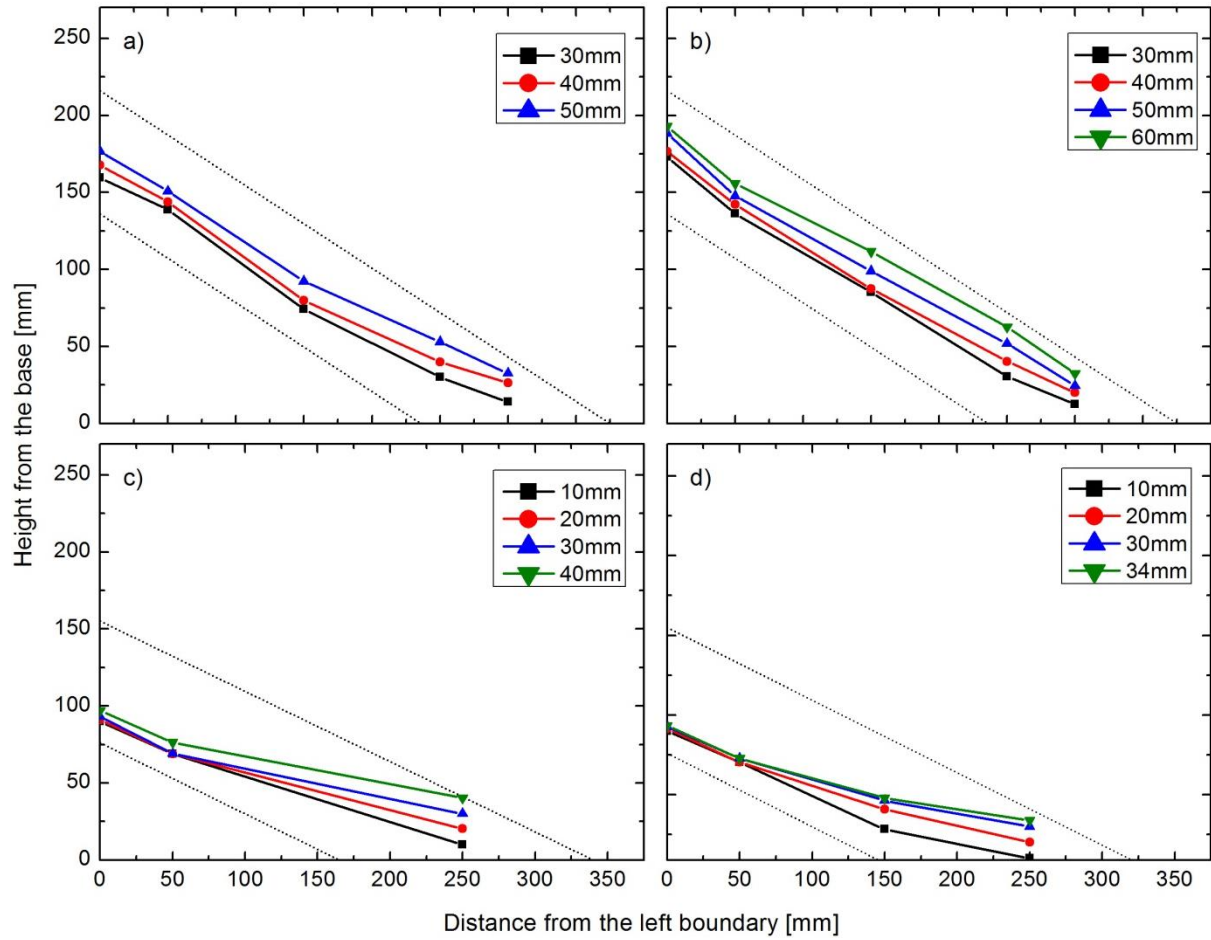
**Figure 8:** Photo of fibre before and after mixing: a) 1% by mass of finishing line and b) 2% by mass of Polyester.



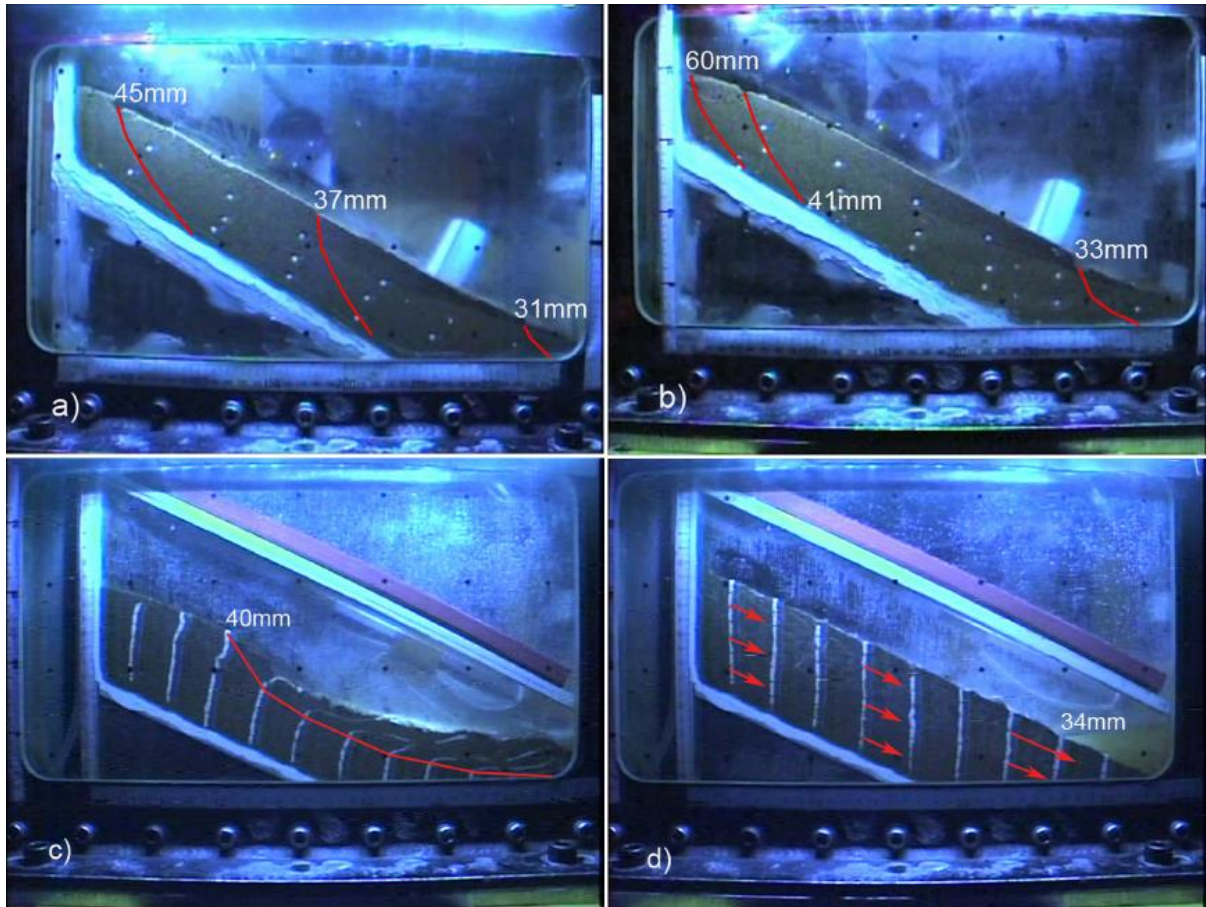
**Figure 9:** Direct shear results of Edosaki sand, fishing line, and polyester fiber mixed with Edosaki sand



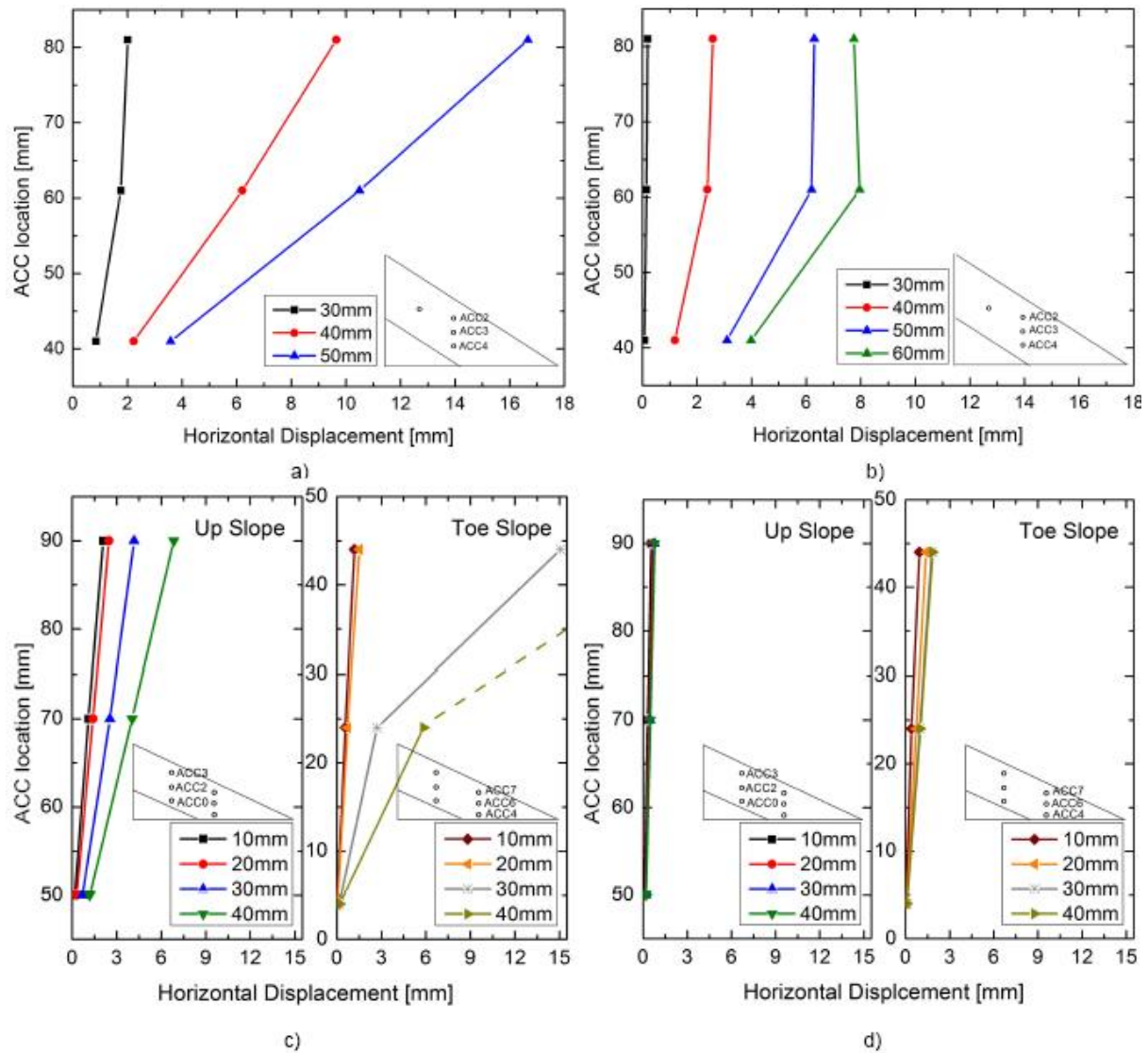
**Figure 10:** Schematic of centrifuge system: a) seepage model test and b) rainfall model test.



**Figure 11:** Variation of phreatic line: a) un-reinforced slope under seepage, b) 20 mm root-reinforced slope under seepage, c) un-reinforced slope under rainfall, and d) 40 mm root-reinforced slope under rainfall.



**Figure 12:** Variation of slip surface line: a) un-reinforced slope under seepage, b) 20 mm root-reinforced slope under seepage, c) un-reinforced slope under rainfall, and d) 40 mm root-reinforced slope under rainfall.



**Figure 13:** Soil displacement calculated from ACCs: a) un-reinforced slope under seepage, b) 20 mm root-reinforced slope under seepage, c) un-reinforced slope under rainfall, and d) 40 mm root-reinforced slope under rainfall.