博士論文

Evaluation of Hydraulic Property of Vegetated Ground based on Monitoring Data of Moisture Contents

（含水量の測定による植生地盤の水の浸透の評価）

By

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ABSTRACT

Vetiver is a clumping grass, which roots are massive and finely structured and grow very fast and deep. Because of its characteristic of special massive large roots, that anchors and penetrates straight into the ground, it can significantly contribute to stabilize soil on slopes and to prevent slopes from eroding and collapsing. The major advantage is a reinforcement of sloped ground by tensile root strength and prevention of scouring by restricting water flow on the slope surface.

However, the hydraulic properties of vegetated slope using vetiver grass have not been investigated and very few studies haves been conducted on negative effects of vegetation. This study aims at investigating the changes in water infiltration properties of ground corresponding to growth of root quantitatively. The hydraulic properties of the vegetated and the non-vegetated ground-slope are evaluated by monitoring the volumetric water contents in 1D column. Hydraulic conductivities in saturated condition are also measured and compared between the vegetated and the non-vegetated columns. By using the delay time analysis, defined as the lapse of time taken by soils before attaining the wetting status, the pick-up points were zoomed and were measured by volumetric water content sensors.

In this study, a method was proposed for evaluating the hydraulic properties of vegetated ground based on monitoring data of moisture contents. The experiments and simulations were: 1) Hydraulic conductivity tests on saturated, vegetated and the non-vegetated soil. 2) One-dimensional column model tests in the laboratory for vegetated and the non-vegetated soil. 3) Field measurement for water infiltration and drainage in vegetated and the non-vegetated ground, and 4) Analysis of the results by using a numerical analysis software HYDRUS 1D.

Based on the results of the analysis from both methodologies [HYDRUS1D and Delayed Time Analysis] the observations were consistent to confirm that the water infiltration rate of the column with covered vetiver was clearly increased more than non-covered vetiver column.

The conclusions derived from the results of experiment and modeling are given below:

- **Permeability tests**

The first tests on hydraulic conductivity were carried out using a none-vegetated soil sample and 3 more experiments were conducted with vegetated soil samples after vetiver were implanted in the following ratios of week per weight of roots: 1 week/ 1.80 g, 2 weeks/2.10 g, 4 weeks/2.35 g and 6 weeks/3.52 g. The objective was to observe the water infiltration into the vegetated soils. The above results of the experiment have shown that with 0.003g/cm3 of root density, the hydraulic conductivity was increased by 2 times for the permeable Edosaki sand and by 2.3 times for the less permeable Kunigami soil. Their increasing ratio is similar to each other.

- **Laboratory of measurement of 1D column model tests**

There is a reduction in delay time for water infiltration into the ground slope, probably due to the generation of water pathways along the surface of the root. The results of the 1D column test clearly indicated that the delay time for infiltration was reduced by the introduction of vegetation: 43 % for Edosaki sand, 33% for Kunigami soil, and 57% for Edosaki 1D.

The results indicated that time for drying was clearly reduced by the introduction of vegetation: 30 % for Edosaki 1D large column test, 5% for Kunigami 1D short column test, and 8% for Edosaki 1D short column test.

- **Site model tests**

The observations and the results of tests of delay time on wetting and drying process are as follows:

Vegetated-zone: The results show that on the vegetated zone, after covering with root network of 7 months, the water wetting was reduced by the introduction of vegetation 26 %. And the water drying was reduced by the introduction of vegetation 3%.

- **Numerical analysis by using the HYDRUS1D**

Effects of root on the material properties were considered in the Hydrus 1D by changing residual water contents and the hydraulic conductivities depending on the root density. The results clearly indicated that the delay time for infiltration was considerably reduced by the introduction of vegetation: 50% for Edosaki 1D large column test, 33% for Kunigami 1D short column test, and 59% for Edosaki 1D short column test.

Delayed time for drainage was reduced by the introduction of vegetation: 30% for Edosaki 1D large and 6 % for Edosaki 1D short, and 5% for Kunigami soil respectively.

The results from both analyses [Model &Experiment] are consistent and well harmonized and show delayed time for infiltration was reduced by the vegetation during the wetting process and drying process.

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CHAPTER 1. INTRODUCTION

1.1 Background

Landslides constitute a major geologic hazard in many Asian countries and in the world. An important factor responsible for landslide occurrences is the triggering mechanism. Worldwide statistics shows that 89.2 percent of fatalities were caused due to landslides triggered by intense and prolonged precipitation (Global distribution of landslides during 2007).

Slope ground stability problems are receiving increasing attention in Laos, particularly in unsaturated soil slope. Slope ground stability analysis of unsaturated slopes requires an extensive and detailed seepage analysis because slope failures in unsaturated conditions are closely related to heavy rainfall and infiltration.

In Laos, the problems encountered are as follows:

- Heavy rainfall causes landslide in more than 6 provinces, yearly
- Economic loss due to a landslide is very significant compared to yearly provincial budget.
- Disruption of the transport of goods and passengers.

A landslide can also be triggered by earthquake, rainfall, snow melting, groundwater variation, or human activities. Of all those, rainfall has the major role in triggering a landslide. For example, in Italy, 69.4% of the landslide is caused by precipitation and infiltration (Kalsnes et al, 2008)

Among natural hazards, landslides occur virtually in every country in the world, causing approximately 1000 casualties and property damages for about U.S. $ 4 billion per year (Orense, R.P. 2003). Rainfall-induced landslides are shallow in nature (Abramson L.W. 2002); often occur on slopes which are marginally stable and consisting of various types of soils such as colluvial and residual soils and can be triggered during or immediately after heavy rainfall (Anderson et al., 1995).

Correlation between rainfall and landslides has been well documented worldwide (e.g., Brand et al. 1984; Lumb, 1975; Pierson, 1977; Slosson and Larson, 1995); there have been many studies to determine rainfall thresholds for slope failures. Rainfall amounts exceeding 140 percent of normal, (mean average over 100 years) in southern California appear to be sufficient to trigger slope failures (Slosson, 1969; Slosson and Krohn, 1982); Lumb (1975) observed the influence antecedent rainfall on landslide occurrences. He examined slope failures in Hong Kong and correlated their occurrences with rainfall intensity as shown in Figure 1-1. It can be seen that:

- Some minor slips have occurred after 1-day heavy rainfall > 100mm with little antecedent rainfall; e.g. NUS and NTU Feb. Mar 1984 data.
- Other minor slips occurred at low 1-day rainfall with significant 5-day antecedent rainfall; e.g. NUS slip 28 Dec 1984 with 18mm rainfall, but after 5-day antecedent rainfall of 85mm.
- The data suggests that a total rainfall of 100mm within 6-day period (equivalent to a sustained 15-20 mm/day for 6 days) is the trigger for minor slips to occur in Singapore clayey residual soils.
- For large landslides; a total rainfall > 320mm seems to be the trigger.

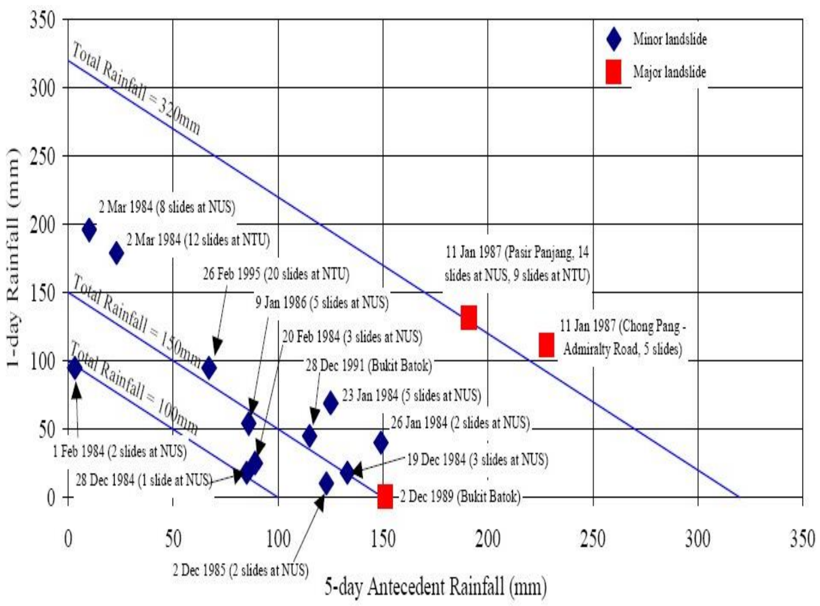

Figure 1-1- Plot of landslides and rainfall data in Singapore (from Siew-Ann, 2007).

The unsaturated zone is an integral component of the hydrological cycle where atmospheric processes play an important role in whether the soil is saturated or unsaturated. Saturated/unsaturated soil mechanics deals with theories that can be applied to both saturated and unsaturated soils, for example, those above the water table as well as those below the water table. By treating saturated soil behavior as a special case of the more general unsaturated soil concept, it can be shown that there is a smooth transition between these two types of soil and the entire soil profile can be treated as a continuum (Fredlund D.G & Rahardjo H., 1993).

Saturated soils consist of two phases: solid phase (representing the soil grains) and water phase (water occupying all the pore spaces). Since the entire pore spaces are not occupied by water in an unsaturated soil, it has a third phase representing the pore air. In this case, the pore water pressure is negative relative to the pore air pressure. The presence of negative pore water pressure (called soil suction) causes the difference in nature and behavior between saturated and unsaturated soils. The pore water pressure always has to be less than the pore air pressure in unsaturated soil due to the surface tension. Surface tension is the force that tends to hold the water together. Inside the pore spaces between grains, water films are also attracted to the grain surfaces and the effect of surface tension is to pull the particles together, as shown in Figure 1-2. Such pressure deficiency (i.e., negative pore water pressure relative to pore air pressure) is generally referred to as matric suction, or simply, suction (Orense R.P., 2003).

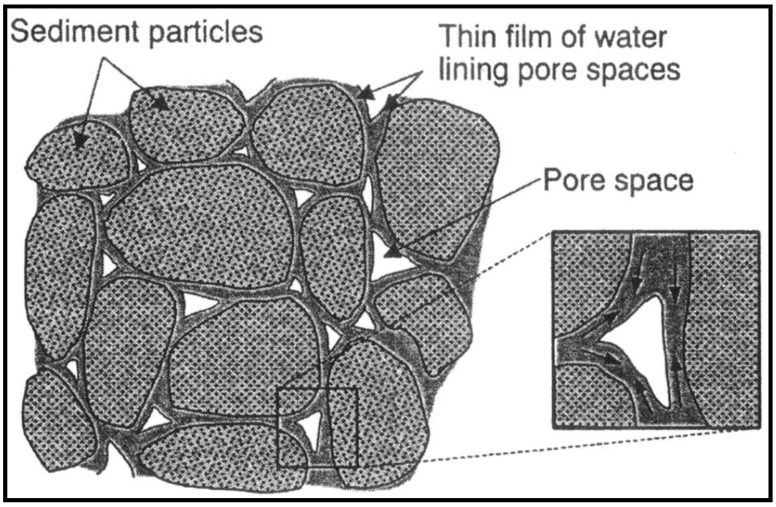

Figure 1-2- Effects of surface tension forces in pulling the soil grains together (from Orense R.P., 2003).

In this study, infiltration is analyzed by performing unsaturated sandy columns and slope model tests subjected to artificial rainfall and considering the influence of rainfall intensity-duration, initial water contents (IWC), dry density (ρ_d) on hydrological response and failure mechanism.

Additionally, the effects of vegetal cover on rainfall infiltration through unsaturated slope models is analyzed and compared with those observed on sandy columns and slope model tests. Rainfall-Induced Landslides

Landslides are often triggered by rainfall, particularly in the tropical climate of SE Asia which is characterized by very intense long duration rainy seasons. Rainfall induced landslides are usually shallow slips, and they have occurred frequently in Laos. Population and infrastructure facilities, particularly the road network infrastructure are frequently affected by the effects natural hazards causing a lot of casualties and material damages around the world; in that sense, rainfall induced landslides can be considered one of the most significant geoenvironmental hazards which make important to understand its mechanism and triggering factors during a rainstorm and to identify the most vulnerable zones where it can happen.

Methods based on the correlation between rainfall and frequency of slope failures The incidence of slope failures has been correlated with rainfall in several instances. Such correlations do not constitute a design method as such, but they enable probabilities of failure to be deduced. Simple correlation has been made for various geographical locations, for example, Lumb (1975) and Brand (1984) for Hong Kong, Nilson et al. (1976) for Alameda county, California Eyles (1979) for Wellington, New Zealand, Fukuoka (1980) for central Japan among others. In the following, some of these methods are briefly described.

For Hong Kong area, Lumb (1975) has examined the effects of rainfall over the period 1950-1973 in terms of the following four categories of slope failure event:

(a) Disastrous event – Territory-wide damage, with more than 50 individual slip recorded
(b) Severe event-widespread damage, with less than 10 and 50 slips in one day
(c) Minor event – localized damage, with less than 10 slips in one day
(d) Isolated event – a single individual slip

The results of his study are shown in Figure 1-1, together with discriminatory or predictive zones for different types of event. According to this method, disasters occur when daily rainfall exceeds 100mm and the antecedent 15-days rainfall exceeds 350mm.

A similar method, to predict the occurrence of a rain-induced failure, was proposed by Fukuoka (1980) for the area of central Japan. His method for obtaining the possible occurrence of slope ground failure was based on the relationship between the preceding total amount of rainfall and the intensity of the rainfall at a particular time. The total area in his diagram was divided into four regions using contours indicating potential slope failure frequency. The contours given are for the no slide case, one slide per square kilometer, five slides per square kilometer and more than ten slides per square kilometer. However, this method is limited to the area of 1000 km^2 – 2000 km^2.

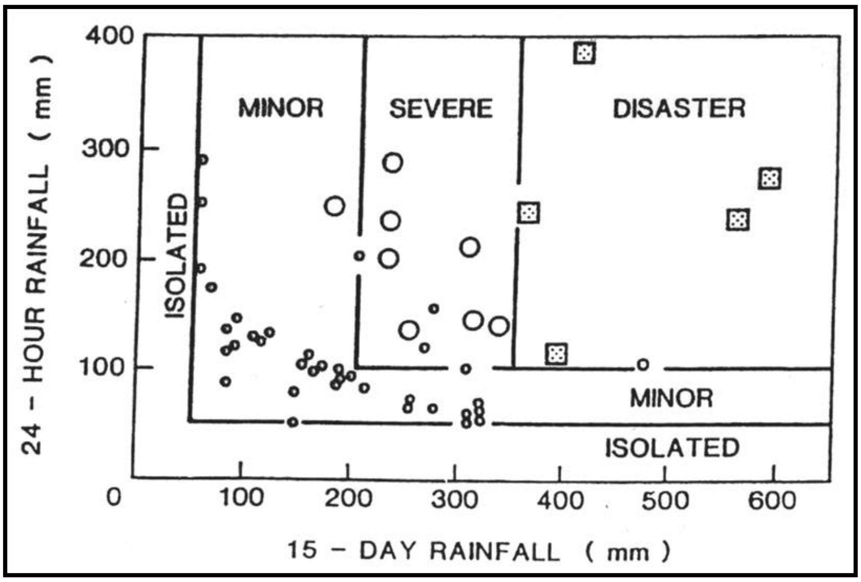

Figure 1-3- Relationship between rainfall and landslides in Hong Kong (Lumb, 1975)

1.2 Mechanism of rainfall-induced landslides

Numerous researchers have been investigated on the mechanism of rainfall-induced landslides (e.g., Brand, 1981; 1982; Brenner et al., 1985; Atkinson and Farrar, 1985; Anderson and Sitar, 1995; Farooq, K. 2002; Chaminda, G. 2006, Yuki M. 2006). Orense, R. P; 2003, explain how when rainwater infiltrates through the soil profile, which initially is unsaturated state reduction is soil suction (or negative pore pressure) occurs; therefore, a decrease in the effective stress on the potential slip surface and reduction in the soil strength, leads the slope to a point where equilibrium cannot longer be sustained.

Failure occurs under constant total stress and increasing pore pressure, in that sense understanding the infiltration process, hydrological response and moisture content distributions throughout the slope during a rainfall event, is important to define the most susceptible zones in which saturation takes place and failure will occur.

Many geotechnical problems such as bearing capacity, lateral earth pressure, and slope stability are related to the shear strength of a soil. The shear strength of a saturated soil is described using the Mohr-Coulomb failure criterion and effective stress concept (Terzaghi 1936) as shown in equation 1.1.

$$\tau = c' + (\sigma_n - u_w)\tan\phi' \qquad (1.1)$$

where:

$\tau =$ shear strength

c' = effective cohesion (shear strength intercept when the effective normal stress is zero)

$(\sigma_n - u_w)$ = effective normal stress

σ_n = total normal stress

u_w =pore water pressure

ϕ' =effective angle of internal friction

The shear strength of an unsaturated soil can be formulated in terms of independent stress state variables (Fredlund et al. 1978). Any two of the three possible stress state variables can be used for the shear strength equation. The stress state variables $(\sigma_n - u_a)$ $(u_a - u_w)$ have been shown to be the most advantageous combination of practice. Using these stress variables, the shear strength equation is written as shown in equation 1.2.

$$\tau = (\sigma_n - u_a)\tan\phi' + c \qquad (1.2)$$

$$c = c' + (u_a - u_w)\tan\phi^b$$

where τ is shear strength of unsaturated soil, c is apparent cohesion, c' is effective cohesion of saturated soil, ϕ' = is the shearing resistance angle which is assumed to be constant for all values of matric suction and is equal to that of saturated condition, ϕ^b is the angle of shearing resistance with respect to suction, σ_n is the total normal stress on the plane of failure, u_a is air-pressure in the soil mass, u_w is pore-water pressure and (u_a-u_w) is the matric suction of the soil in the failure plane.

A comparison of equations 1.1 and 1.2 reveals that the shear strength equation for an unsaturated soil is an extension of the shear strength equation for a saturated soil. For an unsaturated soil, two stress state variables are used to describe its shear strength, while only one stress state variable (i.e. effective normal stress $(\sigma_n - u_w)$) is required for a saturated soil.

The unsaturated soil has been commonly referred to as a three-phase system (soil particles, water, and air) (Lambe and Whitman, 1969), as shown in Figure 1-4.

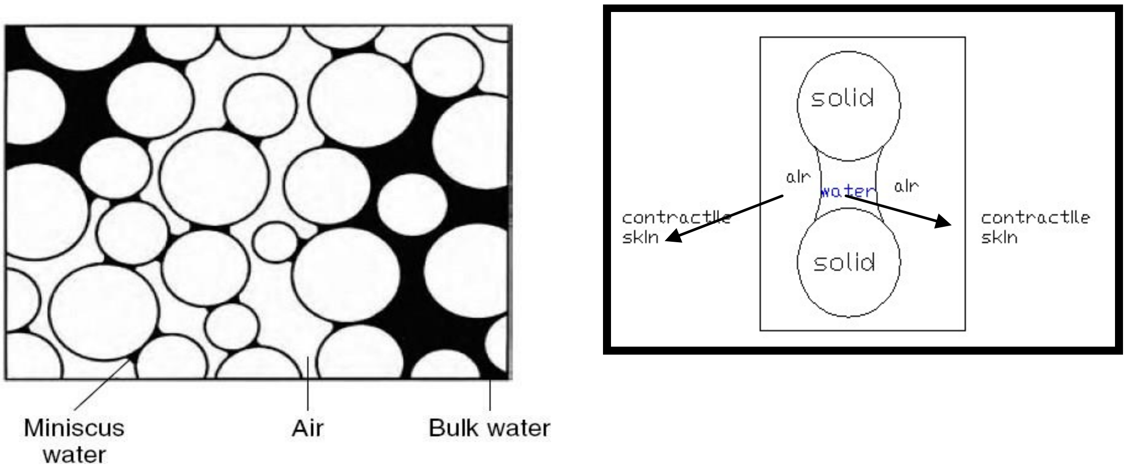

Figure 1-4- Idealized phases in unsaturated soil and air-water interface

Understanding the nature of water movement through the unsaturated zone and its quantification has been of interest by disciplines as hydrologist, geologist, soil scientists geotechnical and environmental engineers, agriculture engineers etc. and is essential to solving a variety of problems like prediction of runoff generated from heavy rainfall for erosion, sediment transport and flooding control, rainfall-induced landslides, estimation of recharge of aquifers, estimation of availability of water for plants growth and velocity at which a contaminant travels across this zone etc.

1.3 Description of previous studies related to the use of vegetation as a tool for erosion and shallow mass movements control

Numerous studies have demonstrated that vegetation coverage is very important to control soil erosion by water. Vetiver grass is a perennial grass of gramineae, which is originated from Southeast Asia, India, and tropical Africa. Nowadays, more than 100 countries or areas cultivated and used vetiver and has been shown to be a simple and economical method to conserve soils, trapping, sediment and filtering out nutrients; In addition, vegetated ground technique on slope stability has been recognized to provide an attractive cost-effective countermeasure against erosion, slope disaster and shallow mass movements etc. Vetiver is a clumping grass, which its roots are massive finely structured and grow very fast and deep. It is a true miracle grass by its character of special massive long roots that anchoring and penetrating straight into the ground.

Vegetation plays an important role in controlling surface erosion restraining aggregates and soil particles and preventing them from being washed out by runoff during heavy rain; in that sense, it has been used for many centuries to control erosion problems on slopes and along river banks in different parts of the world.

Biotechnical stabilization offers a cost-effective and attractive approach against erosion and shallow mass movements; for that reason, it has gained considerable recognition in civil engineering during the recent years (Greenway, 1987; Coppin and Richards 1990; Gray 1994). It has been recognized that by maintaining a dense cover of sod, grasses or herbaceous vegetation, soil losses can be decreased a hundredfold (USDA Soil Conservation Service, 1978). In addition, it has been recognized that vegetation increases the shear strength by reinforcement at the roots zone, increasing the potential application of vegetation as a control tool for erosion and shallow mass movements (Endo and Tsuruta 1969; Ziemer 1981; Coppin and Richards, 1990; Gray and Sotir, 1996).

Vegetation influences the hydrological process by intercepting rainfall and decreasing the runoff velocity at the soil's surface as a consequence of the increase in permeability by roots penetration (Gray and Sotir, 1996; Goldsmith and Bestmann, 1992). Although some roots penetrate deeply, maximum root densities of many plants, are found to be at the top 20 cm or even in only a few centimeters of the soil's profile (Odhiambo et al., 2001); interaction between the rainfall and the soil-water content in the root zone is still unknown (Serrano, 1990). there is hydrologic evidence of the existence of a macropore flow zone in the top layer of most natural soils created by the penetration of roots from plants, animal burrows and natural soil weathering (Sloan, G. et al 1983); Therefore, how vegetation regulates the hydrological response of the slope during a rainstorm has not been well addressed, research techniques and methods are still under development and require the support of interdisciplinary fields.

Root effects on water infiltration (Z.C. Zhou, Z.P. Shangguan, 2006). Figure 1-5 indicates that the initial infiltration rate increased with root growth. With infiltration going on remarkable effect on infiltration appeared compared with the infiltration in the control at different growing stages. In addition, the average infiltration rate increased with increased RSAD during the experiment (Figure 1-6).

The root role of the living plant in improving soil physical properties affecting soil infiltration has been discussed. It is known that roots release various organic and inorganic substances into the soil (Hawes et al., 2000), which can improve soil physical properties around roots and thus increase soil aggregate stability and then infiltration rate (Martens, 2002). It is found that as soil water potential decreases, root exudates begin to release water into the soil. When this occurs, the surface tension and viscosity of the exudates increase. As the viscosity increases the resistance of soil particles contacting root exudates to water movement increases, and the stabilization within rhizosphere is enhanced to some extent. And this promotes soil infiltration (McCully and Boyer, 1997). Meanwhile, previous studies have reported that all plants from root channels which promote water entry as well as increase the infiltration rate (Devitt and Smith, 2002).

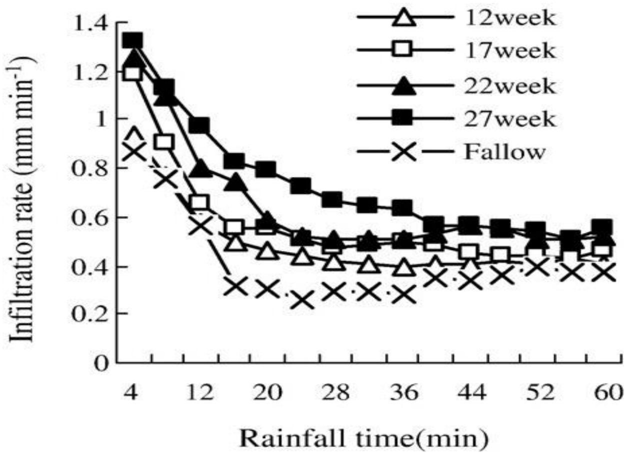

Figure 1-5- Infiltration dynamics at different growing stages in the shoots removed pans and follow pans, (from Zhou, Z.C. And Shangguan, Z.P., 2007).

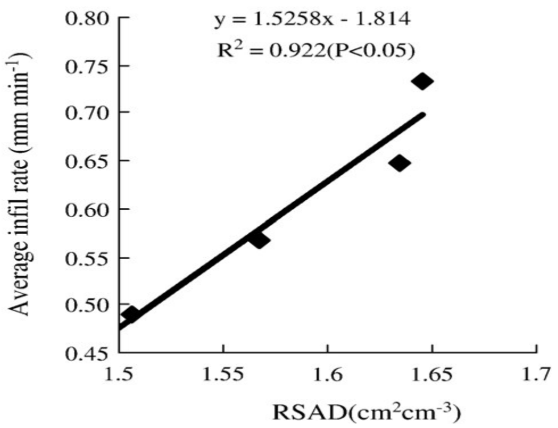

Figure 1-6- Relationship between the average infiltration rate and the root surface area density (RSAD) in the shoots removed pans. **(from** ***Zhou, Z.C. and Shangguan, Z.P.,*** **2007*)***

Special characteristics of vetiver grass make it suitable for infrastructure protection purposes (Truong, 2005). Due to the following unique attributes Vetiver grass has been researched, tested and developed into a very effective bioengineering tool. Some of its characteristics are enlisted:

- Extremely deep and massive finely structured root system, capable of reaching down to 2 to 3m in the first year. This extensive and thick root system binds the soil and at the same time makes it very difficult to be dislodged and extremely tolerant to drought.

- The tensile strength of vetiver roots varies between 40-180 Mpa. The mean design tensile strength is about 75 Mpa - equivalent to approximately one sixth of mild steel. This indicates that vetiver roots are as strong as, or even stronger than that of many hardwood species, which have been proven positive for root reinforcement in steep slopes (Figure 1-7).
- New roots are developed from nodes when buried by trapped sediment. Vetiver will continue to grow with the new ground level eventually forming terraces if trapped sediment is not removed
- Stiff and erect stems which can stand up to relatively deep water flow (0.6-0.8m).
- Dense hedges when planted close together, reducing flow velocity, diverting runoff water and forming a very effective filter.
- Tolerance to extreme climatic variation such as prolonged drought, flood, submergence and extreme temperature from -14^{o}C to 55^{o}C.(Truong et al., 1996)
- Ability to re-grow very quickly after being affected by drought, frost, salt and other adverse soil conditions when the adverse effects are removed .
- High level of tolerance to soil acidity, salinity, sodicity and acid sulfate conditions, (Le and Truong 2003).

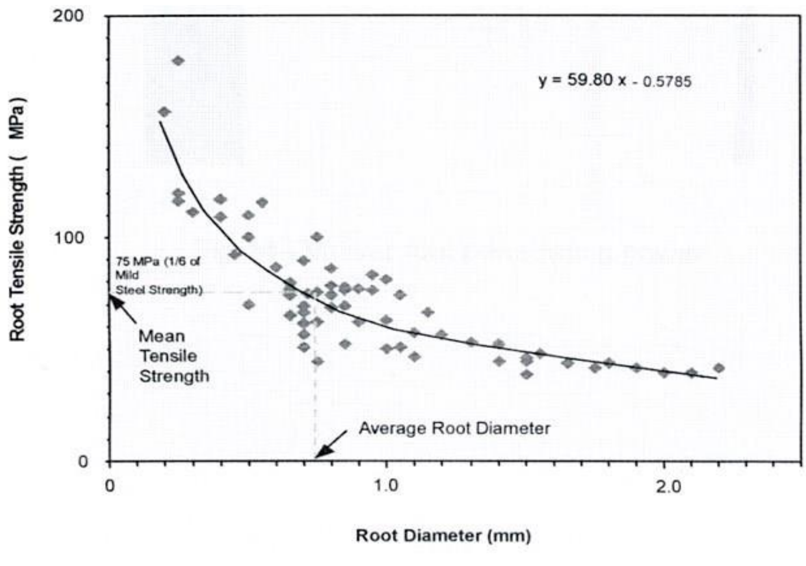

Figure 1-7- Relation between the root diameter and the root tensile strength (from Truong, P., 2005).

Hengchaovanich and Nilaweera (1996) showed that the tensile strength of vetiver roots increases with the reduction in root diameter, implying that stronger fine roots provide higher resistance than larger roots. The tensile strength of vetiver roots varies between 40180 Mpa for the range of root diameter between 0.2-2.2 mm. The mean design tensile strength is about 75 Mpa (equivalent to approximately one sixth of mild steel) at 0.7-0.8 mm root diameter which is the most common size for vetiver roots. This indicates that vetiver roots are as strong as, or even stronger than those of many hardwood species which have been proven positive for slopes reinforcement.

In a soil block shear test, Hengchaovanich and Nilaweera (1996) also found that root penetration of a two-year-old Vetiver hedge with 15cm plant spacing can increase the shear strength of soil in adjacent 50 cm wide strip by 90% at 0.25 m depth. The increase was 39% at 0.50 m depth and gradually reduced to 12.5% at 1.0 m depth. Moreover, because of its dense and massive root system, it offers better shear strength increase per unit fiber concentration (6-10 kPa/kg of root per cubic meter of soil) compared to 3.2-3.7 kPa/kg for tree roots.

Other less well-known characteristics of Vetiver grass is it the power of penetration. Its ‘innate’ strength and vigor enable it to penetrate through difficult soil, hardpan or rocky layers with weak spots. Vetiver roots basically behave like living soil nails or dowels of two to three-meter depth. Together with its fast growing ability in difficult soil conditions, these characteristics make the grass a much better candidate for slope stabilization than other plants.

First intensive tensile strength research on vetiver roots was done by Diti Hengchaovanich. He showed that vetiver root strength is stronger than most trees and grass commonly used for steep slope stabilization as shown in Table 1.1 (Hengchaovanich ,1998).

Table 1.1 Tensile Strength of Roots of Some Plants

Botanical name	***Common name***	Tensile strength (Mpa)
Salix *spp*	Willow	9-36*
Populus spp	Poplars	5-38*
Alnus spp	Alders	4-74*
Pseudotsuga spp	Douglas fir	19-61*
Acer sacharinum	Silver maple	15-30*
Tsuga heterophilia	Western hemlock	27*
Vaccinum spp	Huckleberry	16*
Hordeum vulgare	Barley Grass, forbs Moss	15-31* 2-20* 2-7kPa*
Vetiveria zizanioides	Vetiver grass	40-120 (Average 75**)

(http://www.vetiver.org/ICV3-Proceedings/THAI_slopestab.pdf)

Cheng *et al* (2003) supplemented the Diti Hengchaovanich's root strength research by conducting further tests on other herbs (grasses) as shown in Table 1.2. Although Vetiver has the second finest roots, its tensile strength is almost 3 times higher than on the plant tested.

Table 1.2 Diameter and tensile strength of root of various herbs

Grass	Mean diam. of roots (mm)	Mean tensile strength (MPa)
Late Juncellus	0.38±0.43	24.50±4.2
Dallis grass	0.92±0.28	19.74±3.00
White Clover	0.91±0.11	24.64±3.36
Vetiver	0.66±0.32	85.10±31.2
Common Centipede grass	0.66±0.05	27.30±1.74
Bahia grass	0.73±0.07	19.23±3.59
Manila grass	0.77±0.67	17.55±2.85
Bermuda grass	0.99±0.17	13.45±2.18

More recently a software developed by Claudio Amati, PE with the University of Milan to determine the additional sheer strength provided to the soil by Vetiver roots in various soils under vetiver hedges treatments. This software is particularly suitable to assess the contribution of vetiver roots needed for the application of VS on steep batter stabilization particularly earthen levees, where vetiver hedgerows will protect and consolidate the slopes and therefore the levees themselves.

Vegetation exerts an enormous influence on soil water dynamics, (A. G. Bengough, 2011) Plant roots contribute enormously to the terrestrial cycling of water, to the maintenance of the soil biophysical matrix, and to soil ecosystem function. Evapotranspiration represents approximately 59% of terrestrial precipitation (Oki and Kanae, 2006), so the transpiration component is probably about 40% of terrestrial precipitation. This transpired water will pass through the rhizosphere with a probable mean residence time of hours to days (e.g., 100 cm root cm−2 vegetated surface, root diameter 0.2 mm, 1-mm rhizosphere, 0.3 cm d^{-1} transpiration rate, 0.2 cm^3 cm−3 soil water content, would give a rhizosphere residence time of 2 d). Plant roots continually and efficiently till the soil, with the work done on the soil during root extension of perhaps 10 MJ ha−1 yr−1 for a cereal field (e.g., 0.4-mm-diameter roots, 0.2-MPa growth pressure, 300 cm cm−2 annual root extension, giving 8 MJ ha−1 yr−1). Th seems a remarkably efficient process when compared with the hundredfold greater 1 GJ ha−1 required for plowing using farm machinery (Arvidsson, 2010). The nature of the soil deformation and failure caused by plant roots is physically very different from that caused by a plow, with the length, diameter, and continuity of individual macropores created by roots often being distinct (Jassogne et al., 2007; White and Kirkegaard, 2010).

Similar dynamic information on water content changes in rhizosphere and bulk soil have been obtained recently using neutron imaging, although this technique requires specialist facilities available only in certain countries (Figure 1-8). The rhizosphere of lupin retained a water content greater than expected as the soil dried but was slower to rewet after watering. Such hysteretic behavior is probably due to changes in the rhizosphere water retention characteristics. These changes are associated with physical changes in the soil structure as well as with exudates released by the roots and associated microbes and are discussed below.

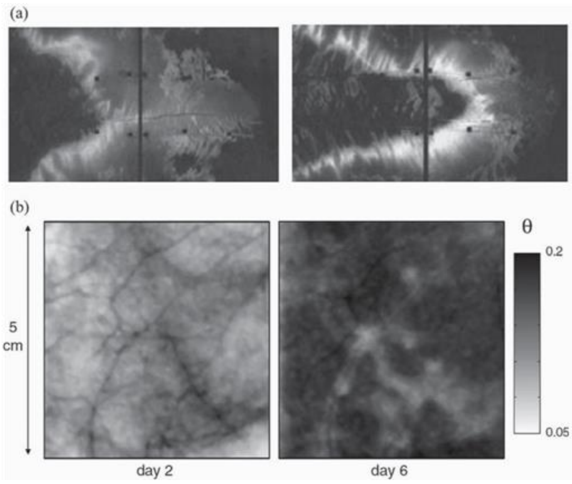

Figure 1-8- Imaging **water dynamics in the root zone: (a) difference images showing a change in water content around lupin roots grown in the sand at 50 d (reproduced from in Garrigues et al., 2006).**

(b) Neutron radiography of soil adjacent to roots, showing that the soil adjacent to the roots is initially darker and so probably wetter than the bulk soil while after rewatering the soil adjacent to the roots is brighter than the bulk soil, suggesting that it is relatively drier (reproduced from Carminati et al., 2010).

Regarding rhizosheath, its mass per unit length increases with root hair length (Haling et al., 2010). The soil in the rhizosheath and rhizosphere may well have properties significantly different from those of the bulk soil due the close proximity of the root as a source of exudates and a sink for water and nutrients (Hinsinger et al., 2009).

How Roots Influence Rhizosphere Physical Properties, roots change the size distribution and connectivity of soil pores. In pushing through the soil, they compress the matrix of soil pores around them to accommodate their own volume; the soil immediately adjacent to the root surface may contain 23% less pore space than the bulk soil (Bruand et al., 1996). Roots release a complex mixture of organic compounds into the soil, including sugars, amino acids, organic acids, phospholipids, and pectin-like polysaccharides. Much of the material is released from the root cap and serves to lubricate the penetration of soil by the root tip, in addition to the production of border cells from the root cap that may completely coat the surface of root tips growing in compacted soils and cushion the root proper from the abrasive soil particles (Iijima et al., 2003). Root hairs, typically 10 μm diameter, emerge from the epidermis behind the elongation zone and persist for a period of days or weeks, typically penetrating the rhizosphere to a distance of up to several millimeters. The root hairs increase the radial distance from which roots extract water and nutrients from the rhizosphere soil and provide an added source of C from root hair exudates and senescing root hair tissue. These hairs are also largely responsible for the soil rhizosheath that forms around excavated root systems; a rhizosheath is almost completely absent in root mutants that lack root hairs (Figure 1-9), while rhizosheath mass per unit length increases with root hair length (Haling et al., 2010). The soil in the rhizosheath and rhizosphere may well have properties significantly different from those of the bulk soil due the close proximity of the root as a source of exudates and a sink for water and nutrients (Hinsinger et al., 2009).

Changes in the water retention properties of the rhizosphere have been studied recently using several different approaches, each with its own advantages and limitations. These include adding particular root exudate compounds to the soil (Read et al., 2003), testing soil aggregates collected from adjacent to the root surface (Whalley et al., 2005), and in situ imaging of the soil water content around roots (Carminati et al., 2010). The advantage of adding compounds to the soil is that the effects of each exudate component can be quantified and understood separately. Adding lecithin to soil and sand resulted in the rhizosphere retaining relatively less water as the suction increased (Figure 1-10). The effect was greater for sand than for sandy loam soil and for relatively small suctions (e.g., 2–15 kPa), probably because the surfactant had to be present in sufficient quantity to cover the menisci in water-filled pores.

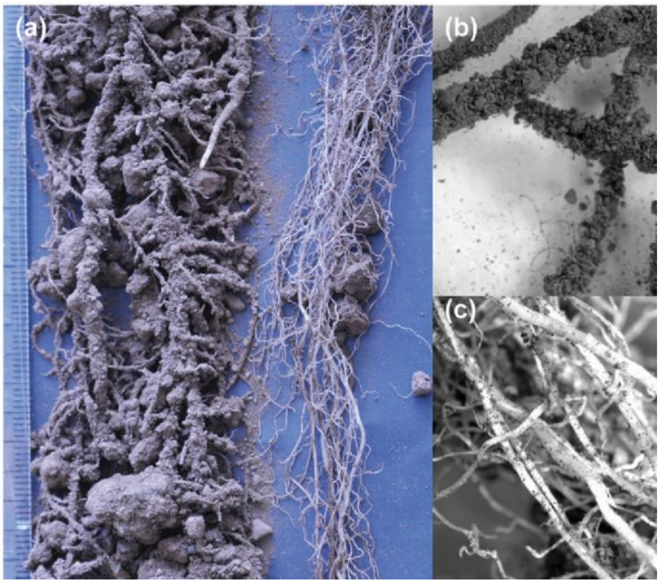

Figure 1-9- The soil rhizosheath around ordinary (wild-type) barley roots, left; b, close-up) is largely absent in root mutants that lack root hairs (a right; c, close-up), millimeter scale is indicated on the ruler.

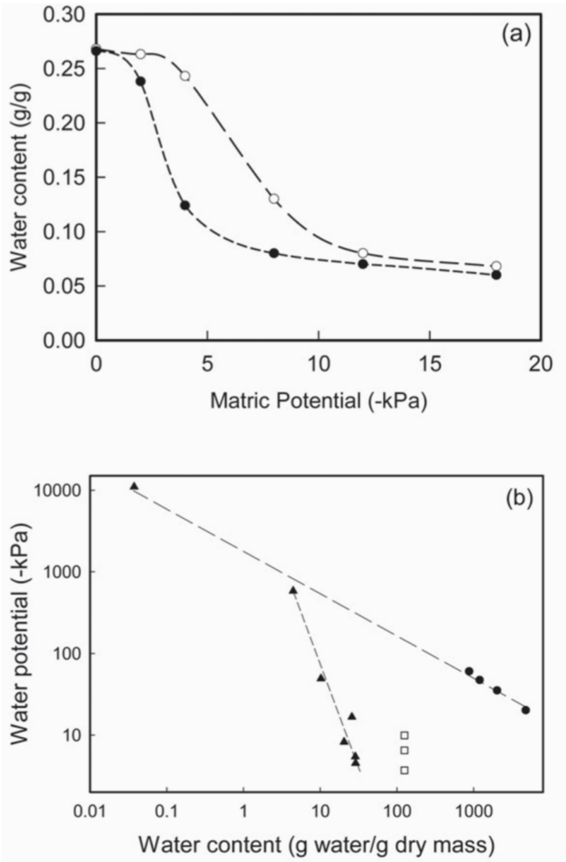

Figure 1-10- Water-release curves for (a) sand with (solid circles) and without (open circles) lecithin (data after Read et al., 2003); (b) root mucilage and artificial gel media (squares are washed gels; triangles are nodal root mucilage from McCully and Boyer, 1997; circles are primary root mucilage from Read and Gregory, 1997).

The characteristics of water flow, matric suction changes, and shear strength of soils are the main parameters associated with rainfall-induced slope failures in unsaturated soils. These parameters are directly affected by the flux boundary conditions (infiltration and evaporation) at the soil-atmosphere interface. The effect of infiltration on water flow through an unsaturated soil can be predicted using unsaturated soil mechanics theories, Yeh, H.F., J.F. Chen and C.H. Lee (2004).

1.4 Motivation and significance

Infrastructural construction of highway and hydropower has been developing rapidly in recent years in South East Asian countries and particularly in Laos. However, the phenomenon of soil and stone erosion and landslip frequently occur on the slopes formed by mountains excavation and ravines filling. The general engineering measurement is to stabilize the slopes with concrete, which needs high investment (Xia et al., 1999). Therefore, it is very difficult to be implemented. Ecological engineering measurement developed in last twenty years, using the powerful root system of plants, to stabilize soil and stone on a slope and to prevent slope from eroding and collapsing.

The growth of world's population is an important factor for the growing of the cities around the world. However, in some cases, a carefully urban planning is not taken into account, allowing people to be settled and developing infrastructure at the zones where natural hazards are high.

Rainfall induced landslides are considered one of the most important natural hazards causing lots of casualties and material damages around the world. In that sense, understanding the failure mechanism and establish the prone areas where failures can occur has been of interest during last decades not only in technical but also in social and economic disciplines.

1.5 Aims and scope of the study

This study aims at the quantitative investigation of changes in water infiltration properties of ground corresponding to growth of the root. The evaluation of hydraulic properties is used as the key parameter to assess the probability of failure events in an area of the ground slope. In order to analyse the hydrological response of vetiver root and to evaluate the effect of root on water seepage, two columns, with and without roots were installed. The hydraulic properties of the vegetated and none-vegetated on the columns were evaluated by using the volumetric water contents (VWC) and pore water pressure (PWP) sensors to measure the behaviors of water passed through the columns.

Mitigation of damages caused by rainfall-induced slope ground failures can be classified broadly into two categories: Hard type approaches, such as slope ground stabilization method as in the use of retaining walls, dewatering techniques, anchor piles, etc. and soft type approaches, such as implementing appropriate alarming and warning systems. Considering the extent of potentially unstable slopes, the first category may not always feasible due to financial and environmental constraints. A monitoring system, therefore, offers viable alternatives. In some locations like Hong Kong(Brand et al. 1984),the san Francisco Bay area(Keefer et al.1987),Honolulu(Wilson et al.1992), and Japan (Okada and Sugiyama 2001)warning systems have been utilized to minimize risk. These warning systems, which are based on the correlation between the rainfall intensity and frequency of landslides, are highly empirical. They do not consider the response of the ground during the infiltration process, i.e., changes within the soil state which is directly related to a landslide, such as the degree of saturation, pore pressure, and deformation are not considered (Orense 2004).

Thence it is essential to establish new criteria for issuing a warning for slope ground failure based on the physical soil mechanics. Therefore, the scope of this study is:

1. Permeability test, the hydraulic conductivities [saturated condition] of vegetated/non-vegetated ground were measured with the standard technique of permeability test with constant water head;
2. One dimensional column test, two columns, vegetated and non-vegetated respectively, were installed for one-dimensional seepage tests. To analyze the hydrological response of vetiver root and to evaluate the effect of root on water seepage;
3. Site model test, locating at the Institute of Industrial Science (IIS), the University of Tokyo in Nishi Chiba. series of volumetric water content sensors are installed in vertical direction just near the plant on the both test field, vegetated and non-vegetated zone; and
4. Numerical analysis by using the HYDRUS-1D modeling and application based on 1d column and site model test results.

1.6 Thesis organization/outlines

This thesis is organized into seven chapters. The present chapter has introduced the background information on the study of the art in the topic of rainfall-induced landslides, including a description of the failure mechanism generated from rainwater infiltration, the most common methods to predict rainfall thresholds which may cause landslides and some historical cases of rainfall-induced landslides around the world and a description of previous studies related to the use of vegetation as a tool for erosion and shallow mass movements control.

In chapter two presents the physical properties of test materials which are used in the experimental investigation of this study.

Chapter three, the explanation about the apparatus used for the experiment together its setup and calibration of sensors used for measurement; it is important to see that in some cases equipment were specifically designed or modified according to the test type, for this reason, this section is presented in two parts; one showing the general equipment as sensors, data logger etc.; and the other refers to the specific apparatus used in each test.

Chapter four elucidates the testing methodology and procedure on the hydraulic conductivities [saturated condition] on the vegetated and non-vegetated ground, including its results and analysis

Chapter five elucidates the testing methodology and procedure on the laboratory column model test [one-dimensional flow] on the vegetated and non-vegetated ground, including its results and analysis and site model test [locating at IIS, Nishi Chiba] on the two fields zone (vegetated and non-vegetated zone), including its results and analysis

Chapter seven presents the results and analysis by using the HYDRUS-1D application and modeling based on 1d column and site model test results, including its results and analysis.

Finally, chapter eight presents the summary and conclusions of this study by describing the main findings in each chapter and coupling all of them on a main central conclusion; also some recommendations for further researchers are made in order to improve the research techniques and methods used in this thesis.

1.7 References

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CHAPTER 2. TEST MATERIALS

2.1 Test material

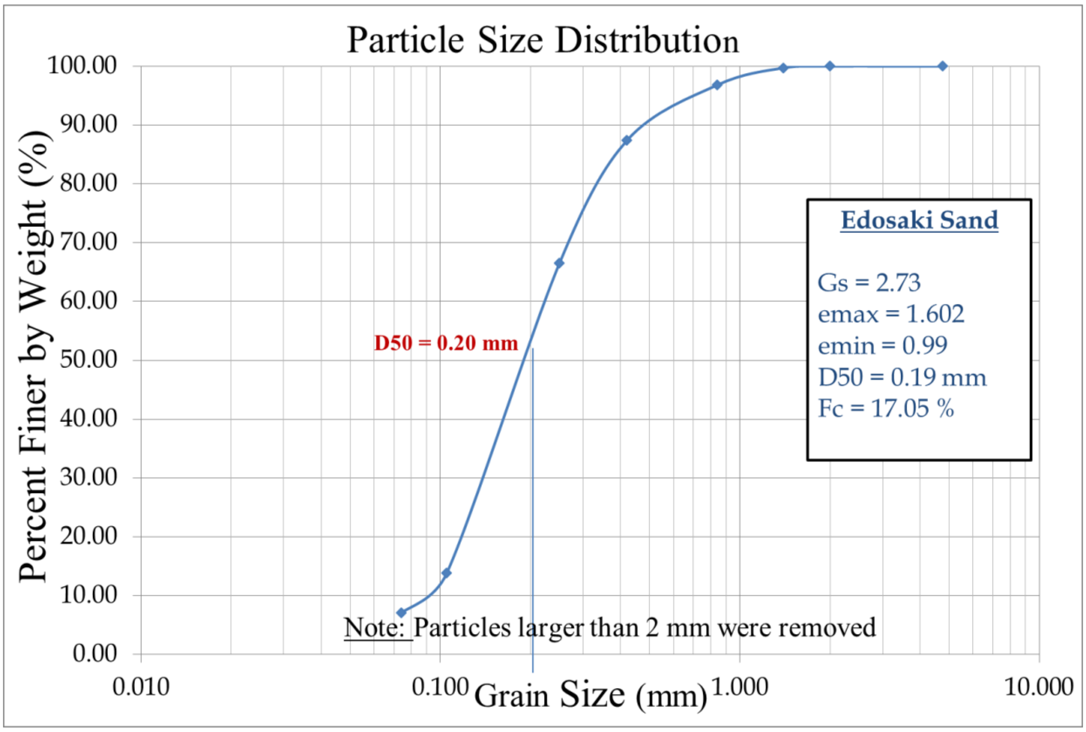
In order to process the experiment properly and to guarantee uniformity of the soil particles on the specimen and implementing a reliable and precautionary process of specimen preparation is necessary.

For this series of tests, three materials from Japan were chosen: Chiba soil, Kunigami soil and well graded natural sand called Edosaki sand which is often used as backfill material in construction sites. Edosaki sand was obtained from a natural slope in Ibaraki prefecture (Japan). Chiba soil was excavated from the Institute of Industrial Science, the University of Tokyo (IIS), Nishi Chiba in Chiba Prefecture (Japan). Kunigami mahji soil was gathered from Okinawa prefecture, which is located in the monsoon region and has a humid subtropical climate, and it is similar to those of tropical regions in South East Asia. Kunigami mahji is red-yellow in color and is regarded as a problem attic soil from the point of view of erosion.

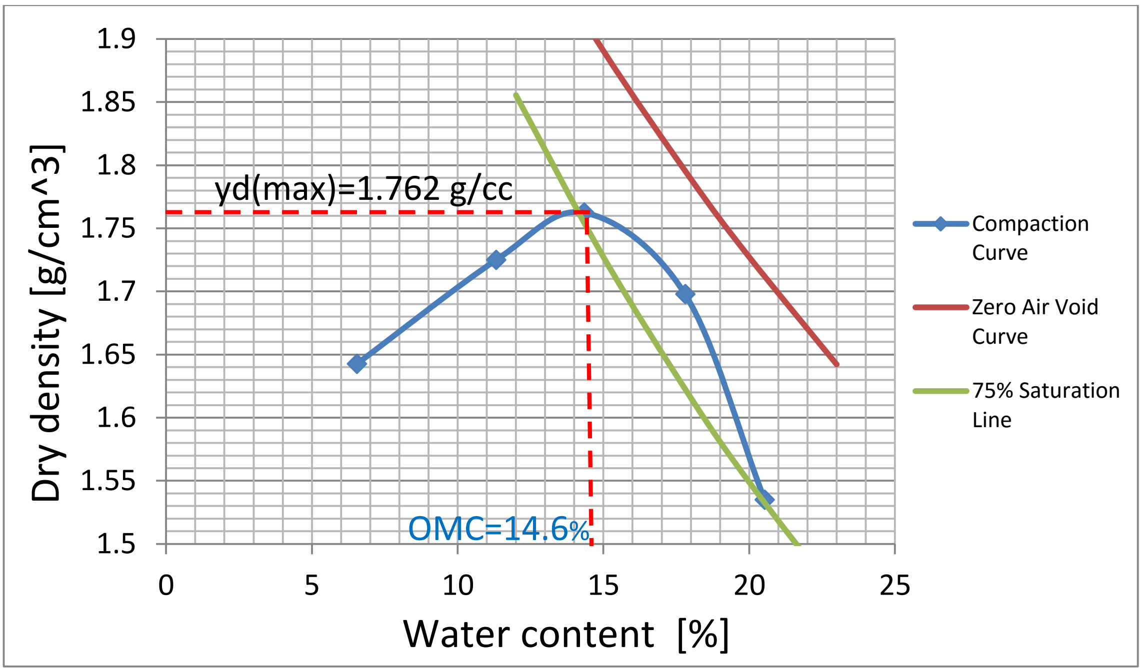
2.2 Physical properties of test materials

The sieve and hydrometer analysis on Edosaki sand and Chiba soil was conducted for the test, since these materials have fines contents of 17.05, and 35.9%, respectively. The grain size distribution curves of testing materials were performed by using mechanical sieve method. Edosaki sand is classified as silty sand; grain size distribution curve is presented in Figure 2.1(a), the dry density and water content, are shown in Figure 2-1.

The mean grain size, the coefficient of uniformity, and the coefficient of gradation are listed the specific gravity (Gs), the maximum void ratio (e_{max}), and the minimum void ratio (e_{min}) for all test materials were determined according to the Japanese standards (5~10 trials were done on each test material for each test) and the results are shown in Table 2.1.



(a)



(b)

Figure 2-1* (a)- *Edosaki Sand Grain Size Distribution Curve, (b)-Edosaki Sand, the relation of the water content and dry density

Table 2.1. Properties of the materials used

Table 2.2

Properties	Edosaki sand	IIS, Chiba soil	Kunigami
Specific gravity, Gs	2.73	2.72	2.75
Mean Grain size, D50 [mm]	0.20	0.139	0.103
Coefficient of uniformity, C_u¼D_{60}/D_{10}	17.10	54.40	57.5
Coefficient of gradation, C_c¼$(D_{30})^2/(D_{10}*D_{60})$ Sand	83.5	64	52.01
Sand content, [%]	84	62	33
Fines content, [%]	17.05	51	35
Maximum void ratio, e_{max}	1.60	1.77	1.82
Dry density [g/cm3]	1.52	1.4	1.28
Minimum void ration, e_{min}	0.99	1.14	2.08
Optimum water content, w (%)	14.6	17.6	18.1
Hydraulic conductivity *k* (cm/s)	3.18E-04	4.89E-05	3.89E-06

Figure 2-2 shows a microscopic view of Edosaki Sand, where it can be seen that is composed about by 95% of sub-angular to subrounded quartz particles with attached fines particles. One possible reason for the high quartz content can be the high resistance presented by quartz to physical and chemical weathering. Additionally, angular particles suggest that soil was developed "*in situ*" or at least under low transportation process. Figure 2-3 shows a penetration test at Nishi Chiba.

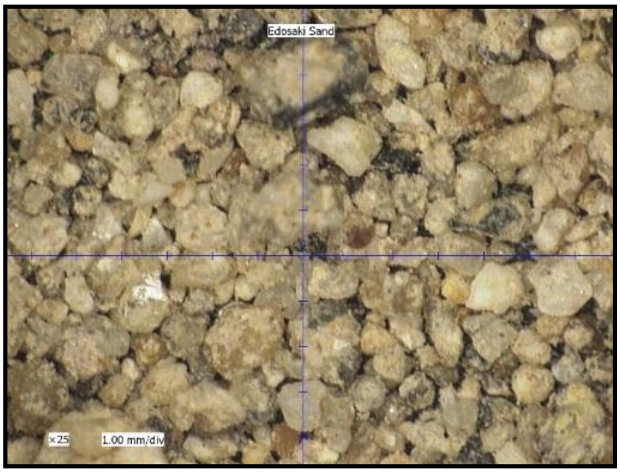


Figure 2-2- Microscopic view of Edosaki Sand (x25), (Motoya, 2007)

Figure 2-3-Penetration test, Chiba soil sample were collected, at IIS, Nishi Chiba

2.3 Vetiver

Vetiver grass was used in this study, vetiver (Chrysopogon zizanioides, formerly known as Vetiveria zizanioides, as shown in Figure 2-4, Figure 2-5 and Figure 2-6) is a perennial grass of gramineae, which is originated from Southeast Asia, India, and tropical Africa. It has been used in many tropical countries, at present, there are more than 100 countries or areas cultivating and using vetiver and has been shown to be a simple and economical method to conserve soils and trapping sediment, filtering out nutrients, and vegetated ground technique on slope stability has been recognized to provide an attractive cost-effective countermeasure against erosion, slope disaster and shallow mass movements etc. vetiver is a clumping grass, roots are massive finely structured and grow very fast and deep. It is a true miracle grass by its character of special massive long roots that anchoring and penetrating straight into the ground.

Although vetiver grass (*Vetiveria zizanioides L.*) has been used first by Indian farmers for soil and water conservation more than 200 years ago, its real impact on land stabilization/reclamation, soil erosion, and sediment control only started in the late 1980's following its promotion by the World Bank. While it still plays a vital role in agriculture, the unique morphological, physiological and ecological characteristics of the grass including its tolerance to highly adverse growing conditions and tolerance to high levels of toxicities provide an unique bio-engineering tool for other, non-agricultural applications such as land stabilization/reclamation, soil erosion and sediment control, (Truong, 2000). The detailed characteristics of vetiver grass have already mentioned in section 1.3 description of previous studies related to the use of vegetation as a tool for erosion and shallow mass movements control.

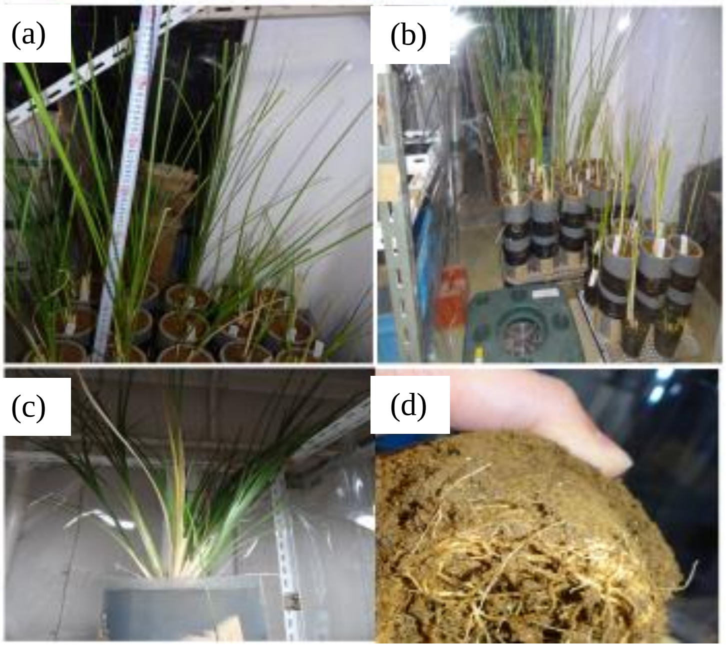


Figure 2-4 (a) Vetiver, (b)-The columns were prepared for permeability test, 2,4,6 and 8weeks respectively, (c) The vetiver was implanted on the one-dimensional column test and (d) Edosaki sand was reinforced by vetiver root.

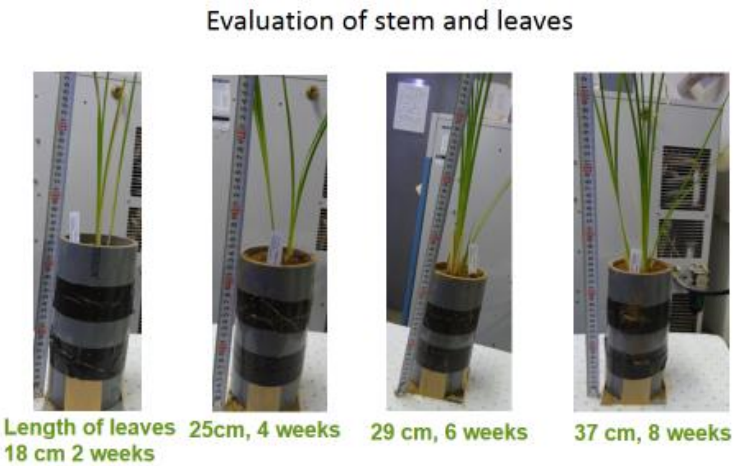


Figure 2-5- Evaluation of the vetiver stem and leave

Figure 2-6- Vetiver at site model test, IIS, Nishi Chiba

2.4 Hydraulic conductivity functions of two unsaturated sandy soils during drying and wetting processes and Soil Water Characteristic Curse (SWCC)

Darcy's law is commonly used to model the flow of water through an unsaturated soil (Buckingham, 1907; Richards, 1931; Childs and CollisGeorge, 1950). Hydraulic conductivity k, in Darcy's law, and coefficient of diffusion or moisture diffusivity D, in Fick's law, are examples of hydraulic properties. The latter can be shown to be the division of k by the gradient of the moisture retention curve or the soil–water characteristic curve (SWCC) (Hillel, 1982). In most cases, the pore air pressure gradient in the soils is assumed to be zero. Therefore, the flow of water in the liquid phase in unsaturated soils is characterized by both hydraulic conductivity and the SWCC, and it is of interest to the present study.

The hydraulic conductivity function of an unsaturated soil (change in hydraulic conductivity with water content) can be determined using either direct or indirect techniques. Direct measurements of hydraulic conductivity can be performed either in the laboratory or in the field. The two most common techniques used in the direct measurement of the hydraulic conductivity function of an unsaturated soil are the steady-state method (Klute, 1965), that can be performed in the laboratory using a permeameter, and the transient method, that can be performed in the laboratory (Hamilton et al., 1981) or in the field (Watson, 1966; Hillel, 1982).

More attention is increasingly being directed to the accurate measurement of unsaturated soil hydraulic properties close to saturation (Leij and van Genuchten, 1999), i.e., moisture conditions that are strongly affected by the soil structure and macro-pores. Traditional transient laboratory methods, such as the horizontal infiltration method (Klute and Dirksen, 1986), outflow methods (Gardner, 1956; Benson and Gribb, 1997), and instantaneous profile methods (Richards and Weeks, 1953; Chiu and Shackelford, 1998) show relatively little sensitivity to the hydraulic conductivity at near-saturated conditions, and hence, are more suitable for estimating the hydraulic conductivity at medium saturation levels. These methods usually fail in the near-saturation range where the hydraulic conductivity is highest, leading to very small hydraulic gradients that cannot be determined with sufficient accuracy (Wendroth and Simunek, 1999). Thus, there is a trend toward determining the hydraulic conductivity in the wet range with the steady-state method. To measure the hydraulic conductivity accurately at low suction values, therefore, it is important to have a permeameter that employs the steady-state method and has a more precious and robust measuring system.

However, the measurement of unsaturated hydraulic conductivity in the laboratory is time-consuming and costly, as it requires special devices and generally the service of a skilled technical person. Therefore, numerous theoretical (indirect) methods have been proposed by researchers to predict the hydraulic conductivity of unsaturated soils (Fredlund et al., 1994; van Genuchten, 1980; Mualem, 1976; Kunze et al., 1968; Brooks and Corey, 1964). Most of these predictive methods require saturated hydraulic conductivity and the soil– water characteristic curve (SWCC) as inputs. Typical characteristic shapes of SWCCs for drying and wetting conditions are shown in Figure 2-7. SWCCs can either be measured in the laboratory or predicted using a grain-size distribution curve taking into account such factors as dry density, porosity, and the void ratio (Aubertin et al., 2003; Fredlund et al., 1997; Tyler and Wheatcraft, 1989; Gupta and Larson, 1979). Nevertheless, predictive methods for unsaturated hydraulic conductivity have not advanced to a similar extent, nor have they been verified using laboratory measurements to a similar extent. Therefore, it is important to verify the accuracy of the unsaturated hydraulic conductivity predictive methods by comparing them with laboratory measurements.

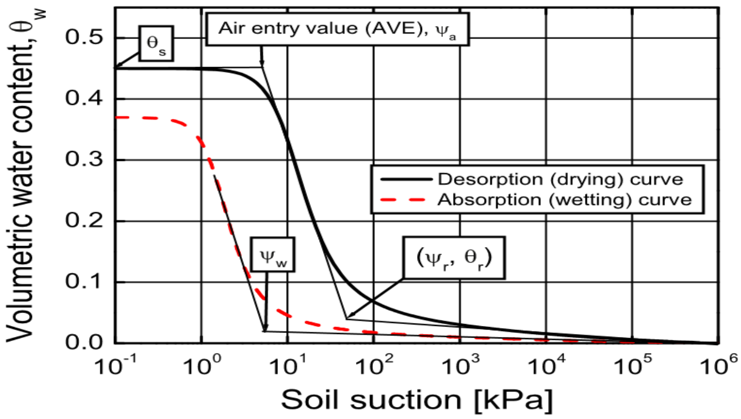


Figure 2-7- Typical Soil Water Characteristic Curve (fromChaminda G., Jayantha K., Taro U. 2013)

The soil-water characteristic curve (SWCC), is a very important concept in unsaturated soil mechanics and shows the relationship between the water content and matric suction of a soil (Orense R.P., 2003); the SWCC can be related to other properties describing the behavior of the soil, such as the unsaturated coefficient of permeability (Fredlung et al 1994) and shear strength (Vanapilli et al. 1996).

Soil water characteristic curve for Edosaki Sand has been extensively analyzed by previous researchers (i.e. Garcia, 2005; Chaminda, 2006). In order to find the best fitting parameters of the SWCC at different dry densities; several techniques and methods were used as direct measurements by using the Temp Pressure Cell Apparatus (Fredlung, 1993) and modeling by using the well-known equations from Van Genuchten 1980 and Fredlung and Xing 1994.

In this study, an approach to the behavior of the SWCC was made by analyzing the direct measurements of matric suction and volumetric water content in the sand column as well as in the slope model tests; therefore, these measurements were compared with the SWCC obtained by using the above-mentioned methods (Chaminda 2006) and plotted in Figure 2-8.

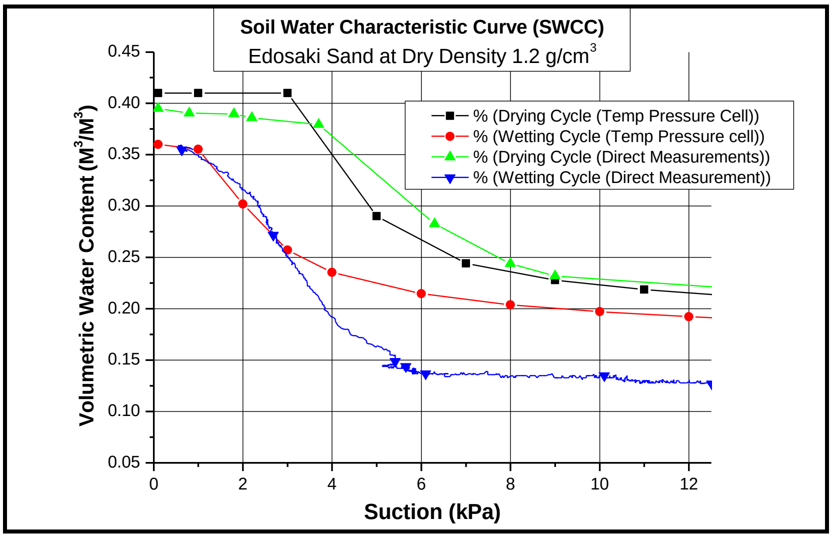


Figure 2-8- SWCC for Edosaki Sand measured in laboratory (Chaminda, 2006) and direct measurements from model tests.

From Figure 2-9, it can be observed how the SWCC measured directly from model tests, nearly matches the same path than the one obtained in laboratory conditions by using the above-mentioned methods. However, the wetting cycle exhibits a better behavior at low suction values.

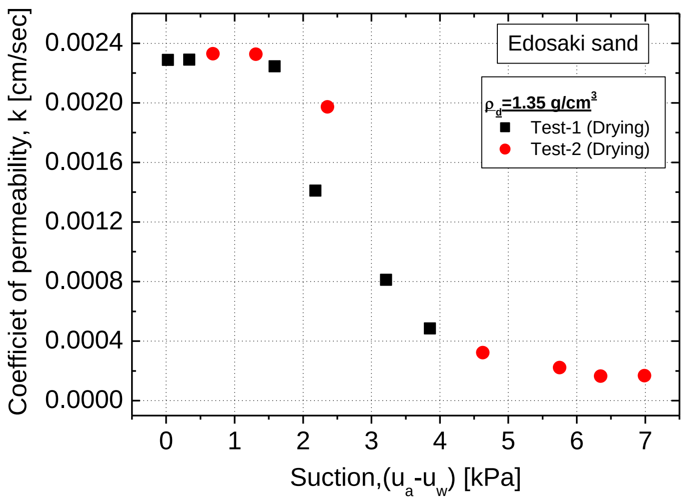
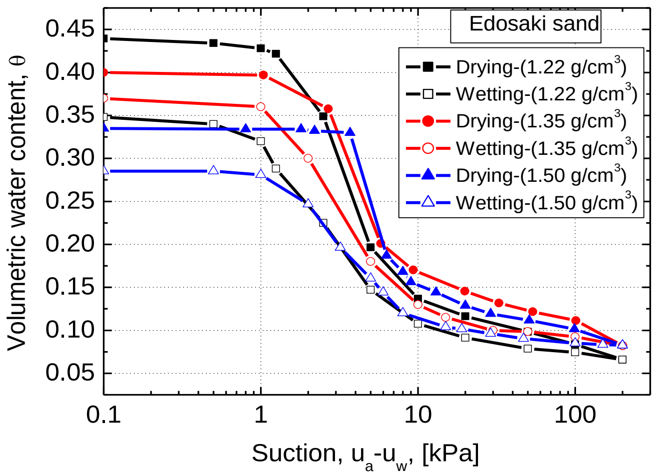


Figure 2-9- Repeatability of the laboratory measurement of the coefficient of permeability, (Chaminda, 2006)

Infiltration of rainwater into an unsaturated soil slope may impair slope stability by changing the matric suction in the soil, which in turn controls the water content of the soil (Figure 2-10). Usually, unsaturated soils experience high matric suction during dry periods, which contributes to the shear strength of the soil. During prolonged wet periods, when there is sufficient infiltration into the slope, the matric suction of the soil decreases, and this, in turn, results in an increase in the soil water content (Figure 2-11). Note that the matric suction for clay is relatively sensitive to rainfall events. As a result, the additional shear strength provided by the matric suction can be reduced enough to trigger a shallow landslide.



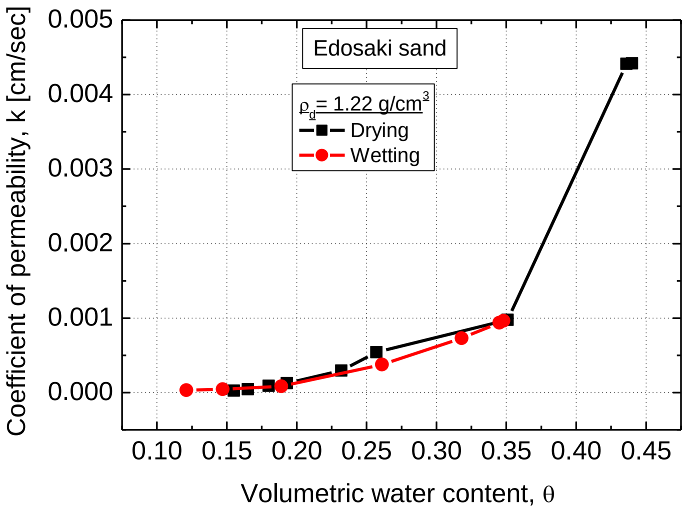


Figure 2-10- Repeatability of the laboratory measurement of the coefficient of permeability, (Chaminda, 2006)

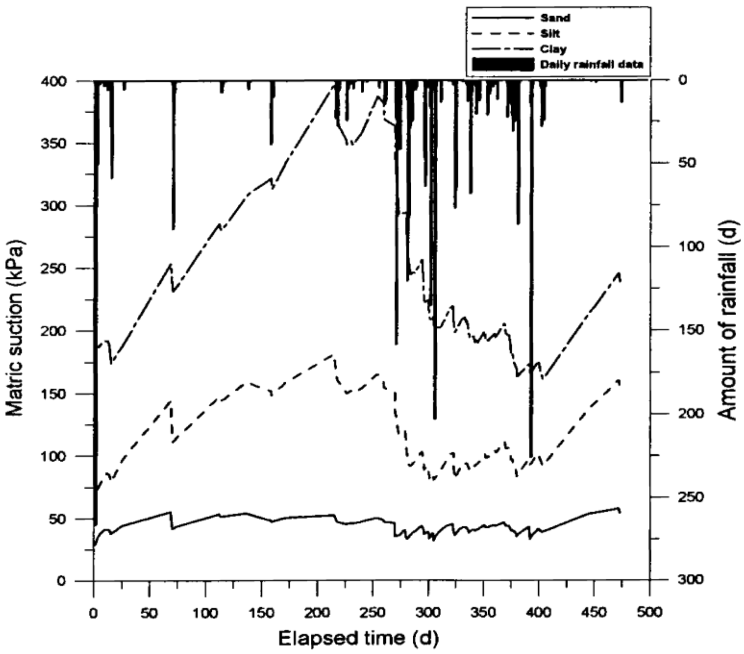


Figure 2-11-The time series of rainfall and matric suction in various representative soils: (a) sand, (b) silt and (c) clay. Yeh, H.F., J.F. Chen and C.H. Lee, (2004)

2.5 Conclusion remarks

These sieve and hydrometer analyses were conducted using the Japanese Geotechnical Society (JGS, 2000) standard test methods.

The physical properties of test materials used in this experimental investigation were presented with the materials' microscopic views. According to the unified soil classification system (USCS) (Jean-Pierre Bardet, 1997).

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CHAPTER 3. EXPERIMENTAL SETUP, METHODOLOGY AND APPARATUS

3.1 General remarks

Different kinds of equipment and devices were used in this study, including temperature, volumetric water content sensors, humidity sensors rain-gauge, data logger Kantaro, mini HOBO, HOBO U-30, solar battery, heater, lighting system, and acrylic containers designed according to the test type. In this section, a description of the equipment is presented and depended on the specific ones designed according to the tests requirements as the following below:

3.2 Apparatus for the permeability test:

Figure 3-1(a), (b), (c), illustrates the concept of permeability of water through a soil column proposed by Darcy's in 1856. The hydraulic conductivity or permeability of vegetated and non-vegetated soils sampling was measured as shown there, where the coefficient of permeability, k, is a product of Darcy's Law established by an empirical relationship for the flow of water through porous media. The hydraulic conductivities of vegetated/non-vegetated soil were measured with the standard technique of permeability test with constant water head. Figure 3-2, sets of Edosaki soil samples were placed in the columns with the prescribed relative density Rd (%), Relative density is defined as the state of compactness of a soil with respect, to the loosest and densest states at which it can be placed by the laboratory, as shown in Figure 3-2. A piece of young vetiver was implanted on the top surface of each and then grown up for 1, 2, 4 and 6 weeks vegetated samples. The other one soil column was tested without vetiver as reference non-vegetated sample. Before the hydraulic conductivity tests, the vetiver was cut at the top surface of the soil specimen while its root was left in the soil. The specimens were vacuumed for 24 hrs, and then water was given to make sure each specimen was completely saturated.

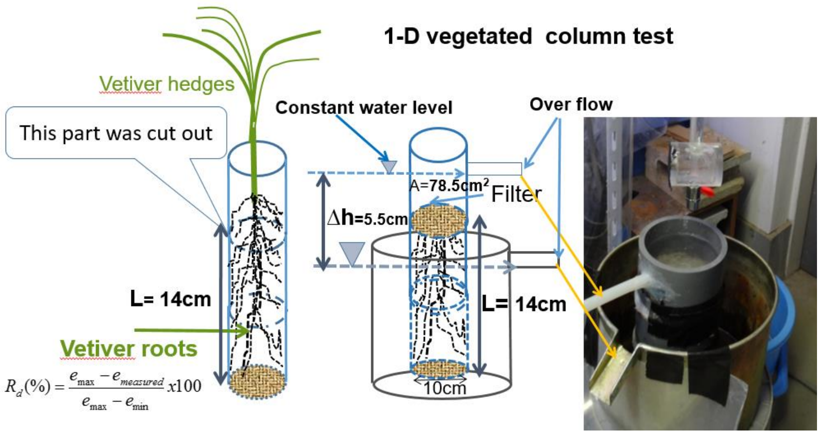


Figure 3-1 (a)-Apparatus for permeability test

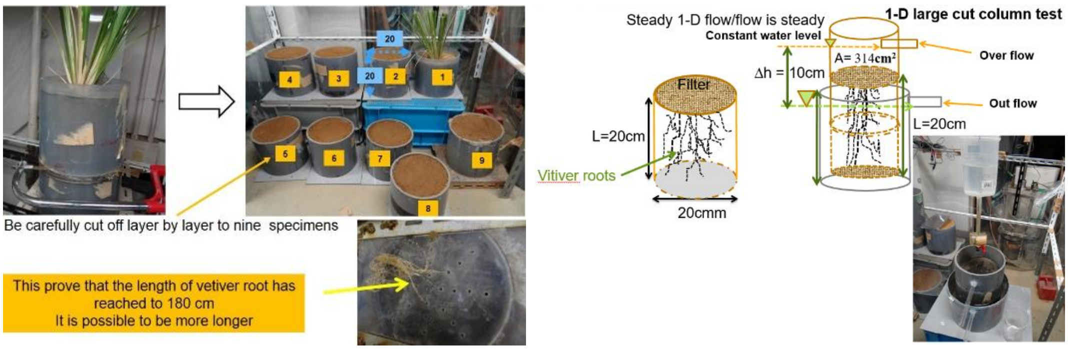


Figure 3.2 (b)-The schematic view of permeability test cylindrical vegetated ground sample [1D large cut column test]

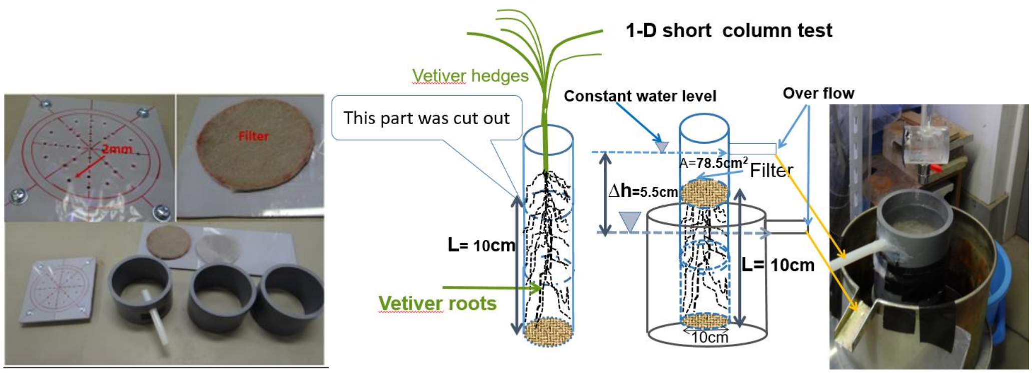


Figure 3.2 (c)-The schematic view of permeability test cylindrical vegetated ground sample [1D short column test]

Figure 3-2-The sets of vegetated Edosaki soil samples

3.3 Apparatus for one-dimensional column test

Two large columns, the vegetated and the non-vegetated were installed for one-dimensional seepage tests. To analyze the hydrological response of vetiver root and to evaluate the effect of root on water seepage. A uniform model ground by using the Edosaki sand soil was constructed in an acrylic pipe with an inner diameter of 200 mm and a total pipe length of 180 cm, with the length of soil sample 170 cm for the two large columns as shown in Figure 3-3 (a) and (b). The bottom of the column is opened to static water layer so that a constant underground level is simulated. The volumetric water contents sensors are installed along the side of the column. The artificial rainfall events were created/given on the top of the column (using the medical drop of about 1 to 420 mm/hr). The conditions of the two columns are the same except that column A is the non-vegetated while column B is vegetated with a vetiver.

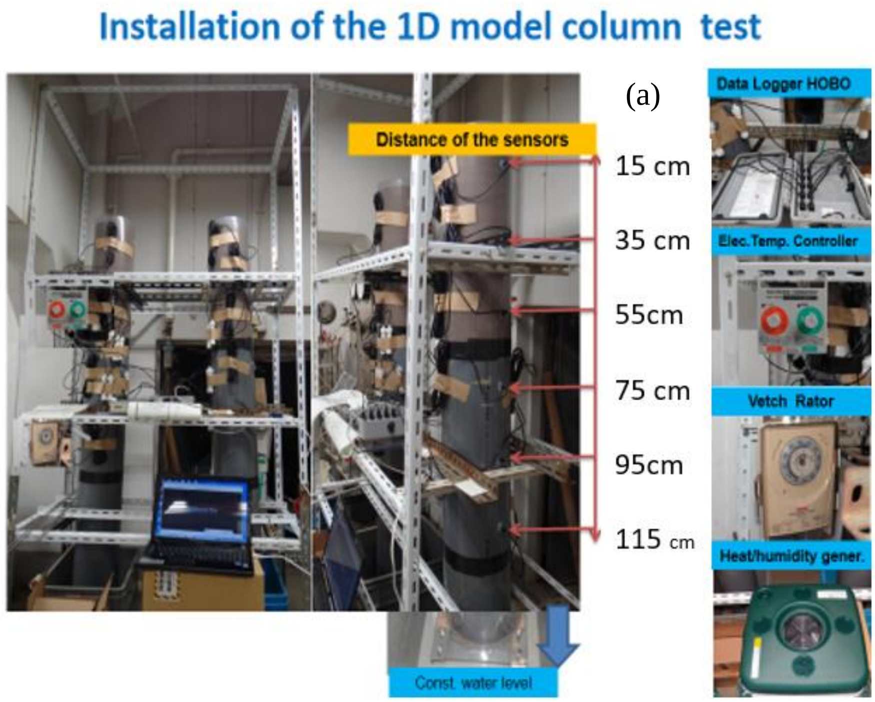


Figure 3-3 (a)- Installation of one-dimensional columns model tests

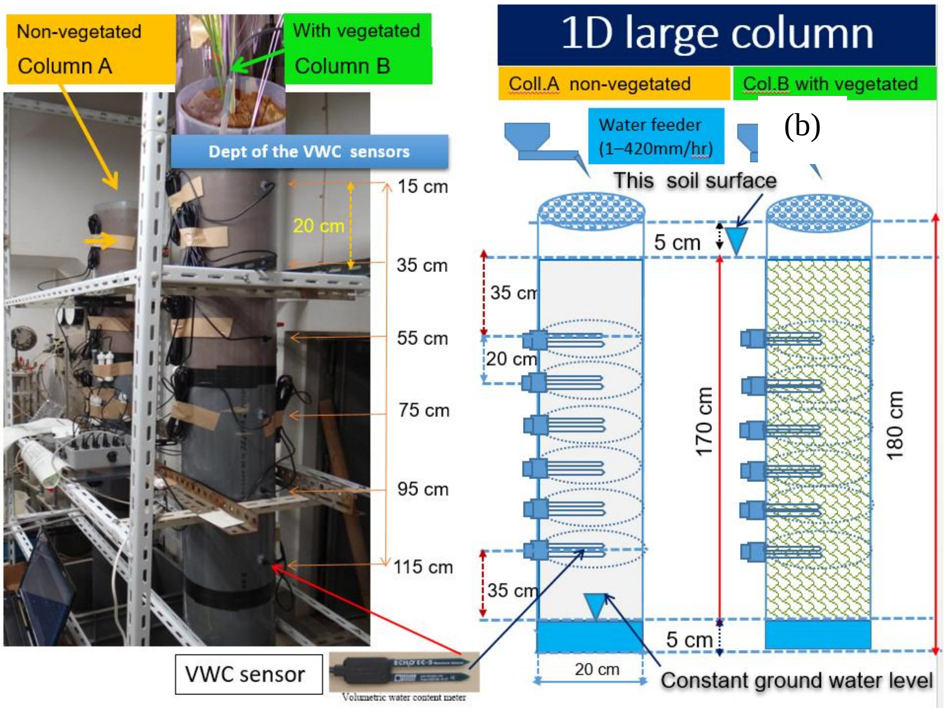


Figure 3.3 (b) - Schematic view of one-dimensional large column model test

The soil moisture smart sensor measures the dielectric constant of soil in order to determine its volumetric water content. The dielectric constant of water is much higher than that of air or soil minerals, which makes it a sensitive measure of the water content. During operation, values of 0 to 0.5 m^3/m^3 are possible to be measured by this sensor. A value of 0 to 0.1 m^3/m^3 indicates oven-dry to dry soil respectively. A value of 0.615 or higher normally indicates a wet to saturated soil.

In order to get an accurate and consensus results from the one-dimensional tests, additional six short columns, the vegetated and the non-vegetated were installed, to conduct (one-dimensional) seepage tests. The main purpose was to analyze the hydrological response of vetiver root and to evaluate the effect of root on water seepage. A uniform model ground by using the Edosaki sand soil was constructed in an acrylic pipe, with an inner diameter of 10 mm and a total height of pipe of 70 cm, having a length/height of soil sample of 60 cm, as shown in Figure 3-4. The bottom of the column was opened/subjected to static water layer so that a constant underground level was simulated. The volumetric water contents sensors were installed along the side of the column. The artificial rainfall events were created/given on the top of the column (using the manual drop of about 300 to 420 mm/hr.). The conditions of the six columns were same, except that the columns A, C, F were non-vegetated, while column B, D, E were vegetated with a vetiver.

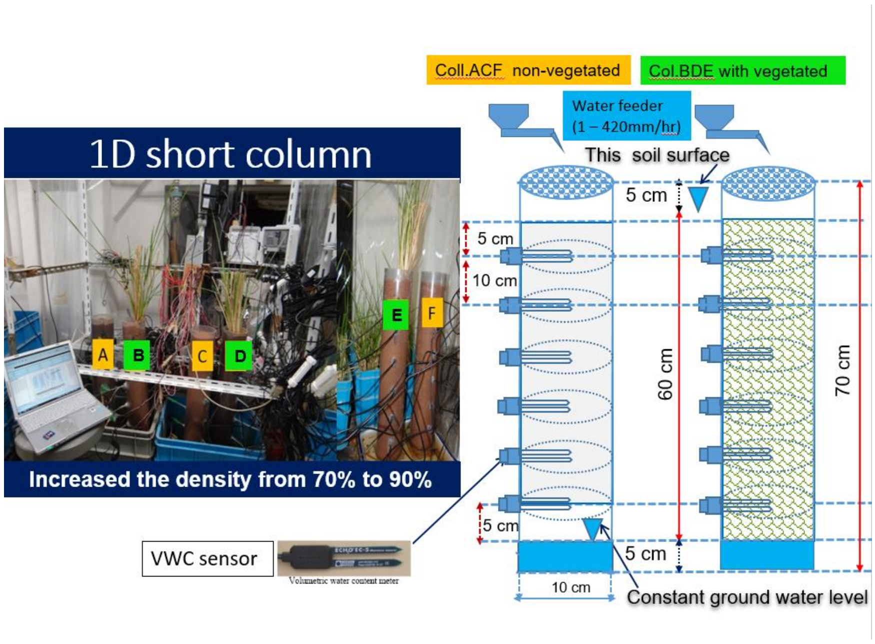


Figure 3-4- One-dimensional short columns model tests

The soil moisture smart sensors measured the dielectric constant of soil, in order to determine its volumetric water content. The dielectric constant of water is much higher than that of air or soil minerals, which makes it a sensitive measure of the water content. During operation, values of 0 to 0.5 m^3/m^3 were possible. A value of 0 to 0.1 m^3/m^3 indicates oven-dry to dry soil respectively. A value of 0.62 or higher, normally indicates a wet to saturated soil.

Table 3.1 specification (EC-5H_2O)

Specifications	**S-SMC-M005**
Measurement Range	In soil: 0 to 0.550 m^3/m^3 (volumetric water content)
Extended range	-0.401 to 2.574 m^3/m^3; see Note 1

Specifications	**S-SMC-M005**
Accuracy	±0.031 m³/m³ (±3%) typical 0 to 50°C (32° to 122°F) for mineral soils up to 8 dS/m ±0.020 m³/m³ (±2%) with soil specific calibration; see Note 2
Resolution	±0.0007 m³/m³ (±0.07%)
Volume of Influence	0.3 liters (10.14 oz)
Sensor Frequency	70 MHz
Soil Probe Dimensions	89 x 15 x 1.5 mm (3.5 x 0.62 x 0.06 in.)
Weight	180 grams (6.3 oz)
Decagon ECH$_2$O Probe Part No.	EC-5
*HOBO ware 3.2.1 or greater is required for the S-SMD-M005 model only.	

3.3.1 Installation (EC-5 H_2O)

This sensor measures the water content in the space immediately adjacent to the probe surface. Air gaps or excessive soil compaction around the probe can profoundly influence soil water content readings. Do not mount the probes adjacent to large metal objects, such as metal poles or stakes. Maintain at least 8 cm (3 inches) of separation between the probe and other objects. Any objects, other than soil, within 8 cm (3 inches) of the probe can influence the probe’s electromagnetic field and adversely affect output readings. The S-SMC-005 sensor must be installed at least 3 cm (1.18 inches) from the surface and the S-SMD-005 sensor must be installed at least 10 cm (3.94 inches) from the surface to obtain accurate readings. Be careful when inserting these sensors into the dense soil as the prongs can break if excessive sideways force is used to push them into the soil.

3.3.2 Connecting (EC-5 H_2O)

To start using the soil moisture smart sensor, stop the logger and insert the sensor's modular jack into an available port on the logger, which allows you to plug the sensors into one port, it will automatically detect the smart sensor. Note that the logger supports a maximum of 15 data channels; this sensor uses one data channel. Launch the logger and verify that the sensor is functioning correctly.

3.3.3 Operation (EC-5 H_2O)

The soil moisture smart sensor measures the dielectric constant of soil in order to determine its volumetric water content. The dielectric constant of water is much higher than that of air or soil minerals, which makes it a sensitive measure of the water content. During operation, values of 0 to 0.5 m^3/m^3 are possible. A value of 0 to 0.1 m^3/m^3 indicates oven-dry to dry soil respectively. A value of 0.3 or higher normally indicates a wet to saturated soil. Values outside the operating range may be a sign that the sensor is not properly installed (poor soil contact or foreign objects are adjacent to the sensor) or that a soil-specific calibration is required.

3.3.4 Calibration (EC-5 H_2O)

The soil moisture smart sensor was calibrated for different kinds of Edosaki soil to convert the data provided by the probe with a specific calibration for specific individual Edosaki soil type. In order to get the maximum precision on volumetric water content measurements, sensors were calibrated by compacting Edosaki sand at a dry density of 1.2g/cm^3 on a cylindrical acrylic container of 14 cm height by 10 cm radius at different moisture contents. The procedures used to obtain the calibration factor of each sensor is summarized as follows:

- Sample with pre-determined gravimetric water content (GWC %) is obtained by mixing the calculated amount of water with 24-hour oven dried sand.
- Sand is compacted at a dry density of 1.2 g/cm^3 on the acrylic container.

- The sensor is installed on the sample and voltage measure (mV) is recorded. ***Figure 3-5*** shows the procedures for the installation of the sensor on the soil container.

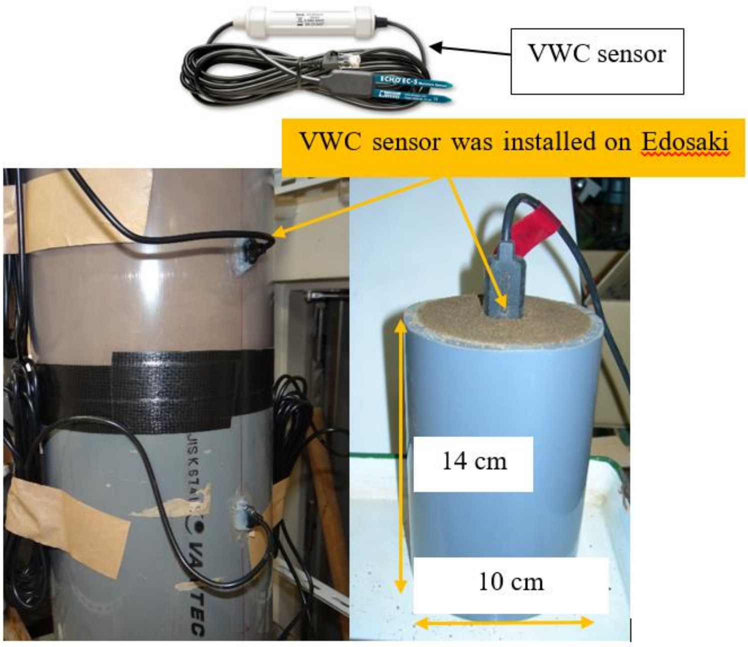


Figure 3-5- WVC sensor and calibration on Edosaki sand

- New sample at higher gravimetric water content is prepared and the process is repeated.
- Volumetric water content (VWC %) is obtained by multiplying gravimetric water content (GWC %) by dry density ρ_d at which the specimen was prepared.
- Voltage readings (mV) are plotted against VWC (%), to obtain the linear relationship which gives the calibration factor in the form: $\boldsymbol{y = mX + b}$
- Voltage readings (mV) are plotted against VWC (%), to obtain the linear relationship which gives the calibration factor in the form: y = m X + b; those calibration factors for moisture sensors are presented in Table 3.2.

Table 3.2 the calibration factor of the sensors

Sensor	Calibration Factor	Type
VWC01	0.001x - 0.4146	ECH_2O-EC5
VWC02	0.001x - 0.4268	ECH_2O-EC5
VWC03	0.001x - 0.4002	ECH_2O-EC5
VWC04	0.0009x - 0.3875	ECH_2O-EC5
VWC05	0.0009x - 0.377	ECH_2O-EC5
VWC06	0.0009x - 0.3462	ECH_2O-EC5
VWC07	0.001x - 0.42199	ECH_2O-EC5
VWC08	0.0011x - 0.4401	ECH_2O-EC5

(Internet: http://www.decagon.com/manuals/echomanual.pdf)

3.3.5 Verifying Sensor Functionality

To quickly check sensor functionality before deployment, perform the following two tests:

1. Wash the probe with water and let it dry.
2. Plug the sensor into the logger.
3. Open the logging software and go to the status screen.
4. Conduct an air test: Hold the sensor by the cable letting the sensor hang freely in the air, and compare the value in the status screen with the Table 3.3 below.

Table 3.3 Conduct an air test

Sensor	Air	Water
S-SMC-M005	-0.193 to -0.139	+0.521 to +0.557
S-SMD-M005	-0.473 to -0.134	+0.474 to +0.692

3.4 Rainfall simulator system

A medical drip connected to the water tank and placed 1 meter above the slope model's surface was used as rainfall simulator system; the rainfall intensity was controlled by adjusting a water pressure regulator located between the water tank and medical drip, rainfall was applied as homogeneously as possible on an area of 314 cm^2 approximately. However, irregularities in the rainfall were registered as a consequence of wind disturbance or pressure variations on the water supplier. Figure 3-6 shows the rainfall simulation system used for the experiments.

Figure 3-6- Medical drip used as a rainfall simulator

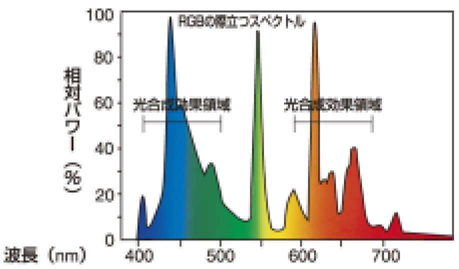
Typical rainfall intensities achieved with the used method were between 60 and 420 mm/hr, suggesting that most of the tests were made under heavy rain.

3.5 Installation of lighting and heating to make an efficient vetiver

Vetivers need sunlight to grow because they use light energy to change the materials carbon dioxide and water into food substances. Green plants are only able to manufacture food in the presence of light in the process of photosynthesis. The substances produced in the process of photosynthesis facilitate the growth of the plant as they provide energy to support the various plant processes . Therefore, the installation of the lighting for efficient greenhouse design is supplemental lighting. In order to make the efficient plant/vetiver, the lighting has provided is needed. Since we have covered the basics inefficient greenhouse design (small plastic house), efficient heating and lighting will work well to accelerate plant grow up (Figure 3-7).

Lighting system to efficiency plant/vetiver

Name	Fluorescent lamps
Features light color	Biorukusu HG (BR-HG)
Classification	Starter form a straight tube
Classification of the size	20 form
Product code	611-2757
Rated lamp power (W)	20
Pipe diameter (mm)	32.5
President / External (mm)	580
Mass (g)	127
Lamp current (A)	0,360
Total luminous flux (lm) (25 °C)	800
Rated average life (in hours)	7,500



FL 20 -SBR HG Energy distribution, Figure

Figure 3-7- Installation of the lighting system to efficiency plant/vetiver

3.6 Volumetric water content sensor (EC-5 H2O)

In this study, 16 EC-5 H2O moisture content sensors were used for the 1D test, and 12 EC-5 H2O were used for site model test, produced by Decagon Devices Inc. Probes measure the dielectric constant of the soil in order to find its volumetric water content from 0 to 100%. Since the dielectric constant of water is much higher than that of air or soil minerals, the dielectric constant of the soil is a sensitive measure of water content. The EC-5 H_2O probe has a very low power requirement and high resolution, making possible to do as many measurements as wanted (even hourly) over a long period of time (like a growing season, for example), with minimal battery usage.

3.7 Apparatus for site model test

The effects of vegetation on hydraulic properties in the ground were investigated by site vegetation test, the location of the site test was selected and conducted at the Institute of Industrial Science (IIS) the University of Tokyo, Nishi-Chiba, as shown in Figure 3.8, since the early May 2013. One series of volumetric water content sensors were installed in the vertical direction just near the plant on the both test fields, vegetated and non-vegetated zone are shown in Figure 3.11 and Fig. 3.13. The conditions of the two zones are the same/similar except that the zone 1 is non-vegetated while zone 2 is vegetated with eighteen vetiver grasses. The distance between two zones is 3 meters. In order to get uniform distribution of the root, the position and range of the vetiver grasses were implanted in the surrounding among the volumetric water content sensors, as shown in Figure 3.13. The volumetric water content, the rainfall intensity (rain gauge), and temperature sensors monitored and recorded continuously, during the vegetation growth period of 8 months. The water content in the ground changes corresponding to the water infiltration and consequent drainage for every rainfall events. These behaviors should be a function of the hydraulic properties of the ground soil as well as the intensity and period of rainfall.

The detailed designed the inserting instrument of soil moisture meter and the installation of the volumetric water content sensors, as shown in Figure 3.12, Figure. 3.14 and Fig.3.15. The volumetric water content, the rainfall intensity (rain gauge), and temperature sensors monitored and recorded continuously, during the vegetation growth period of 8 months. The water content in the ground changes corresponding to the water infiltration and consequent drainage for every rainfall events. These behaviors should be a function of the hydraulic properties of the ground soil as well as the intensity and period of rainfall. The effects of the plant root can be detected as long-term changes in the water infiltration.

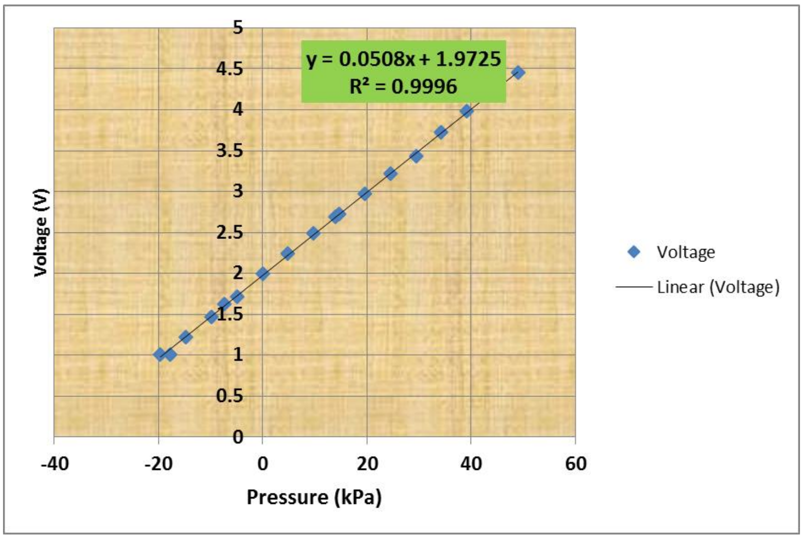


Figure 3-8- The relation of Pressure (kPa) and Voltage (V)

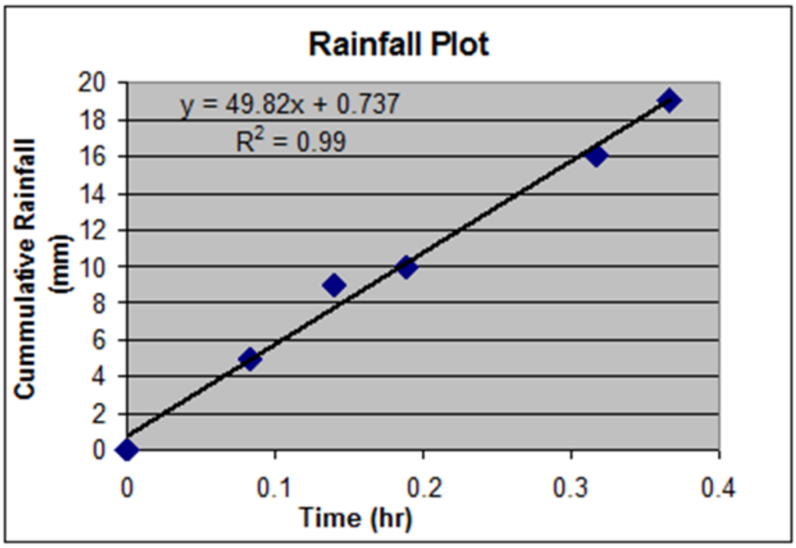


Figure 3-9-Typical rainfall plots showing a rainfall intensity of 49.82 mm/hr.

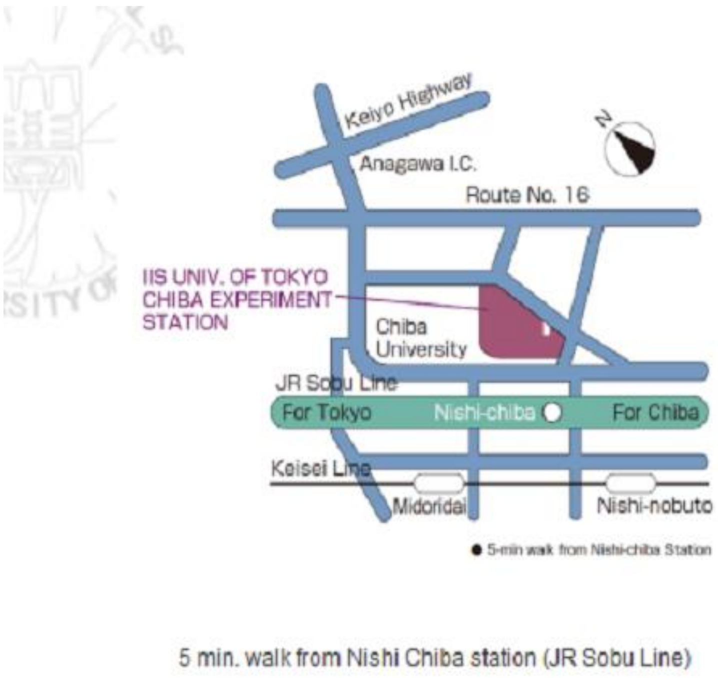


Figure 3-10- Location of the site model test (Sitemap//www.iis.u-tokyo.ac.jp/access/access.html)

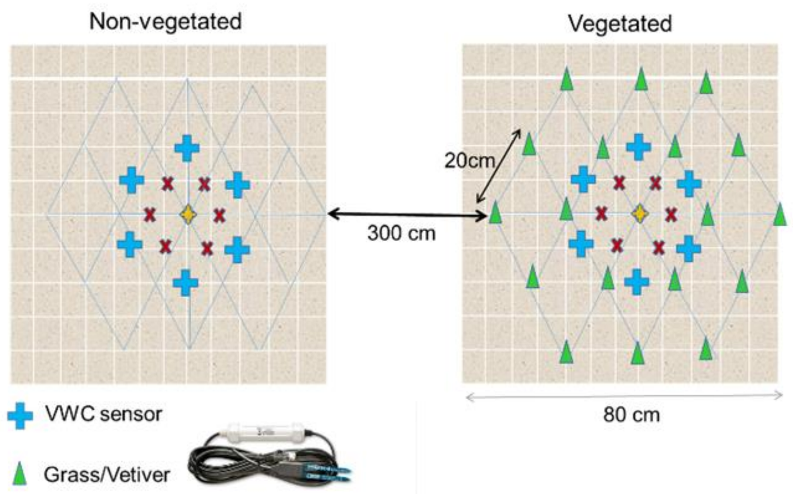


Figure 3-11- Schematic view of the position among the VWCs and vetivers

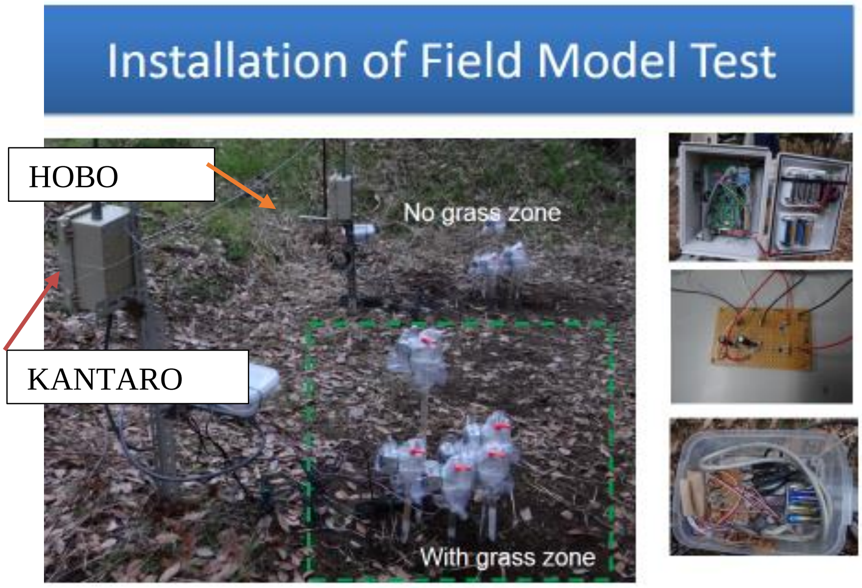


Figure 3-12- Installation for the field model test

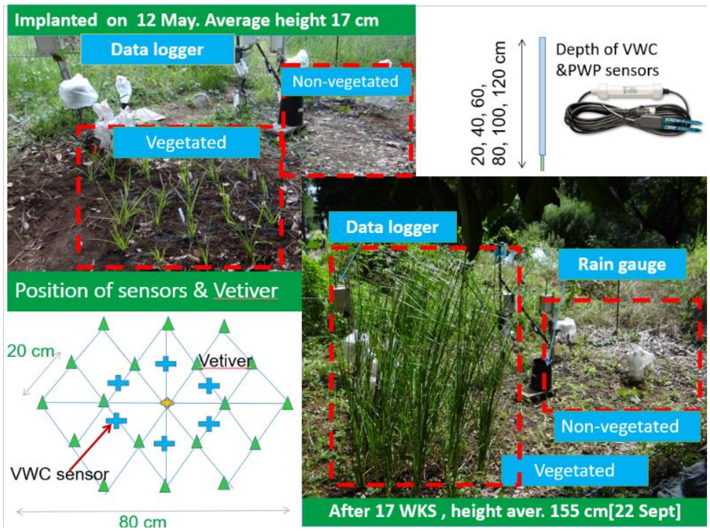


Figure 3-13- Schematic view of site model test after completely installed and implanted the vetiver

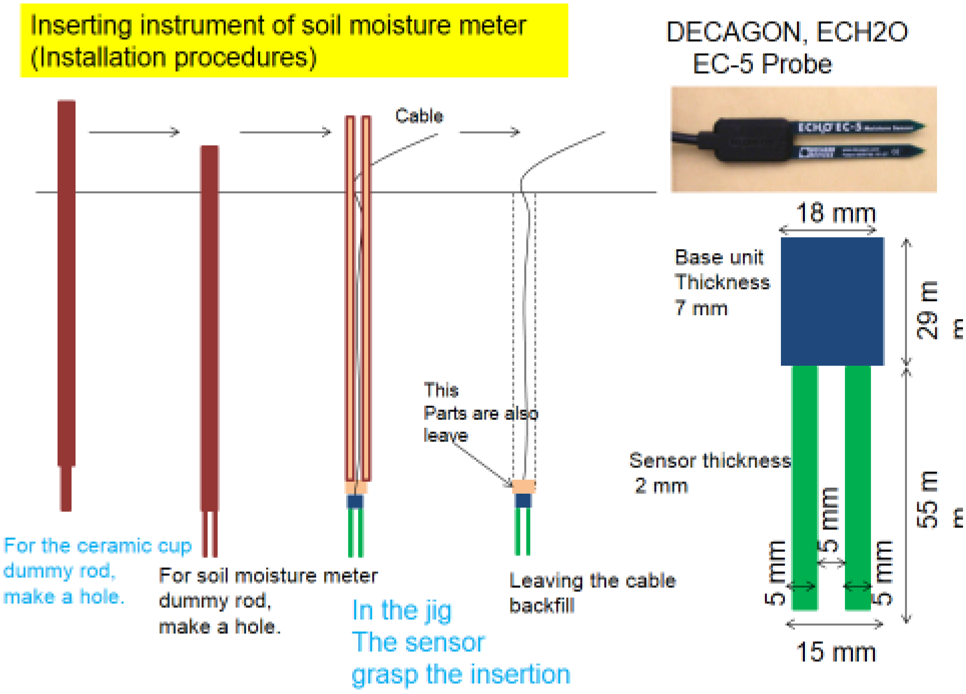


Figure 3-14- Detailed designed the inserting instrument of soil moisture meter

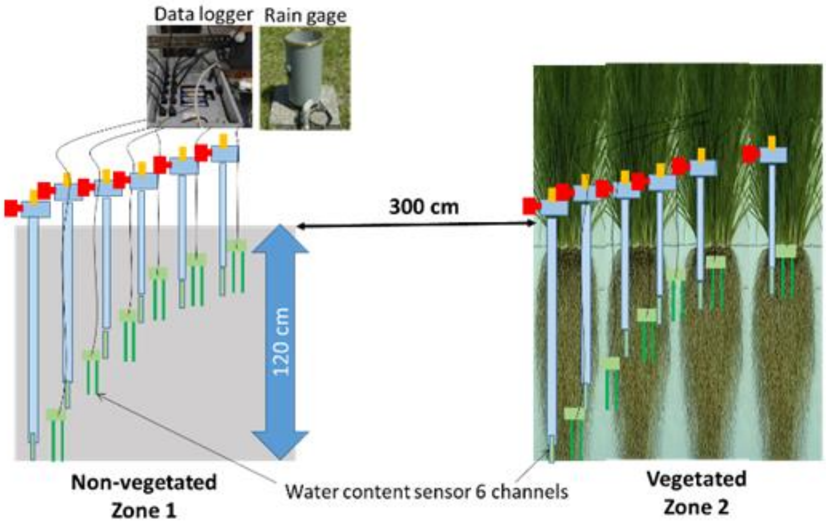


Figure 3-15-Accessories for the field model test

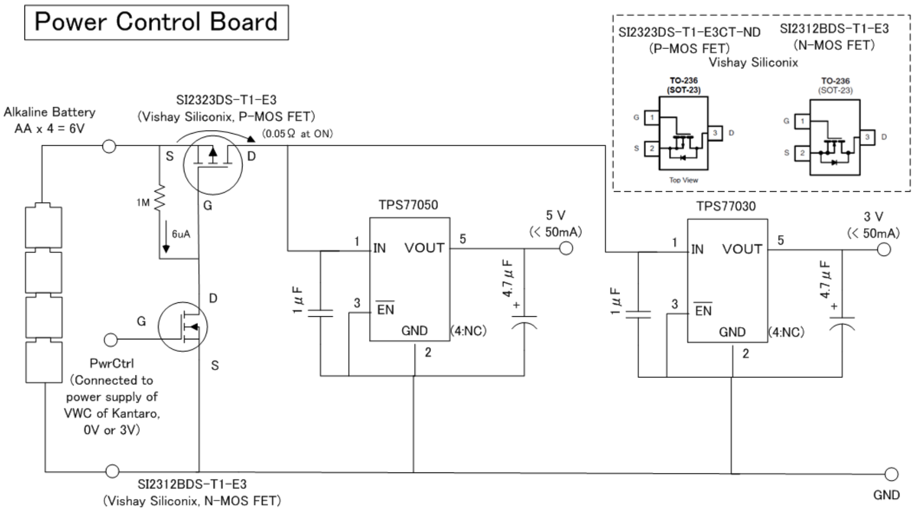


Figure 3-16- Schematic view of the power control board (Internet: http://www.decagon.com/manuals/echomanual.pdf)

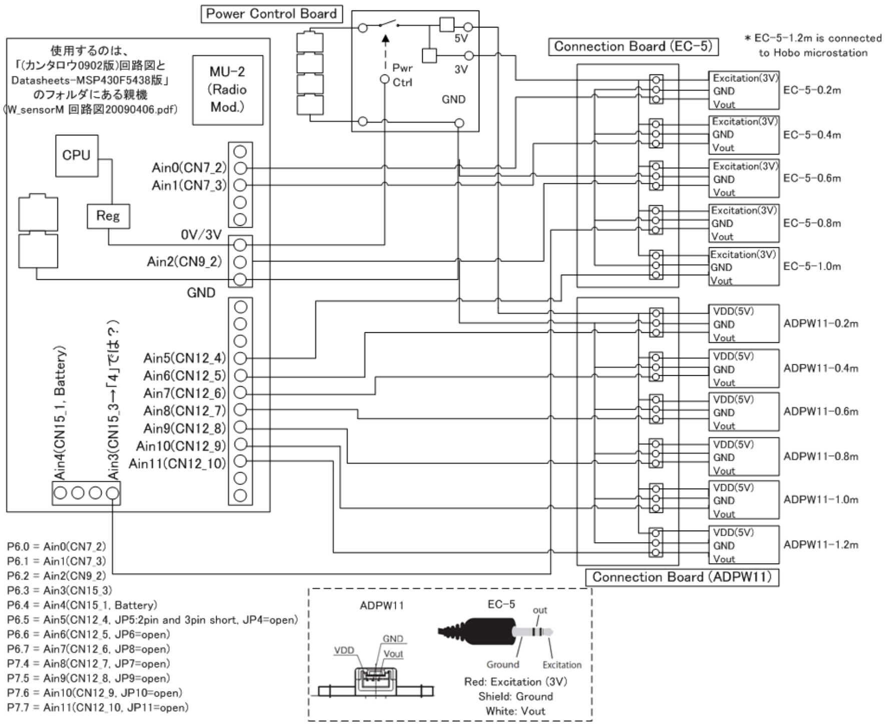


Figure 3-17- Inclinometer of electronic components system for site model test (Internet: http://www.decagon.com/manuals/echomanual.pdf)

3.8 Concluding remarks

Created ideas, research techniques and methods developed in this study requires specific modifications and design of the equipment, apparatus used during the testing procedures those procedures involve the measurements of volumetric water contents, pore water pressures or tension-meter, rainfall intensities, temperature, and rain-gauge. For that reason, it was necessary to use a different type of data loggers, moisture and pore pressure sensors and inclinometers with the objective of obtaining experimental information of the evaluation of hydraulic properties of vegetated slope based on monitoring data and moisture contents under different conditions.

3.9 References

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CHAPTER 4. HYDRAULIC CONDUCTIVITIES IN SATURATED CONDITION AND ANALYSIS OF THE ROOT ON THE VEGETATED AND NON-VEGETATED GROUND

4.1 General remarks

Study of hydraulic conductivity and water seepage (flow of water through the soil) is a very important aspect in soil mechanics beyond the the stability of slope ground. Some of the most relevant factors to consider in this matter are:

- The rate at which water flows through soil (i.e. determination of rate of leakage through earth dams)
- Rate of settlement of a foundation
- Strength (i.e. the evaluation of factor of safety of embankment), (Todd 1980; Domenico and Schwartz, 1998, and Fetter, 2001)

As used in geotechnical engineering, permeability is that property of soil which permits water to flow through it; through its voids. Thus, soils with large voids are more permeable than those whose voids are small, (Cernica, 1994).

In 1856, the French engineer Henri Darcy demonstrated through an experiment that it is possible to relate the discharge rate of water flowing from a soil to the hydraulic or total head gradient in the soil and a property of the soil which we refer to as the coefficient of permeability or the hydraulic conductivity. Darcy's Law, as it is called, is a very useful law because it is not possible to derive a theoretical law for the flow of water in the soil. Soils samples are tested in the laboratory using the constant head or falling head test procedures in order to obtain the coefficient of permeability. The coefficient of permeability is used to compute the quantity of flow for all types of flow problems in soil where laminar flow conditions exist.

Table 4.1 lists some typical ranges of hydraulic conductivity values for common rocks and soils. These ranges are mostly based on data compiled by Davis (1969) and were summarized by Freeze and Cherry (1979).

Table 4.1 Typical Values of Hydraulic Conductivity

Material	**K(cm/sec)**	**Sources**
Gravel	10−1 to 100	1
Sand	10−4 to 1	1
Silty sand	10−5 to 10−1	1
Silt	10−7 to 10−3	1
Glacial till	10−10 to 10−4	1
Clay	10−10 to 10−6	1.2
Limestone and dolomite	10^{-7} to 1	1
Fractured basalt	10−5 to 1	1
Sandstone	10^{-8} to 10^{-3}	1
Igneous and metamorphic rock	10−11 to 10−2	1
Shale	10−14 to 10−8	2

Sources: (1) Freeze and Cherry (1979); (2) Neuzil (1994).

The most common units for hydraulic conductivity are meters/day and feet/day for field studies and cm/sec for laboratory studies.

4.2 Objective of the hydraulic conductivities test

There are very few previous studies on the effects of root of plant on water infiltration, and the hydraulic properties of vegetated ground using vetiver grass are not clearly known. Moreover, there are few studies on both positive and negative effects of vegetation. In this work, the evaluation of hydraulic properties is used as the key parameter to evaluate the probability of failure events in an area of slope ground.

4.3 Testing method, apparatus, and procedures

Figure 4-1, Figure 4-4 and Figure 4-5, illustrate the concept of permeability of water through soil column proposed by Darcy's in 1856. The hydraulic conductivity or permeability of vegetated and non-vegetated soils sampling was measured as shown in Figure 4-1, where the coefficient of permeability, k, is a product of Darcy's Law established by an empirical relationship for the flow of water through porous media. The hydraulic conductivities of vegetated/non-vegetated soil were measured with the standard technique of permeability test with constant water head. Figure 4.2, sets of Edosaki soil samples were placed in the columns with the prescribed relative density R_d (%), Relative density is defined as the state of compactness of a soil with respect to the loosest and densest states at which it can be placed by a certain procedure. A piece of young vetiver was implanted on the top surface of each and then grown up for 1, 2, 4 and 6 weeks vegetated samples. The other one soil column was tested without vetiver for reference, hereinafter called the non-vegetated sample. Before the hydraulic conductivity tests, the vetiver was cut at the top surface of the soil specimen while its root was left in the soil. The specimens were vacuumed for 24 hrs, and then water was flowed to make sure the specimens were completely saturated.

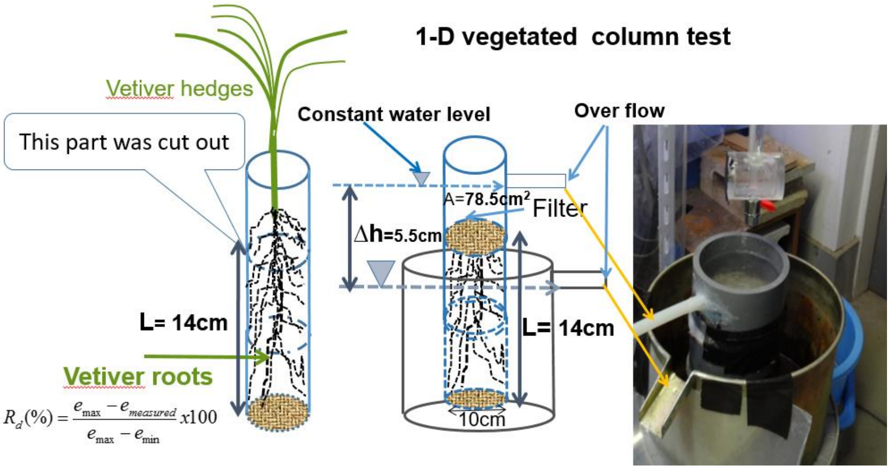

Figure 4-1- Schematic view of hydraulic conductivity test cylinder sample with vegetated specimen [vegetated specimen column test, 1D/Flow is steady]

Figure 4-2-The sets of vegetated Edosaki soil samples

Figure 4.3(a), shows the test results. Each vegetated specimen was opened after the permeability test and its density of root was measured: the density of root is defined as the dry weight of the root divided by total volume of the soil column. The density of root for the non-vegetated sample is 0. As shown in Figure 12(b), the density of root increases with the permeability increase correspondingly.

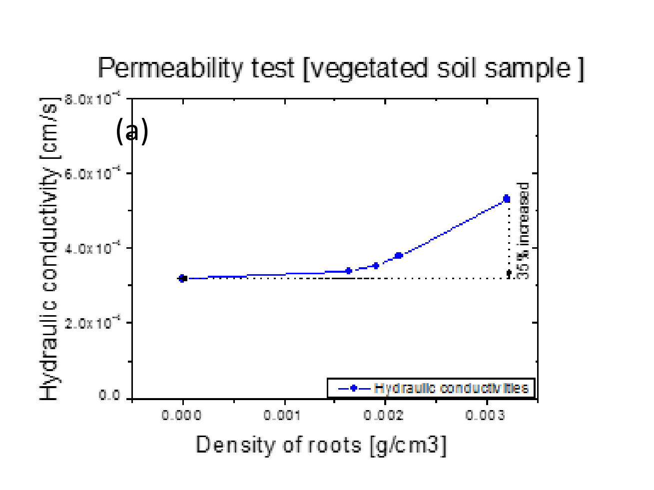

Figure 4-3(a)-The relation of hydraulic conductivity vs. density of roots

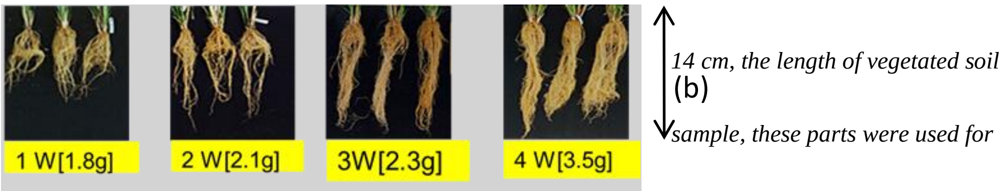

Figure 4.3 (b)- Observation of the root taken out from each sample.

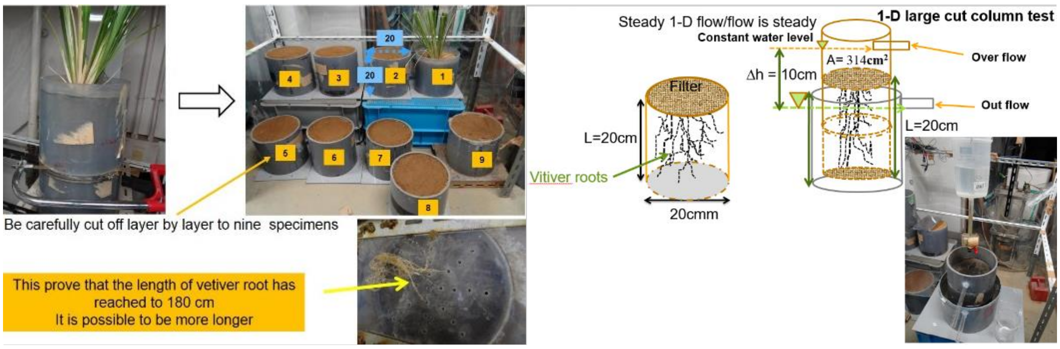

***Figure 4-4*- The schematic view of permeability test cylindrical vegetated ground sample [1D large cut column test]**

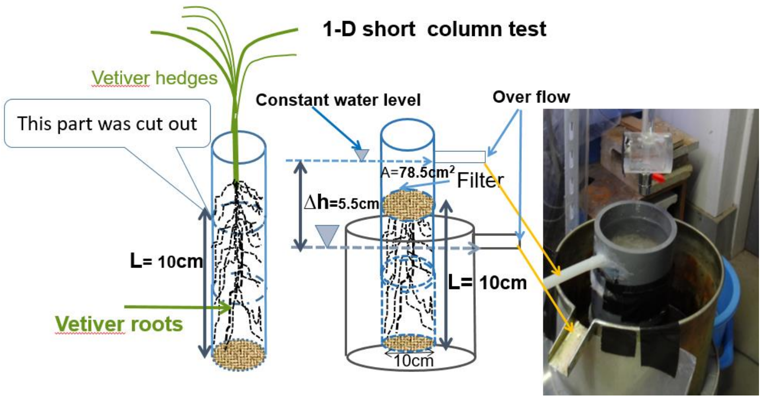

Figure 4-5- **Schematic view of permeability test cylinder sample with vegetated ground sample [1D/Flow is steady shortcut column test]**

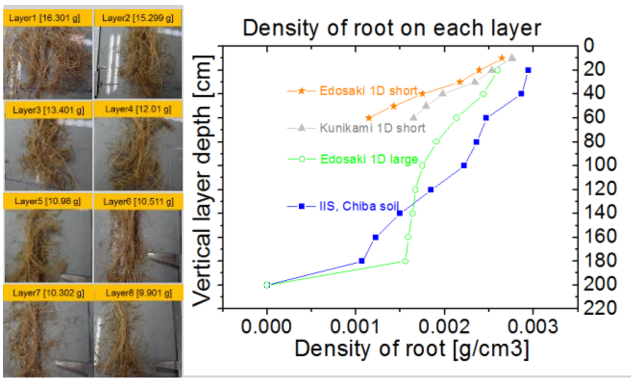

Figure 4-6- **Summary of the density of root in each layer**

The density of root is defined as the dry weight of the root divided by total volume of the soil column. As shown in Figure 4.6, the high root density increase in the top soil layers observation of the root taken out from each sample.

4.4 Permeability tests results and discussion

Figures 4.3(a) shows the result of the permeability test (vegetated soil sampling), and the Figures 4.7(a) the results of permeability test by 1D-Edosaki shortcut column after implanting the vetiver 6 weeks, Figure 4.7(b) by 1D-Edosaki large cut column after implanting the vetiver 24 weeks, the length of the root has well-uniformed reach to the bottom of the column Figure 4.7(c), the result of the permeability test by using IIS-Nishi Chiba soil sample, 4.7(d) the results of permeability test by 1D-Kunigami shortcut column after implanting the vetiver 6 weeks. The Figures 4.8 summarize the results of the permeability test. It has shown a general finding that root system (in the case of vetiver) will increase the hydraulic conductivity by 2 to 3 times for 3 different types of soil. Figure 4.9 is the graph of Lambda plotted against the density of root system (g/cm3). These results are directly applicable only to Edosaki, Kunigami and IIS soils deployed in experiments. The obtained results represent a curve:

$$\boldsymbol{\lambda} = \frac{K_{root} - K_{root=0}}{K_{root=0}}$$ and Curve fit: $\boldsymbol{\lambda} = RD^4 \times 2.47 \times 10^{11}$

For Edosaki long column, having a density of root system above a value of 0.0031, Lambda has attained a value of nearly 1.86. Edosaki short column has attained Lambda value of 0.87 when the root density is 0.026. For vegetated soil samples of different ages (1W, 2W, 3W, 4W), Lambda has attained a value of around 1.4, when root density is 0.003. The density of root system below the value 0.001, Lambda value is practically zero for all soils experimented.

For Kunigami soils, Lambda reaches 1.35, when the root density is around 0.0027. These experimental data shows that with the increase in root density, Lambda increases greatly/exponentially. (Kunigami mahji soil chosen is similar to those of tropical regions in South East Asia. Kunigami mahji in red-yellow in color, and is regarded as a problem attic soil from the point of view of erosion). The Permeability tests: High density of root increased hydraulic conductivity. With 0.003g/cm3 of root density, the hydraulic conductivity was increased by 2 times for the permeable Edosaki sand and by 2.3 times for the less permeable Kunigami soil. Their increasing ratio is similar to each other.

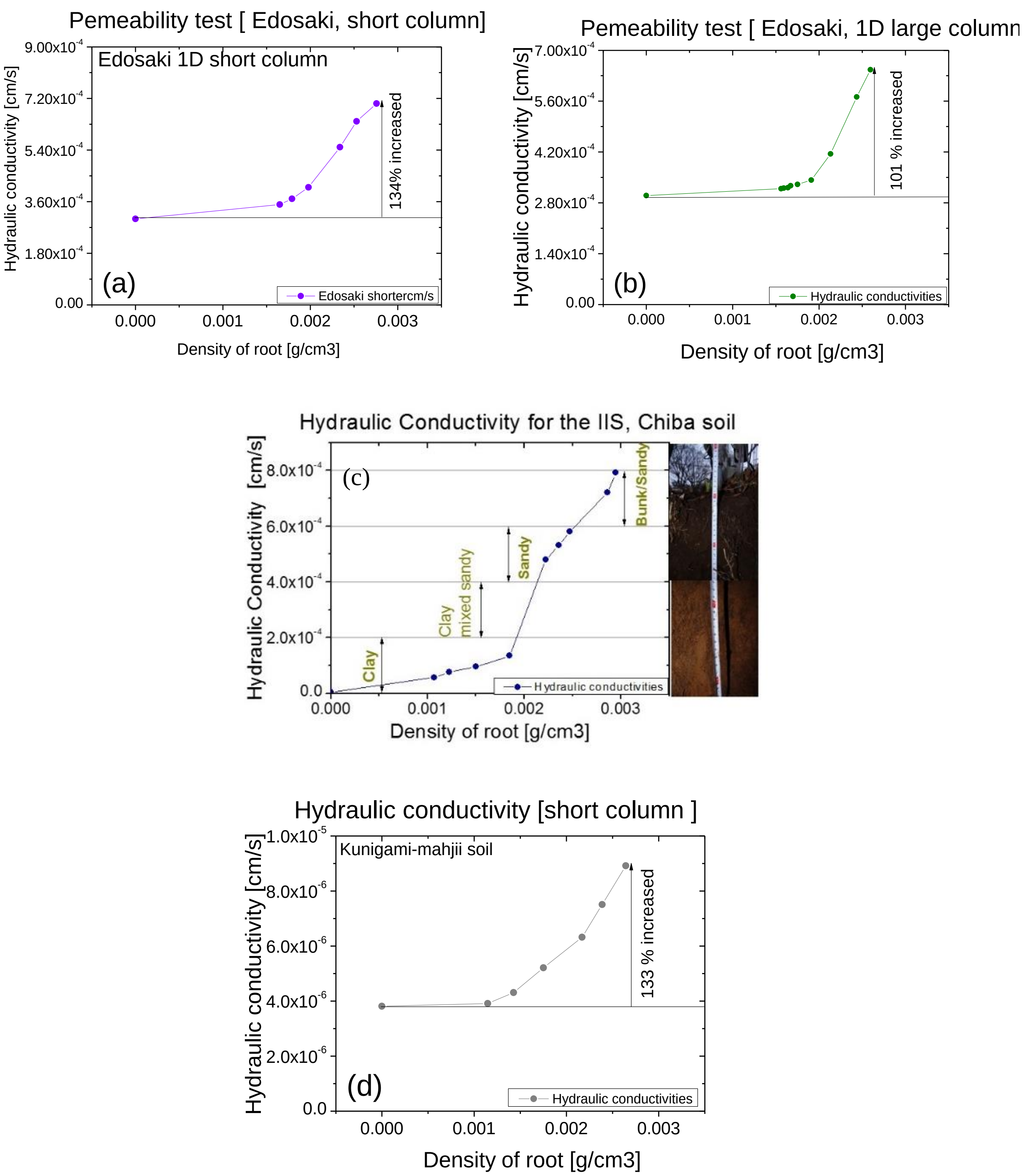

Figure 4-7 (a)-The results of permeability test by 1D-Edosaki shortcut column with vegetated 6 weeks, (b)-The results of permeability test by 1D-Edosaki large cut column with vegetated 24 weeks, the length of the root has well-uniformed reach to the bottom of the column, (c)-The result of the permeability test by using IIS-Nishi Chiba soil sample, (d)-The results of permeability test by 1D-Kunigami shortcut column with vegetated 6 weeks

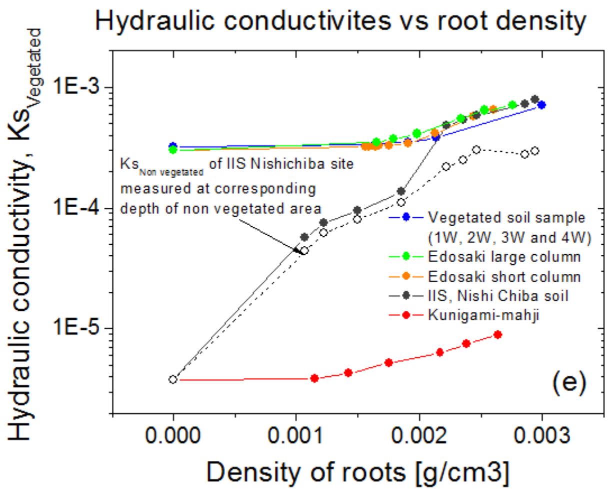

Figure 4-8-The result was a better indicator to quantify the relationship between Density of Roots vs. Hydraulic conductivity ''high density of root increase water infiltration''

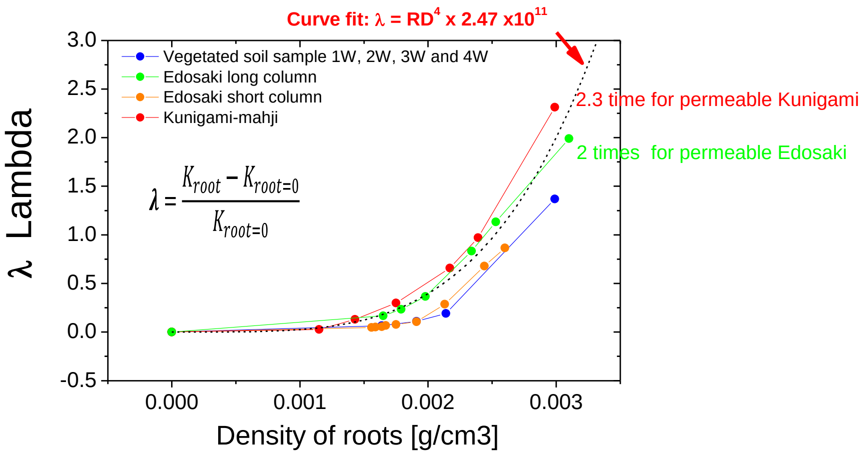

Figure 4-9-The result was better indicator to quantify the relationship between Density of Roots vs. Lambda "higher density of root networks increased lambda"

In order to expand the results of these experiments on different types of soils, the associated parameters to the materials used (Edosaki, Kunigami, and IIS) were identified and related to the permeability. However, it is important to remark that these results are only applicable to vetiver grass.

Error! Reference source not found. shows the relationship between permeability and two istinctive parameters: relative density and fine content.

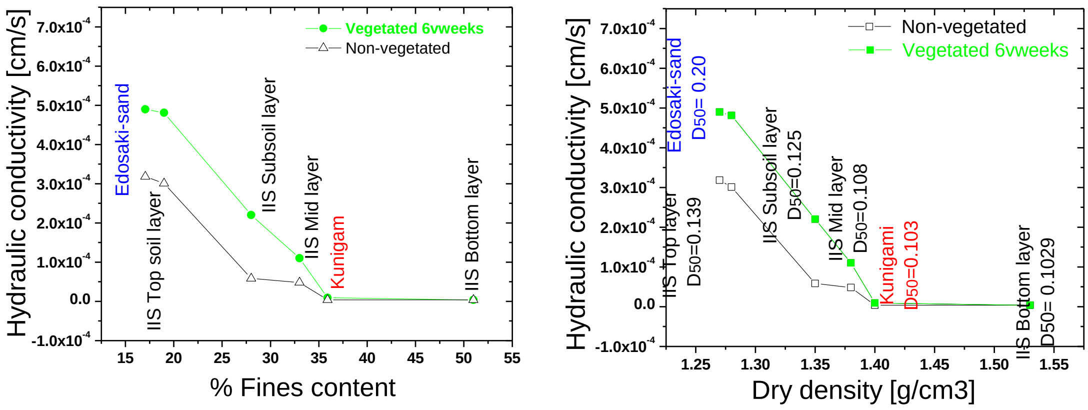

Figure 4-10 Plot graphs for different types of FC and dry density used in experiments

4.5 Estimate the water content ON SOIL and root

Tests in Figure 4-11 were conducted in order to understand the physical process occurring: the water percolation in soils, absorption of water by roots and evapotranspiration from the leaves of Vetiver plants. These experiments were designed to reflect atmospheric condition encountered by the Vetiver grass planted for stabilization of slopes, under rains of different intensities.

A closed chamber of height 60 cm of diameter D=10 cm was chosen to conduct experiments, as shown in Figure 4.11. The closed chamber was equipped with sensors to measure moisture content and temperature. Changes in moisture content of air in the closed chamber were measured. Evaporation from leaf (water absorbed by root) was measured for an estimated amount of water 500 ml and the rate of the water feeder 60 mm/hr., given on the top of the column.

The objective of the experiment was to determine the water content in the root, soils, evapotranspiration from leaves under different conditions of water given at the top.

Results obtained from experiments and the use of theoretical measurements such as water content of root, soil and evapotranspiration are summarized in Table 4.2.

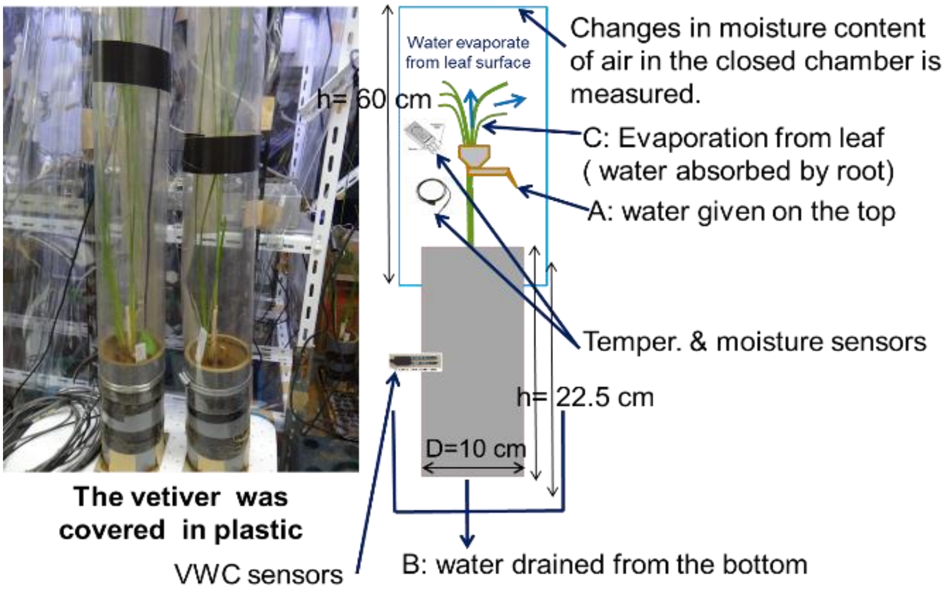

Figure 4-11-**A closed chamber with the body of the plant will give an estimation.**

Table 4.2 The results of the estimation of the water evapotranspiration from leaf

Description	Unit
T, Temperature inside the closed chamber	25.5 Celsius
A Water gave on the top of column [60mm/h]	500 ml
B, Water drained from the bottom	333.716 ml
C, ET from the leaf(measured by humidity sensor) Where $V_{supply} = 2.7$ Initial Voltage = 0.55 Final voltage at 72 hours [period of 3days] voltage = 0.98 Therefore, *Initial S.RH= 23.2 and Final S.RH= 48.2* $e(T) = 6.1078X10\frac{7.5T}{(T+273.15)}$	

$TruRH = \frac{SensorRH}{1.0546 - 0.00216T}$ $RH = \frac{\overline{W}_{air,saturated}}{\overline{V}_{air}}$ T at Temperature 25 Celsius Moisture content weight [in air chamber volume] $= 217x \frac{e(T)}{T + 273.15} xTrueRH$ $= 0.7\ g/cm^3$	
Moisture content weight [in air chamber volume]	0.7 g/cm^3
$Water_{given} = \Delta\overline{W}_{Seepage} + \Delta\overline{W}_{Evaporation}$ $\Delta\overline{W}_{Seepage} \gg \Delta\overline{W}_{Evaporation}$	

4.6 Calculation of the water content in the root and soil

Total volume:

$$V_{total} = V_{soil} + V_{root} = 1766\ cm^3$$

- Where, weight of the root

$$W_{root,water} = W_{wet\ root} - W_{dried\ root} = 69 - 35 = 34\ g$$

The water content in root = 34 /1766 = 0.019

- Weight of the soil

$$W_{soil,water} = W_{wetsoil} - W_{driedsoil} = 2540 - 2079 = 461g$$

The water content in soil = 461 /1766 = 0.26

- Total water content in root + soil = 0.26 + 0.019 = 0.279 [m3/m3]
- The total water content in the root is ***= 0.019 / 0.279 = 7%***

Total water content in root + soil = 0.279 m3/m3

VWC was measured by ECS = 0.283 m3/m3

Evaporation from leaf = 0.7 g/cm3

$$V_{root} = V_{total} - V_{soil} = 1766.25 - 1665.479 = 100.771\ cm^3$$

$$V_{root} = V_{total} - V_{soil} = 100.771\ cm^3$$

$$V_{water,soil} = W_{wet\ soil} - W_{dried\ soil} = 2540.07 - 2079.93 = 460.14\ cm^3$$

$$V_{water,soil} = W_{wet\ soil} - W_{dried\ soil} = 460.14\ cm^3$$

$$V_{water,root} = W_{wet\ root} - W_{dried\ root} = 68.99 - 35.12 = 33.87\ cm^3$$

$$V_{water,root} = W_{wet\ root} - W_{dried\ root} = 33.87\ cm^3$$

$$V_{water} = V_{water,soil} + V_{water,\ root} = 494.01\ cm^3$$

$$VWC = \frac{V_{water}}{V_{total}} = 0.279$$

$$\theta = \frac{V_{water+soil}}{V_{soil}} = 0.276$$

Table 4.3 Results of the estimation of the water content in root and soil

VWC by experiment and calculation = [VWC in soil] + [VWC in root] = 0.276	
VWC by EC5 sensor = [VWC in soil] + [VWC in root] = 0.27901	
VWC consumed by	Water content [cm3/cm3]
The roots	33.87
The soils	460.14

In the conclusion of the table 4.2 the results of the estimation of the water content in root and soil, both results were compared between the experiment and measurements by volumetric water sensor (EC5)., They were similar and indicated consensus, as given: the results of experiment, the VWC consumed by the root and the soils were equal to 0.276 and measurement by volumetric water sensor (EC5) was equal to 0.279. The water evapotranspiration from leaf was measured by humidity sensor during the period of 72 hours inside the closed chamber, with the temperature at 25.5 Celsius. The moisture content weight in air chamber volume, which is water evaporation from leaf was equal to 0.7 g/cm3.

4.7 Concluding remarks

The first tests on the hydraulic conductivity were conducted by using the none-vegetated soil sample and the 2nd 3rd and 4th experiments were conducted by using the vegetated soil samples after vetiver were implanted in 1 week/weight of roots 1.80g, 2 weeks/2.10g, 4 weeks/2.35g and 6 weeks/3.52g. The objective was to observe the respond water infiltration into the vegetated soils. The above results of the experiment have shown that, with 0.003g/cm3 of root density, the hydraulic conductivity was increased by 2 times for the permeable Edosaki sand and by 2.3 times for the less permeable Kunigami soil. Their increasing ratio is similar to each other. And the result was better indicator to quantify the relationship between densities of roots vs. Lambda “higher density of root networks increased lambda”

The results of the estimation of the water content in root and soil, both results were compared between the experiment and measurements by volumetric water sensor (EC5)., They were similar and indicated consensus, as given: the results of experiment, the VWC consumed by the root and the soils were equal to 0.276 and measurement by volumetric water sensor (EC5) was equal to 0.279. The water evapotranspiration from leaf was measured by humidity sensor during the period of 72 hours inside the closed chamber, with the temperature at 25.5 Celsius. The moisture content weight in air chamber volume, which is water evaporation from leaf was equal to 0.7 g/cm3.

4.8 References

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CHAPTER 5. ONE DIMENSIONAL COLUMN TEST, SITE MODEL TEST, AND MONITORING

5.1 General remarks

Water infiltration through the unsaturated zone can be generally assumed as a result of precipitation or surface processes which involves the use of water, the dynamics of such processes is mainly controlled by capillary and gravity forces involved at a determined point, and can be mathematically formulated for most of the practical problems as one-dimensional flow in the vertical direction, Romano et al. (1998).During rainfall infiltration process, if the vertical flux reaches a material of lower permeability; flow will be impeded and a perched water table can be build up, as consequence, there will be increase in pore water pressure and lateral flow will take place along the less permeable layer; Figure 5.1 shows models of groundwater flow (Abramson L.W. et al., 2002).

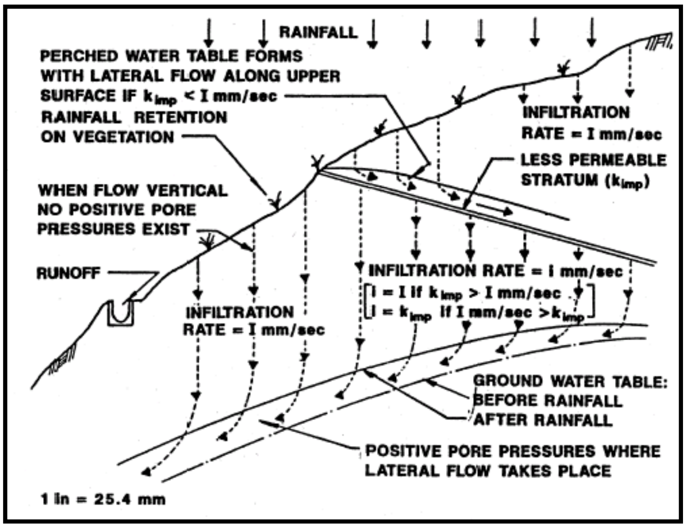


Figure 5-1- Modes of groundwater flow (Abramson, L.W. et al, 2002)

When the infiltrating rainfall reaches the groundwater table, most of the vertical component of flow will take place as lateral flow in the general direction of groundwater flow. Within this zone, lateral flow takes place and positive pore pressure exists. Above the phreatic surface, the infiltration rainfall raises the degree of saturation of the soil, which reduces the negative pore pressure and thus the shear strength.

Water movement through the unsaturated zone is generally conceptualized as occurring in the three stages, infiltration, redistribution and drainage (Ravi and Williams 1998), Infiltration is defined as the initial stage of water entering the soil after application at the soil surface, capillary forces, or matric potentials, are dominant during this phase; redistribution occurs as the next stage where the infiltrated water is redistributed within the soil profile after the cessation of water application at the soil's surface; during redistribution, both capillary and gravitational effects are important (Figure 5.2).

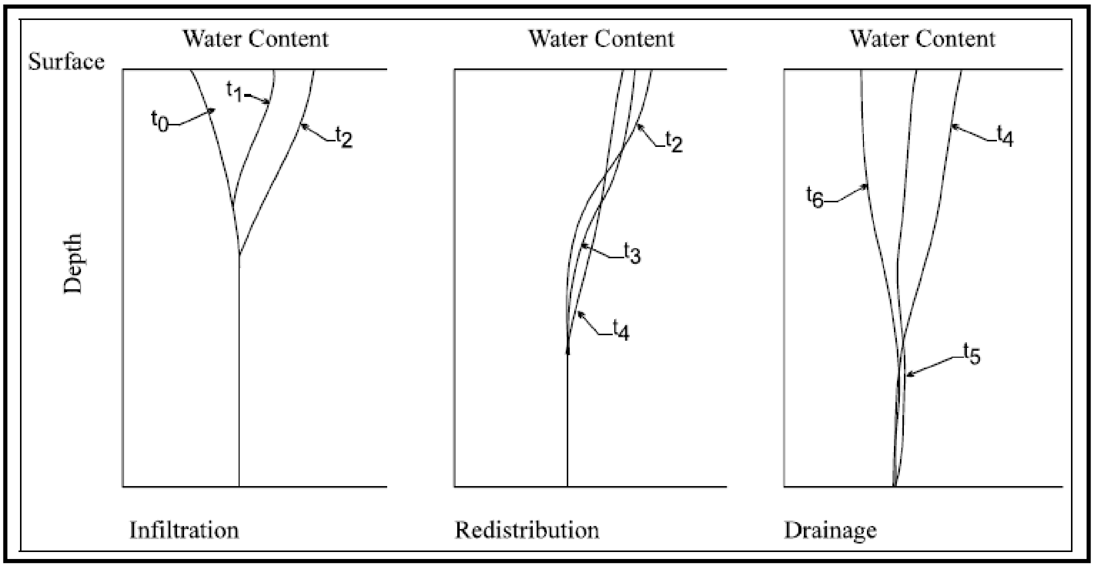


Figure 5-2- Conceptualization of water content profiles during infiltration, redistribution, and percolation (Ravi, V., and Williams, J.R. 1998)

During redistribution, simultaneous drainage and wetting take place and the impact of hysteresis may be important. Hysteresis is the phenomenon illustrated in Figure 5.3, which means that the wetting and drying curves of a specific soil will not be identical. Soil hysteresis may be very significant after infiltration ceases and redistribution begins; wetting and drying occur simultaneously; different points in the soil follow different scanning curves.

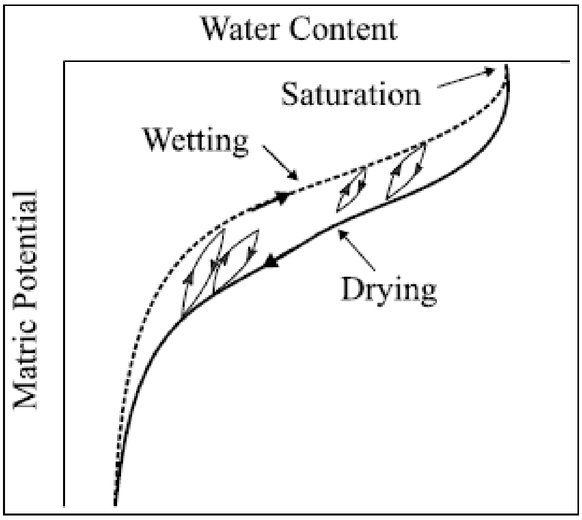


Figure 5-3- Illustration of the impact of hysteresis on wetting and drying curves for water content (Hillel, 1980).

The final stage of water movement is termed deep percolation or recharge, which occurs when the wetting front reaches the water table; evapotranspiration takes place concurrently during the redistribution stage, and will impact the amount of water available for deeper penetration within the soil profile.

In this study, the first and second stages of the water movement through unsaturated soil are considered, for simplicity these stages are recognized as infiltration and drainage respectively.

5.2 One-Dimensional flow

5.2.1 Objective of one-dimensional column test on vegetated and non-vegetated ground

The main objective of this study aims to investigate the changes in water infiltration properties of ground corresponding to growth of root quantitatively. The hydraulic properties of a vegetated ground are evaluated by monitoring the volumetric water contents and pore water presser to measure the behaviors of water passing through the vegetated and non-vegetated soil in 1D column. Hydraulic conductivities are also measured and compared between vegetated and non-vegetated columns. Additionally, to understand the infiltration through unsaturated sand column subjected to artificial rainfall is to analyse the effects of vetiver root on water infiltration. And the results probably helpful to understand the hydrological behavior of the ground slope.

5.2.2 Testing procedures and program

Two large columns, the vegetated and the non-vegetated were installed for one-dimensional seepage tests. To analyze the hydrological response of vetiver root and to evaluate the effect of root on water seepage. A uniform model ground by using the Edosaki sand soil was constructed in an acrylic pipe with an inner diameter of 200 mm and a total pipe length of 180 cm, with the length of soil sample 170 cm for the two large columns as shown in Figure 5.4. The bottom of the column is opened to static water layer so that a constant underground level is simulated. The volumetric water contents sensors are installed along the side of the column. The artificial rainfall events were created/given on the top of the column (using the medical drop of about 1 to 420 mm/hr). The conditions of the two columns are the same except that column A is the non-vegetated while column B is vegetated with a vetiver.

The Soil moisture smart sensor measures the dielectric constant of soil in order to determine its volumetric water content. The dielectric constant of water is much higher than that of air or soil minerals, which makes it a sensitive measure of the water content. During operation, values of 0 to 0.5 m3/m3 are possible to be measured by this sensor. A value of 0 to 0.1 m3/m3 indicates oven-dry to dry soil respectively. A value of 0.615 or higher normally indicates a wet to saturated soil.

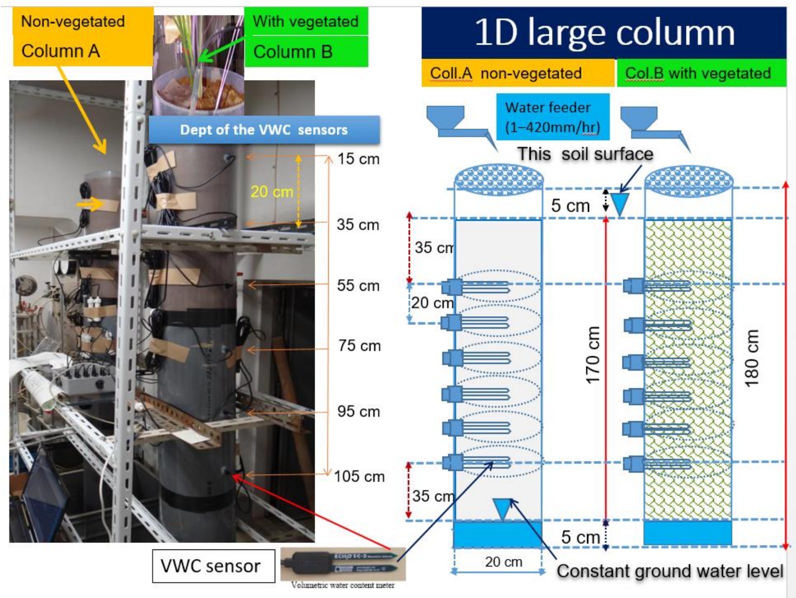


Figure 5-4- Illustrated one-dimensional column model test

In order to get an accurate and consensus results from the one-dimensional tests, additional six short columns, the vegetated and the non-vegetated were installed, to conduct (one-dimensional) seepage tests. The main purpose was to analyze the hydrological response of vetiver root and to evaluate the effect of root on water seepage. A uniform model ground by using the Edosaki sand soil was constructed in an acrylic pipe, with an inner diameter of 10 mm and a total height of pipe of 70 cm, having a length/height of soil sample of 60 cm, as shown in Figure 5.5. The bottom of the column was opened/subjected to static water layer so that a constant underground level was simulated. The volumetric water contents sensors were installed along the side of the column. The artificial rainfall events were created/given on the top of the column (using the manual drop of about 300 to 420 mm/hr.). The conditions of the six columns were same, except that the columns A, C, F were non-vegetated, while column B, D, E were vegetated with a vetiver.

The Soil moisture smart sensors measured the dielectric constant of soil, in order to determine its volumetric water content. The dielectric constant of water is much higher than that of air or soil minerals, which makes it a sensitive measure of the water content. During operation, values of 0 to 0.5 m3/m3 were possible. A value of 0 to 0.1 m3/m3 indicates oven-dry to dry soil respectively. A value of 0.62 or higher, normally indicates a wet to saturated soil.

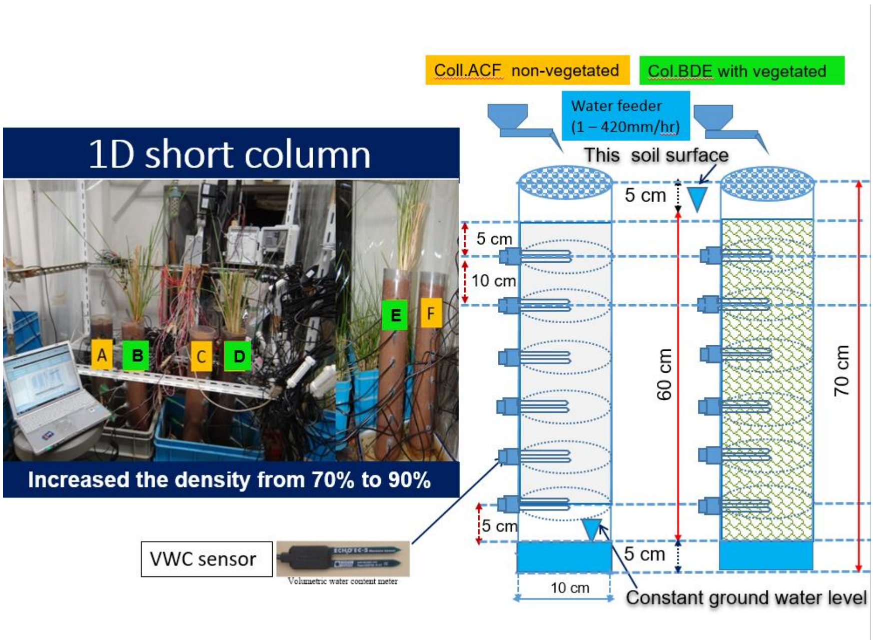


Figure 5-5- One-dimensional six short columns model tests

5.2.3 One-dimensional column test result [the heavy rainfall, 300-420 mm/hr.]

Tests were conducted to investigate the changes in water infiltration properties of ground corresponding to growth of root quantitatively. The delay time analysis is the most important key finding to understand how water infiltration is effected by root. Figure 5.7, represents the test results conducted by the artificial rainfall tests [1-420 mm/hr.], by using different densities of roots, as shown in Figure 5-67: (a-NV) the non-vegetated compared with(a-V) the vegetated columns of 0 week ; (b-NV) the non-vegetated compared with(b-V) the vegetated columns of 6 weeks; (c-NV) the non-vegetated compared with (c-V) the vegetated columns of 12 weeks and (d-NV) the non-vegetated compared with (d-V) the vegetated columns of 24 weeks, respectively. These plots were zoomed out to show the pickup points in each of depth layers [35, 55, 75, 95, 115 and 135 105 cm], when rainfall started, before the wetting process. The infiltration has taken some time before starting the initial volumetric water content. The results of the delay time analysis were compared between non-vegetated and vegetated columns at 0 week, 6 weeks, 12 weeks and 24 weeks. The results show that delay time for infiltration was reduced by 43% by the introduction of vegetation, for Edosaki 1D large column test. In Figure 5-76, a zoom up was made to show the pickup points before the wetting and drying process.

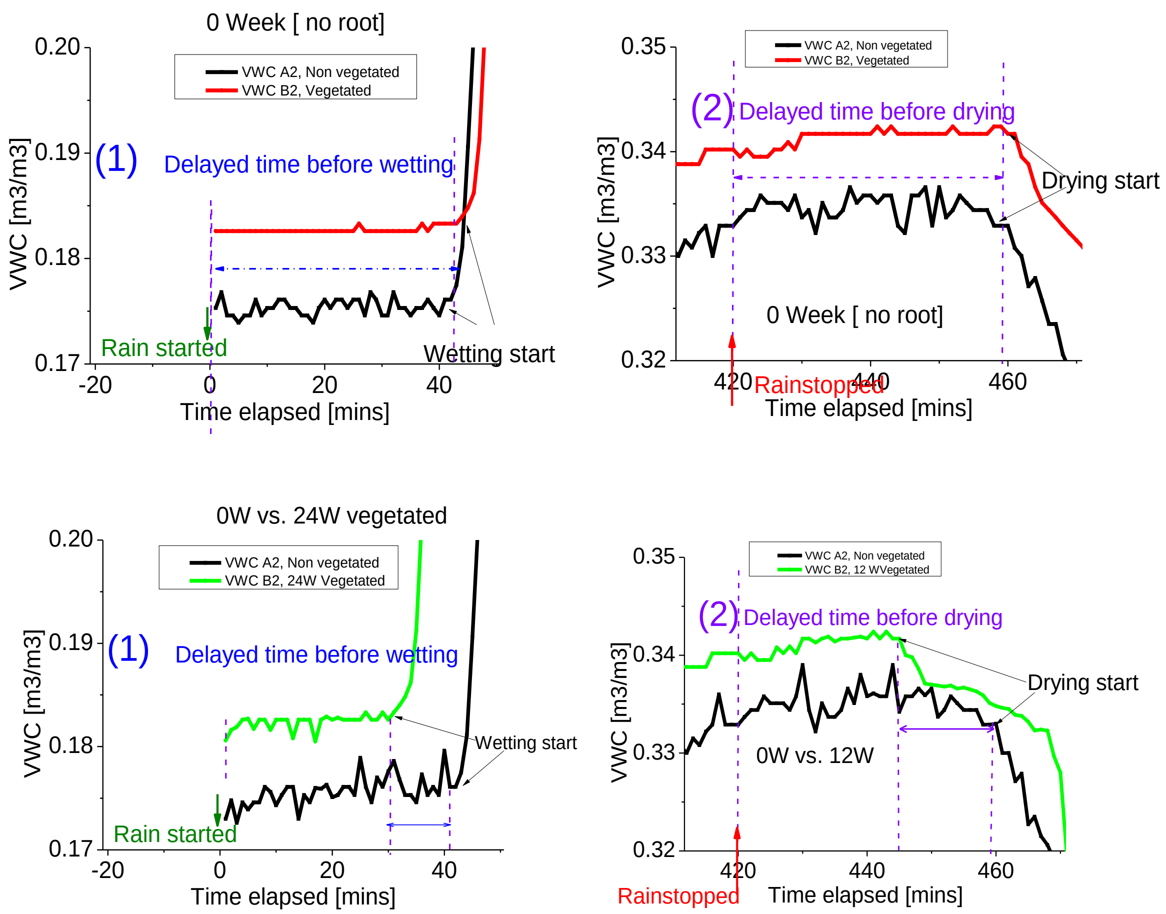


Figure 5-6. Behavior of Water infiltration vs. Delayed time.

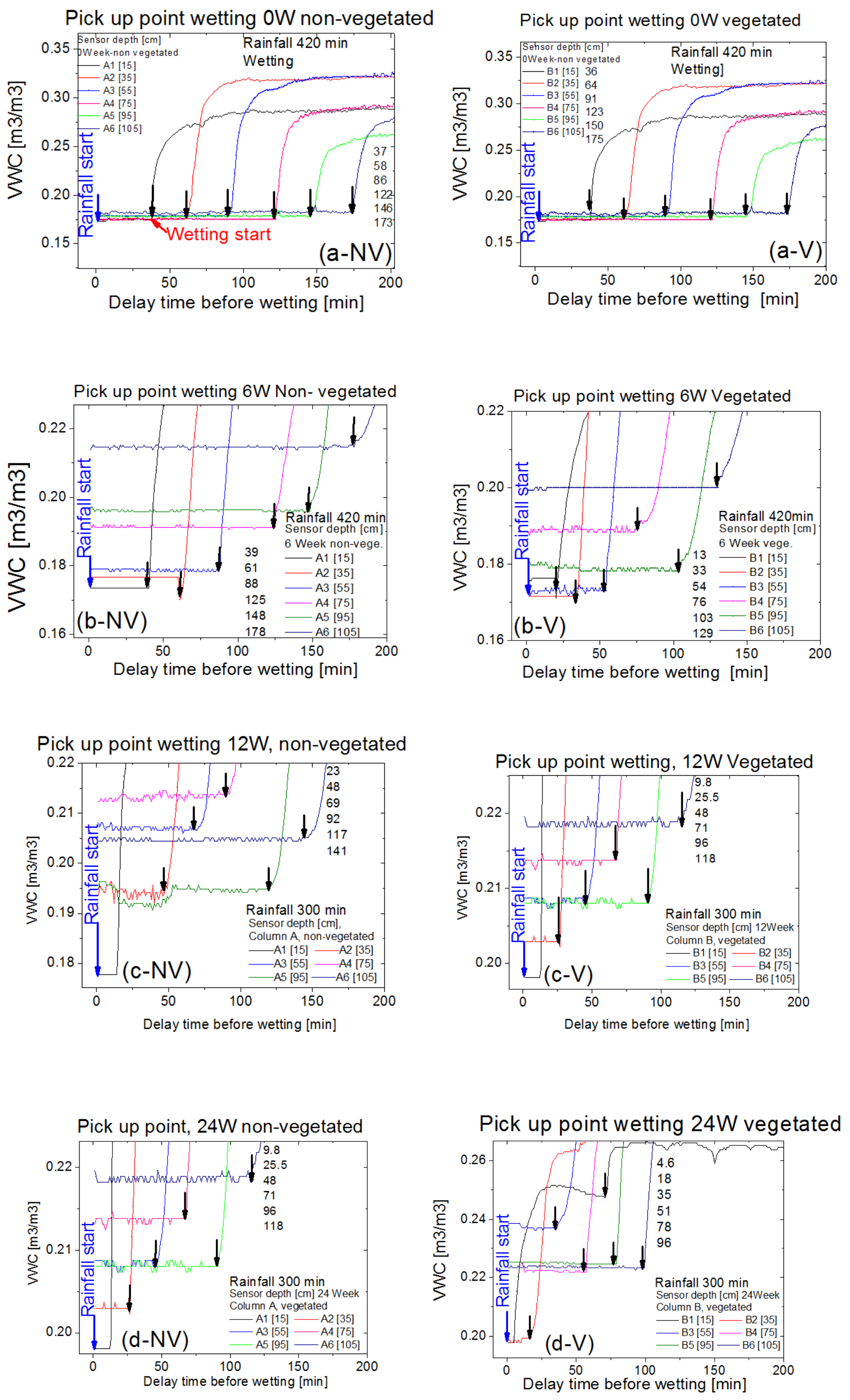
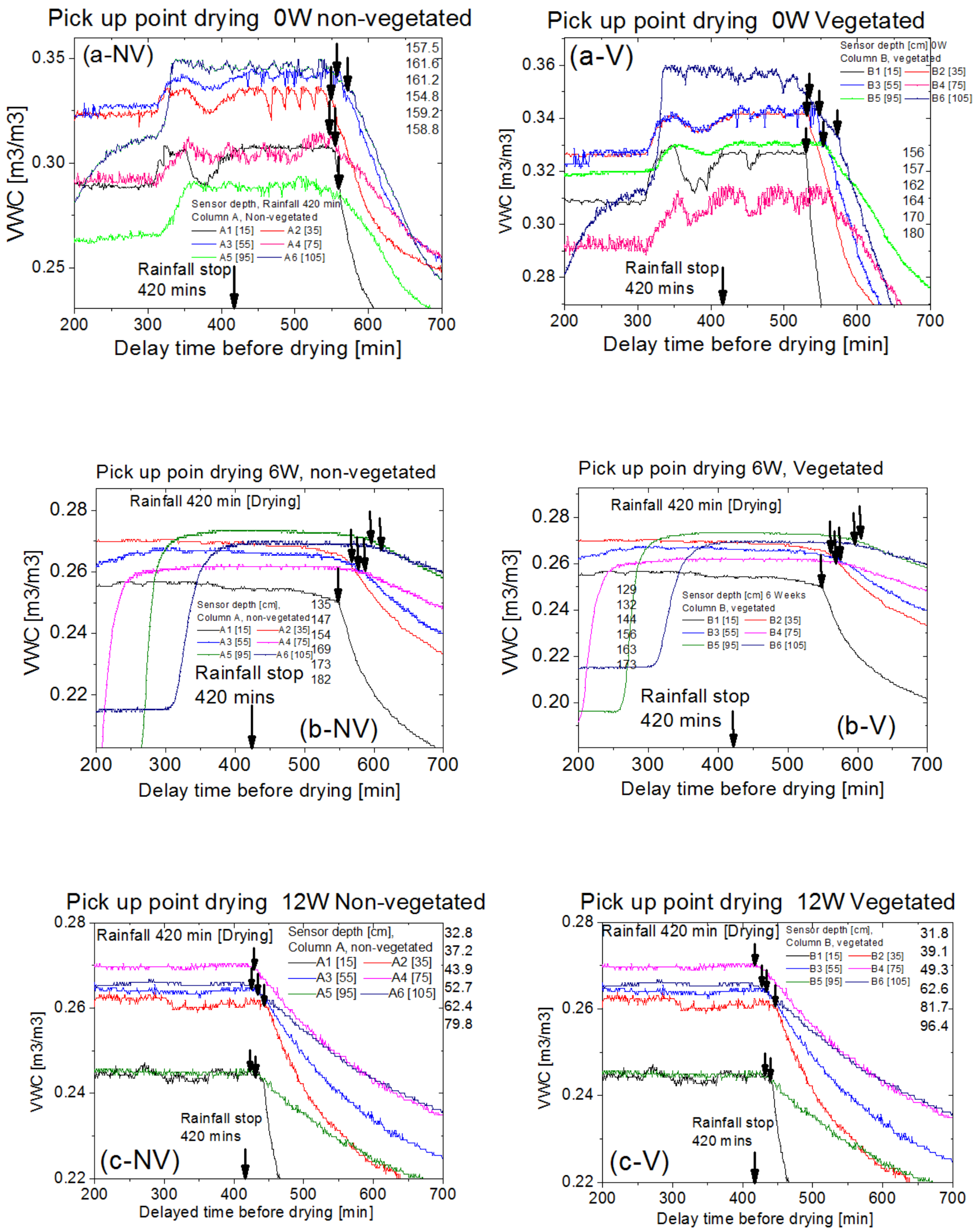


Figure 5-7- (a-NV),(a-V) ; (b-NV),(b-V); (c-NV),(c-V) and (b-NV),(b-V) relationship of the volumetric water content and elapsed time between non-vegetated and vegetated columns of

different ages: 0W, 6W, 12W and 24W. These results are from the giving rainfall tests: 300mm/hr. and 420 mm/hr. and the volumetric water contents were measured at the depth 35 cm, 55cm, 75 cm, 95 cm, 115 cm, and 135 cm.

Figure 5-8 shows the results of delay time analysis and the comparison between non-vegetated and vegetated root networks of different ages : (a-NV) and (a-V), vegetated and non-vegetated columns of ages: 0 week ; (b-NV) and (b-V), vegetated and non-vegetated columns of 6 weeks; (c-NV) and (c-V), vegetated and non-vegetated columns of 12 weeks and (d-NV) and (d-V), vegetated and non-vegetated columns of 24 weeks. In these plots, it was zoomed out to show on the pickup point in each depth of layers [35, 55, 75, 95, 115 and 135 cm], after rainfall stop, before the drying process. By using the delay time analysis, or defined as the lapse of time taken by soils before attaining drying status, the pick-up points were zoomed and were measured by volumetric water content sensors. The results of the delay time analyses were compared between non-vegetated and vegetated column at the ages of weeks: 0 , 6 , 12 and 24 . The results show that the delay time for drainage was probably affected by the introduction of vegetation.

Furthermore, Figures 5.7 and Figures 5.8 have shown that vetiver root has conserved high volumetric water contents (VWC) on root networks of vegetated columns of 6W, 12W and 24W, compared to non-vegetated, as shown the differences in peaks of VWC on the Figures 5.8(b-V);(c-V); and (d-V); they have conserved high VWC, more than non-vegetated column. VWC plays an important role in the stability of slopes. The results shown in the comparison of 24W old root network compared to non-vegetated status is highly evident of this fact. The grown root network accelerates infiltration of rainwater into the ground slope, both in the wetting and drying process stages. These were probably due to generating water pathway along the surface of the root. Therefore, it could be concluded that high densities of root networks could protect the slopes in a stable manner.


Pick up point drying 0W non-vegetated
(a-NV)
VWC [m3/m3]
Sensor depth, Rainfall 420 min
Column A, Non-vegetated
A1 [15] A2 [35]
A3 [55] A4 [75]
A5 [95] A6 [105]
157.5
161.6
161.2
154.8
159.2
158.8
Rainfall stop
420 mins
Delay time before drying [min]
Pick up point drying 0W Vegetated
(a-V)
VWC [m3/m3]
Sensor depth [cm] 0W
Column B, vegetated
B1 [15] B2 [35]
B3 [55] B4 [75]
B5 [95] B6 [105]
156
157
162
164
170
180
Rainfall stop
420 mins
Delay time before drying [min]
Pick up poin drying 6W, non-vegetated
Rainfall 420 min [Drying]
VWC [m3/m3]
Sensor depth [cm],
Column A, non-vegetated
A1 [15] A2 [35]
A3 [55] A4 [75]
A5 [95] A6 [105]
135
147
154
169
173
182
Rainfall stop
420 mins
(b-NV)
Delay time before drying [min]
Pick up poin drying 6W, Vegetated
Rainfall 420 min [Drying]
VWC [m3/m3]
129
132
144
156
163
173
Sensor depth [cm] 6 Weeks
Column B, vegetated
B1 [15] B2 [35]
B3 [55] B4 [75]
B5 [95] B6 [105]
Rainfall stop
420 mins
(b-V)
Delay time before drying [min]
Pick up point drying 12W Non-vegetated
Rainfall 420 min [Drying]
VWC [m3/m3]
Sensor depth [cm],
Column A, non-vegetated
A1 [15] A2 [35]
A3 [55] A4 [75]
A5 [95] A6 [105]
32.8
37.2
43.9
52.7
62.4
79.8
Rainfall stop
420 mins
(c-NV)
Delayed time before drying [min]
Pick up point drying 12W Vegetated
Rainfall 420 min [Drying]
VWC [m3/m3]
Sensor depth [cm],
Column B, vegetated
B1 [15] B2 [35]
B3 [55] B4 [75]
B5 [95] B6 [105]
31.8
39.1
49.3
62.6
81.7
96.4
Rainfall stop
420 mins
(c-V)
Delay time before drying [min]

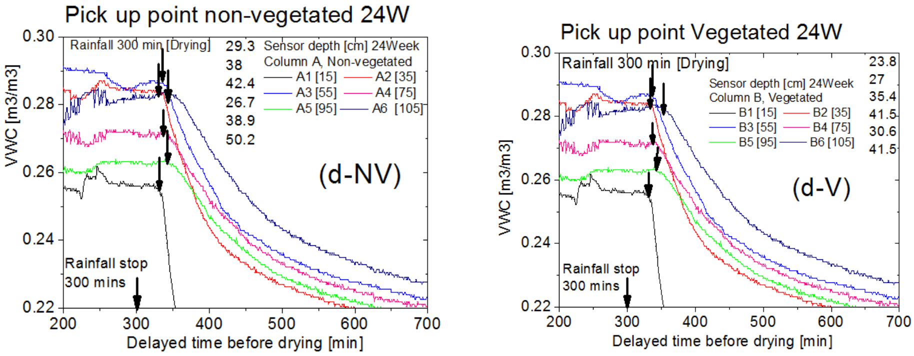


***Figure 5-8**- (a-NV),(a-V) ; (b-NV),(b-V); (c-NV),(c-V) and (b-NV),(b-V) the relation of the volumetric water content and elapsed time between non-vegetated and vegetated column of different ages: 0W, 6W, 12W and 24W. These results from the giving rainfall tests 300-420 mm/hr. and the volumetric water contents were measured at the depth 35 cm, 55cm, 75 cm, 95 cm, 115 cm, and 135 cm.*

Figures 5.10a represents the summary of the delay time before the wetting process and Figure 5.11b shows the summary of the delay time before drying process by the experimental data [for all cases]. The results of the delay time analysis meant the comparison between non-vegetated and vegetated columns, at the period of growth of vegetation of weeks: 0, 6, 12 and 24. The results clearly indicated that the delay time for infiltration was considerably reduced by the introduction of vegetation: 43 % for Edosaki 1D large column test, 33% for Kunigami 1D short column test, and 57% for Edosaki 1D short column test.

The objective of tests was to observe the responding of water infiltration into the vegetated soils, and the results of the experiments have shown that high density of roots tends to reduce delay time for water infiltration into the vegetated ground. As shown in the Figure 5.9a, it is clearly understood that the grown root accelerates infiltration of rainwater into the ground slope, probably due to generating water path along the surface of the root.

Figure 5-9 depicts the case-by-case results of the delayed time before wetting and drying processes, with different root ages, using Kunigami and Edosaki sands. Tests were conducted on 1D short and long column apparatuses for Edosaki sand and 1D short column for Kunigami sand. Vegetated root networks of different ages: 0 W, 6 W, 12 W and 24 W were tested and comparisons were made with the non-vegetated columns of similar dimensions.

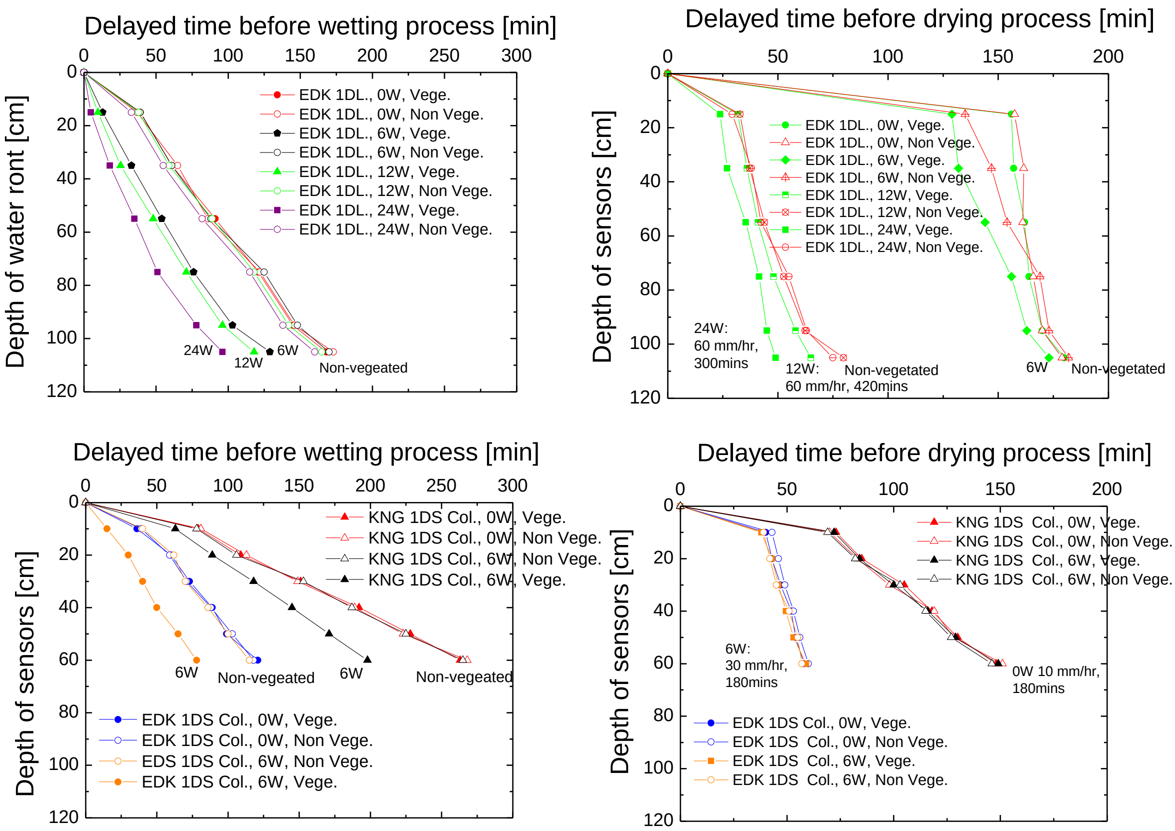


Figure 5-9 Comparison of delayed time before wetting process

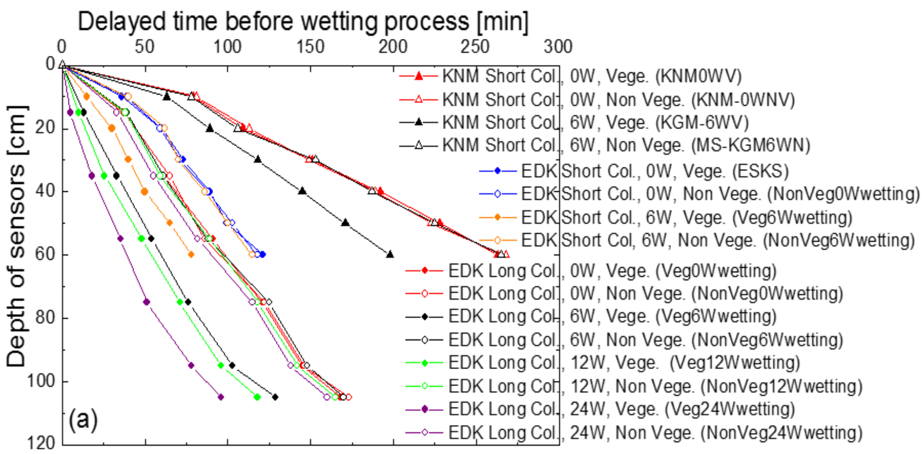


Figure 5-10-Summary of the wetting process

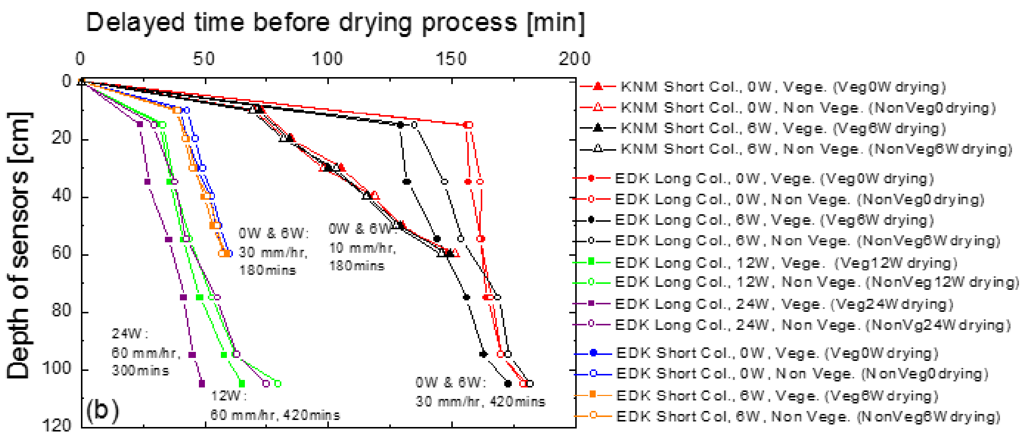


Figure 5-11- Summary of drying process

5.2.4 One-dimensional test results and discussion for heavy rainfall (1-420 nm/h)

The observations and the results of delay time tests on the wetting process could be summarized as follows:

- Kunigami sand 1D long column test: the vegetated one dimensional short columns after covering with roots network of 6W, the water infiltration responded very positively by roots, clearly revealing high increase, compared to the non-vegetated column.
- Edosaki sand 1D short column test: the vegetated one dimensional short columns after covering by roots of 6W, the water infiltration had responded positively by roots, clearly indicating the increase, compared to the non-vegetated column.
- Edosaki sand 1D long column test: the vegetated one-dimensional long column after covering by root networks of 6W, 12W, and 24W, the water infiltrations were very high, clearly responded by roots, with considerable increases compared to the non-vegetated

Experiments were conducted to identify the delay time before drying process, using Kunigami and Edosaki sands. Tests conducted used same apparatuses used for the wetting process, using root networks /vegetation of weeks: 0W, 6W, 12W and 24 W.

Figure 5-11 shows the results obtained. The observations and the results of tests of delay time on drying are as follows:

- Kunigami sand 1D short column test: The results show that on the vegetated one dimensional short columns after covering by roots of 6W, the water drying was reduced by the introduction of vegetation 5%.
- Edosaki sand 1D short column test: The results show that on the vegetated one dimensional short columns, after covering with root network of 6W, the water drying was reduced by the introduction of vegetation 8%.
- Edosaki sand 1D long column test sand: The results show that on the vegetated one dimensional long columns, after covering by root networks of 6W, 12W, and 24W, the water drying was reduced by the introduction of vegetation 30%.

5.3 Site model test and monitoring

5.3.1 Objective of Site model test and monitoring

The effects of vegetation on hydraulic properties in the ground were investigated by site vegetation test, the location of the site test was selected and conducted at the Institute of Industrial Science (IIS) the University of Tokyo, Nishi-Chiba, since the early May 2013. One series of volumetric water content sensors were installed in the vertical direction just near the plant on the both test fields, vegetated and non-vegetated zone are shown in Figure 5.12 and Figure 5.13. The conditions of the two zones are the same/similar except that the zone 1 is non-vegetated while zone 2 is vegetated with eighteen vetiver grasses. The distance between two zones is 3 meters. In order to get uniform distribution of the root, the position and range of the vetiver grasses were implanted in the surrounding among the volumetric water content sensors, as shown in Figure 5.14. The volumetric water content, the rainfall intensity (rain gauge), and temperature sensors monitored and recorded continuously, during the vegetation growth period of 8 months. The water content in the ground changes corresponding to the water infiltration and consequent drainage for every rainfall events. These behaviors should be a function of the hydraulic properties of the ground soil as well as the intensity and period of rainfall. The effects of the plant root can be detected as long-term changes in the water infiltration, the results from the site test are shown in Figure 5.16.

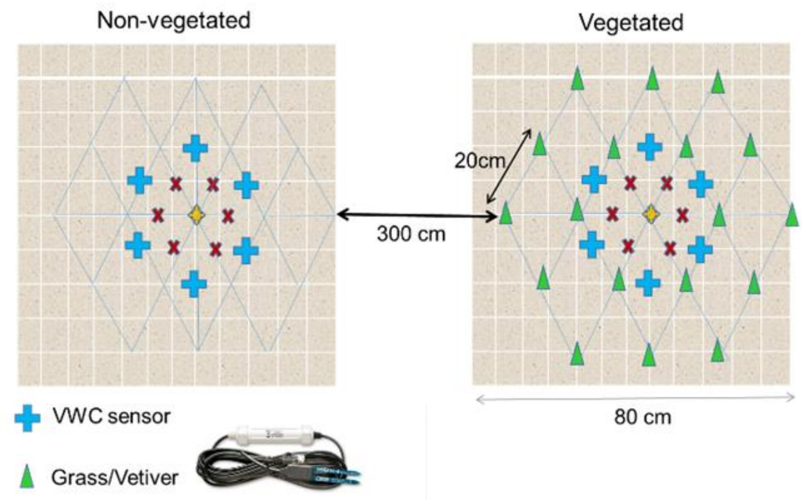


Figure 5-12-The position among the VWC and PWP sensors and Vetiver

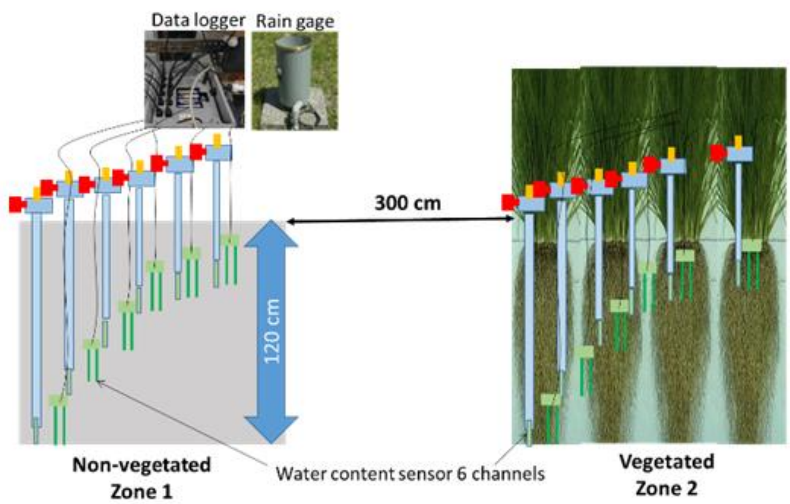


Figure 5-13- Arrangement of test plant and sensors

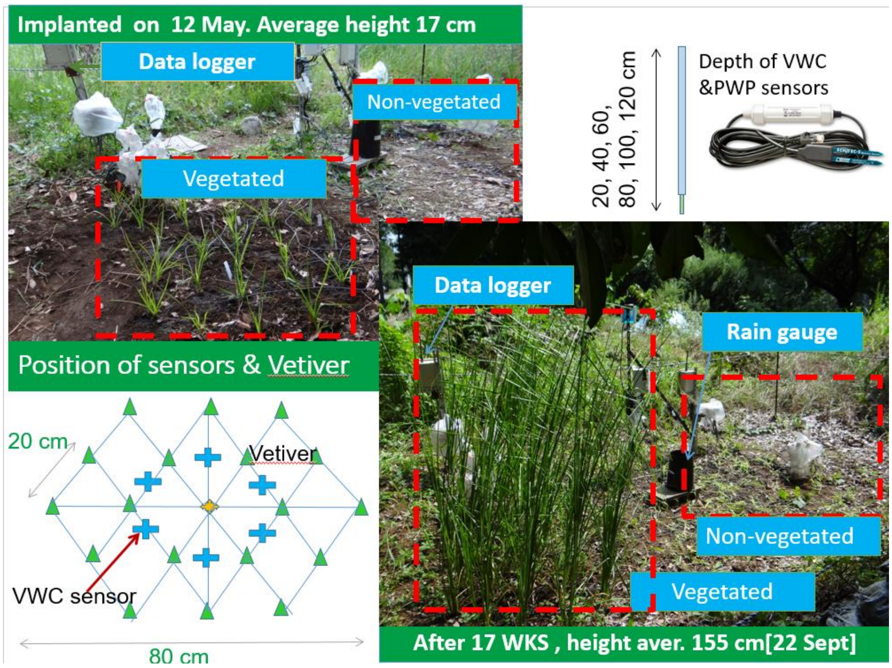
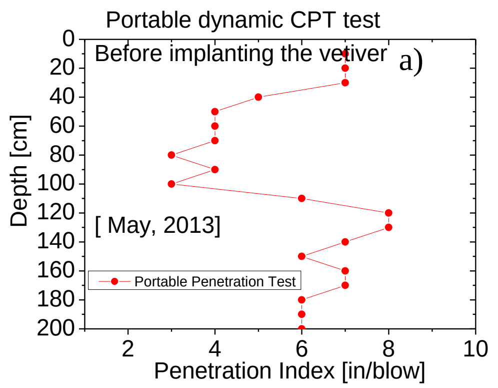


Figure 5-14- Site model test, in at IIS, Nishi Chiba

Figures 5.15 The results of the portable dynamic CPT test at the IIS, Nishi Chiba site test.

The figure 5.15 (a) the CPT test was conducted before implanting the vetiver in the early May 2013 and fig.5.15 (b) the CPT test was conducted after implanting the vetiver 8 months in the end of Jan. 2014 and based on the number of penetration index on the fig. 5.15(b) is slightly greater than (a), this is probably because of the increased moisture contents on the soil and they may effect by root.



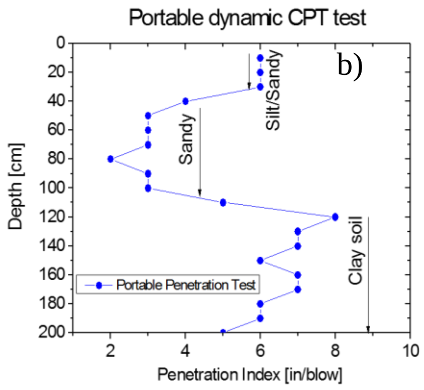
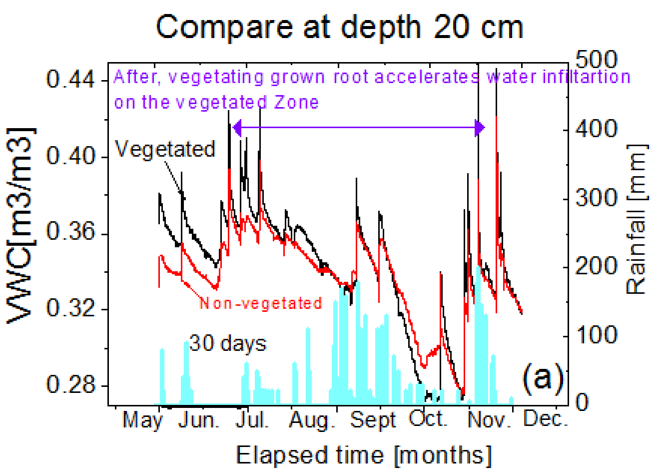


Figure 5-15- Portable dynamic CPT test, at IIS- Chiba a) before and b) after implanting the vetivers

5.3.2 Site model test result and discussion

In Figures 5.16 it can be observed that vetiver roots have conserved high volumetric water contents (VWC) on root networks of vegetated zone as defined on the black graphs at the depth of 20cm, 40cm, 60 80 cm and all depths as shown difference in peaks of VWC on the Figures 5.16 (a), (b), (c) and (d); they have conserved high VWC more than non-vegetated zone as defined on the red graphs and the grown root accelerates infiltration of rainwater into the ground slope. These were probably due to generating water pathway along the surface of the root. The results from the site test it was very clearly increased infiltration rate on vegetated zone more than non-vegetated zone and their increasing ratio is similar to each other.



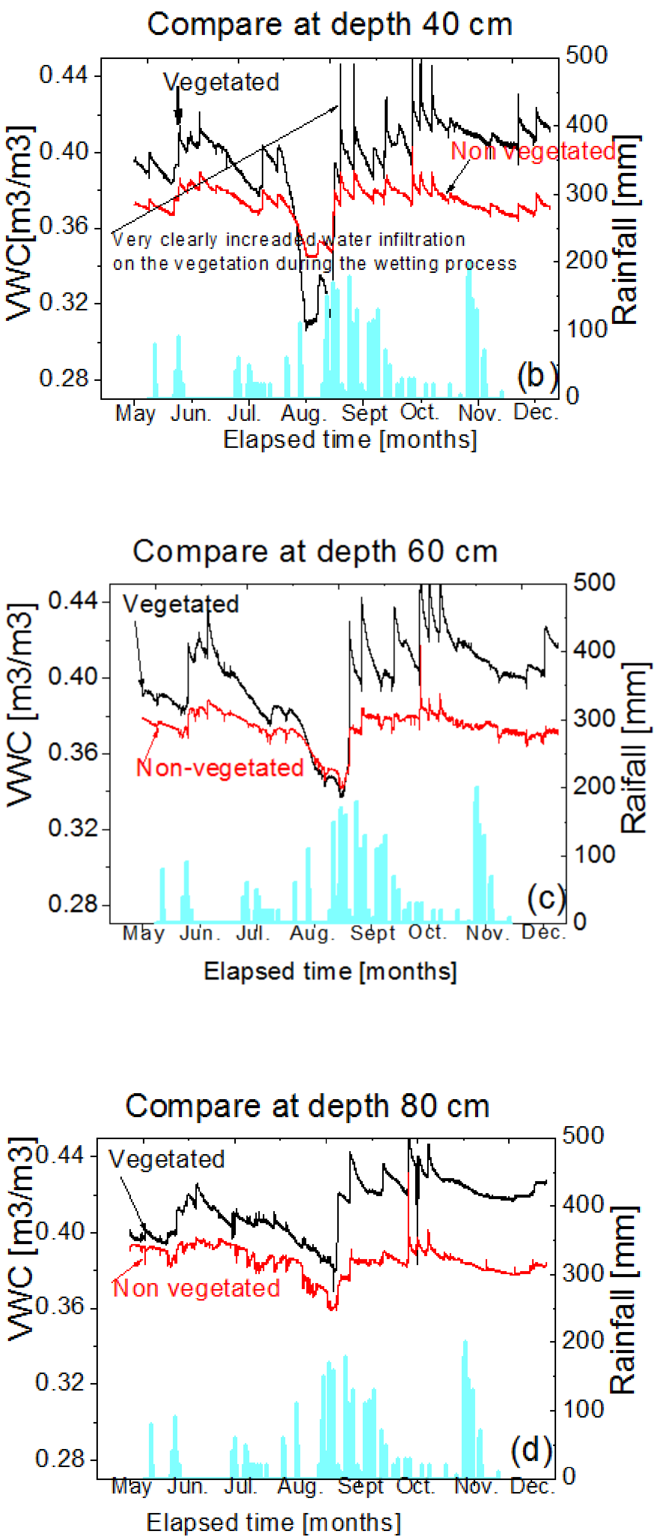


Figure 5-16 (a), (b), 9c) and (d)-Time hysterias' of volumetric water content

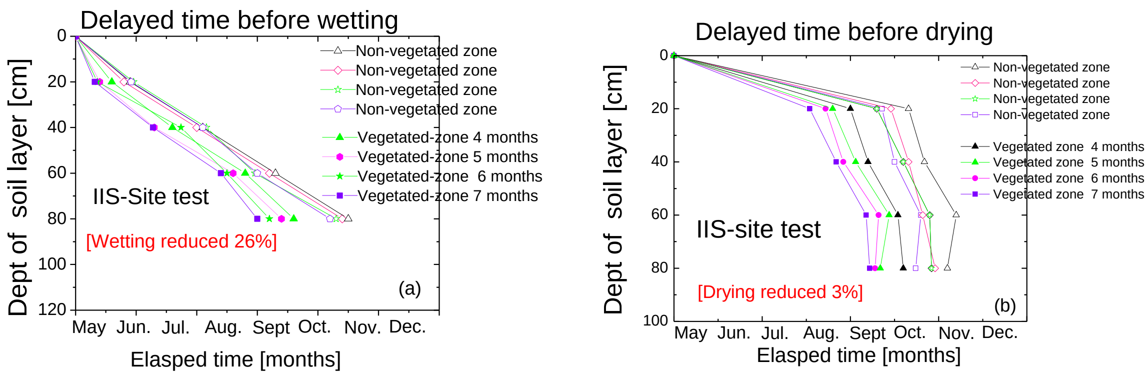


Figure 5-17(a) Summary of the wetting process (b) Summary of the drying process

Figure 5-117**(a)** shows the results obtained. The observations and the results of tests of delay time on wetting are as follows:

- Vegetated-zone: The results show that on the vegetated zone, after covering with root network of 7 months, the water wetting was reduced by the introduction of vegetation 26 %.

Figure 5-117**(b)** shows the results obtained. The observations and the results of tests of delay time on drying are as follows:

- Vegetated-zone: The results show that on the vegetated zone, after covering with root network of 7 months, the water drying was reduced by the introduction of vegetation 3%.

5.4 Concluding remarks from the laboratory measurements of 1D column model tests

They are certainly reduced delay time for water infiltration into the ground slope, probably due to generating water pathway along the surface of the root. The results clearly indicated that the delay time for infiltration was clearly reduced by the introduction of vegetation:

- Delayed time for wetting was reduced by the introduction of vegetation: 32% and 25% for Edosaki sand, and for Kunigami soil respectively.
- Delayed time for drainage was reduced by the introduction of vegetation: 30% and 5% for Edosaki sand, and for Kunigami soil respectively.

Site model test, the results indicated that the delay time for drying was clearly reduced by the introduction of vegetation: 30 % for Edosaki 1D large column test, 5% for Kunigami 1D short column test, and 8% for Edosaki 1D short column test.

The data from site tests shows that the vegetated zones have higher volumetric water content value than those of non-vegetated zones.

5.5 References

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CHAPTER 6. HYDRUS 1D MODELLING AND APPLICATION

6.1 General remarks

The HYDRUS numerical models are widely used for simulating water flow and solute transport in variably saturated soils and groundwater. Applications involve a broad range of steady-state or transient water flow, solute transport, and/or heat transfer problems. They include both short-term, one-dimensional laboratory column flow or transport simulations, as well as more complex, long-duration, multi-dimensional field studies.

Numerical models have become much more efficient and can now be applied to one-dimensional problems of saturated and unsaturated water flow etc. The importance of the unsaturated zone as an integral part of the hydrological cycle has long been recognized. The vadose zone plays an inextricable role in many aspects of hydrology, including infiltration, soil moisture storage, evaporation, plant water uptake, groundwater recharge, runoff, and erosion. Initial studies of the unsaturated (vadose) zone focused primarily on water supply studies, inspired in part by attempts to optimally manage the root zone of agricultural soils for maximum crop production. Interest in the unsaturated zone has dramatically increased in recent years because of growing concern that the quality of the subsurface environment is being adversely affected by erosional, agricultural, industrial and municipal activities.

HYDRUS-1D is a software package for simulating water, heat and solute movement in one-dimensional variably saturated media. The software consists of the HYDRUS computer program, and the HYDRUS1D interactive graphics-based user interface. The HYDRUS program numerically solves the Richards equation for variably saturated water flow and advection-dispersion type equations for heat and solute transport. The flow equation incorporates a sink term to account for water uptake by plant roots. The flow equation may also consider dual-porosity type flow in which one fraction of the water content is mobile and another fraction immobile, or dual-permeability type flow involving two mobile regions, one representing the matrix and one the macrospores.

6.2 Objective of the using the HYDRUS-1D

Numerical models are increasingly used for predicting or analysing water flow and contaminant transport processes in the subsurface, including the vadose zone.

Hydrus-1D is a modeling for simulation and analysis of water flow through soil root uptake evaporation application and solute transport in variably saturated porous media. The software package includes the one-dimensional finite element model HYDRUS for simulating the movement of water, heat, and multiple solutes in variably saturated media. The model is supported by an interactive graphics-based interface for data pre-processing, discretization of the soil profile and graphic presentation of the results.

The objective of using the Hydrus 1D for analysing and understanding how water infiltration is effected by root, behavior of water flow through the vegetated and non-vegetated soils. Hydrus 1D models include the Rosseta based pedo-transfer function, which to illustrate soil water characteristic curve relationship. The Hydrus 1D is used for a solution that demonstrates water infiltration evaporation and percolation of water through the soils of different textures and layered soils.

6.3 Processing and Procedure

Van Genuchten (1980) defined the residual volumetric water content as the water content for which the gradient $d\theta/d\psi$ becomes zero at high matric suction. From a practical point of view, it seemed sufficient to define θr as the water content at some large matric suction, e.g. at the permanent wilting point ψe=1500kPa.

The Van Genuchten's soil water retention curve model (Van Genuchten, 1980) is described by:

1. Soil water content is relative water content or effective saturation (Se)

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}$$

2. One of the most widely used water retention function is that developed by Van Genuchten :

$$S_e(h) = \frac{1}{[1 + (-\alpha h)^n]^m}$$

3. Effective saturation has been writing here as $S_e(h)$ instead of S_e to emphasize that it is a function of h. Substituting Equation 1 and solving for the Water retention function $S_e(h)$

$$\frac{\theta-\theta_r}{\theta_s-\theta_r}=\frac{1}{[1+(-\alpha h)^n]^m}, and$$

$$\theta(h)=\frac{\theta_s-\theta_r}{[1+(-\alpha h)^n]^m}+\theta_r$$

6.3.1 Measurement of the Residual water content for Hydrus 1D:

In order to measure the residual water content for the Hydrus, the soil samples were taken, layer by layer of the 1D column and the details equation are given below:

$$\theta_{Residual}^{For\ hydrus}=\left(1-\frac{RD}{\rho_{Root}}\right)*\theta_{Residual,N\overline{V}}(z,t)+\left(\frac{RD}{\rho_{Root}}\right)*\theta_{Root}$$

Where,

$RD=\frac{M_B}{\overline{V}_A+\overline{V}_B+\overline{V}_C+\overline{V}_D}$ [g/cm^3]

$\theta_{Residual}^{For\ hydrus}$ = Residual water content for hydrus 1D

ρ_{Root} = The density of weight of root

$\boldsymbol{\theta_{root}}$ = Water content of root

$\rho_{Root}=\frac{M_B}{\overline{V}_B+\overline{V}_D}$

$\theta_{Root}^{Measurement\ layer\ by\ layer}=\frac{\overline{V}_D}{\overline{V}_B+\overline{V}_D}$

$\theta_{Soil,residual}=\theta_{N\overline{V}}(z)=\frac{\overline{V}_C}{\overline{V}_A+\overline{V}_C}$ (Non-vegetated)

$\overline{V}_A$= Volume of soil

$\overline{V}_B$= Volume of root (dry)

$\overline{V}_C$= Volume of water

$\overline{V}_D$= Volume of root (wet)

And

$\overline{M}_A$= Mass of soil

$\overline{M}_B$= Mass of root (dry)

$\overline{M}_C$= Mass of water

$\overline{M}_D$= Mass of root (wet)

On the table below the example of the calculation of residual water content:

Table 6.1 Residual water content increase depending on the density of root

Layer	RD	Rho, the density of weight root	RD/Rho	WC of root	Residual WC
35	0.0026	1.3	0.002	0.19	0.17503
55	0.00244	1.25	0.001952	0.21	0.170078
75	0.00213	1.23	0.001732	0.252	0.168145
95	0.00191	1.21	0.001579	0.275	0.165174
105	0.00175	1.19	0.001471	0.28	0.162174
125	0.00167	1.175	0.001421	0.289	0.159185
145	0.00164	1.16	0.001414	0.295	0.156197
165	0.00159	1.153	0.001379	0.3	0.153203

Table 6.2 Soil hydraulic parameter obtained [Edosaki]:

α	0.035 [/hrs.]	Where α, n and i are constant, the value of the alpha, n and i were measured by the fitting of drying soil water characteristic (SWCC) data of Edosaki soil for initial dry density 1350 kg/m^3.
n	3.1	
i	0.5	
[Ks]	cm/s	Where using the Ks decided by permeability test of each layer with the respective amount of root density
Rainfall	1-420mm/hrs.	Depth of the soil profile 1700 mm
θ_s and θ_r	m3/m3	[θs of non-vegetated soil] ; [θr of non-vegetated soil] $\theta_{Soil,residual} = \theta_{N\bar{V}}(z,t) = \frac{\bar{V}_{of\ water}}{\bar{V}_{of\ soil} + \bar{V}_{of\ water} + \bar{V}_{of\ air}}$
Then obtain the θ(z,t) and add the root component of VWC, then be able to compare the results between vegetated and non-vegetated columns.		$\boldsymbol{\theta^{For\ hydrus}_{Residual}} = \left(\mathbf{1} - \frac{\boldsymbol{RD}}{\boldsymbol{\rho_{Root}}}\right) * \boldsymbol{\theta_{Residual,N\bar{V}}(z,t)} + \left(\frac{\boldsymbol{RD}}{\boldsymbol{\rho_{Root}}}\right) * \boldsymbol{\theta_{Root}}$

Table 6.3 Soil hydraulic parameter obtained [Kunigami]

α	0.019 [/hrs.]	Where α, n and i are constant, the value of the alpha, n and i were measured by the fitting of drying soil water characteristic (SWCC) data of Kunigami soil for initial dry density 1400 Kg/m^3.
n	1.31	
i	0.5	
[Ks]	cm/s	Where using the Ks decided by permeability test of each layer with the respective amount of root density
Rainfall	1-180 mm/hrs.	Depth of the soil profile 1700 mm
θ_s and θ_r	m3/m3	[θs of non-vegetated soil] ; [θr of non-vegetated soil] $\theta_{Soil,residual} = \theta_{N\bar{V}}(z,t) = \frac{\bar{V}_{of\ water}}{\bar{V}_{of\ soil} + \bar{V}_{of\ water} + \bar{V}_{of\ air}}$
Then obtain the θ(z,t) and add the root component of VWC, then be able to compare the results between vegetated and non-vegetated columns.		$\boldsymbol{\theta^{For\ hydrus}_{Residual} = \left(1 - \frac{RD}{\rho_{Root}}\right) * \theta_{Residual,N\bar{V}}(z,t) + \left(\frac{RD}{\rho_{Root}}\right) * \theta_{Root}}$

Figure 6.1 shows the initial water content in each depth (0W, 6W, 12W and 24 W), the initial water content is increased by an increment of the density of grown root after implanting 6, 12, and 24 weeks, respectively.

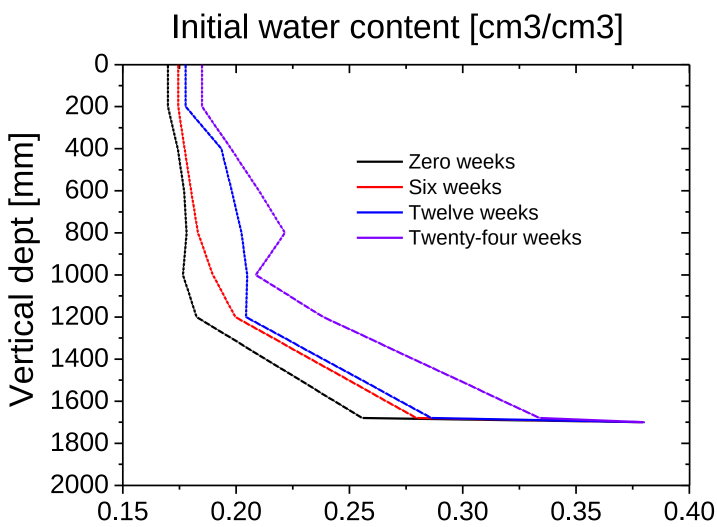


Figure 6-1 -The initial water content in each depth (0W, 6W, 12W and 24 W)

Figure 6.1(a) the residual water content is increased with the increment of the density of grown root after implanting 6, 12, and 24 weeks, respectively. Figure 6.1(b) using the Ks decided by permeability test of each layer with the respective amount of grown root, the values of the Ks for the 6, and 12 weeks was a proportional compressed assumption.

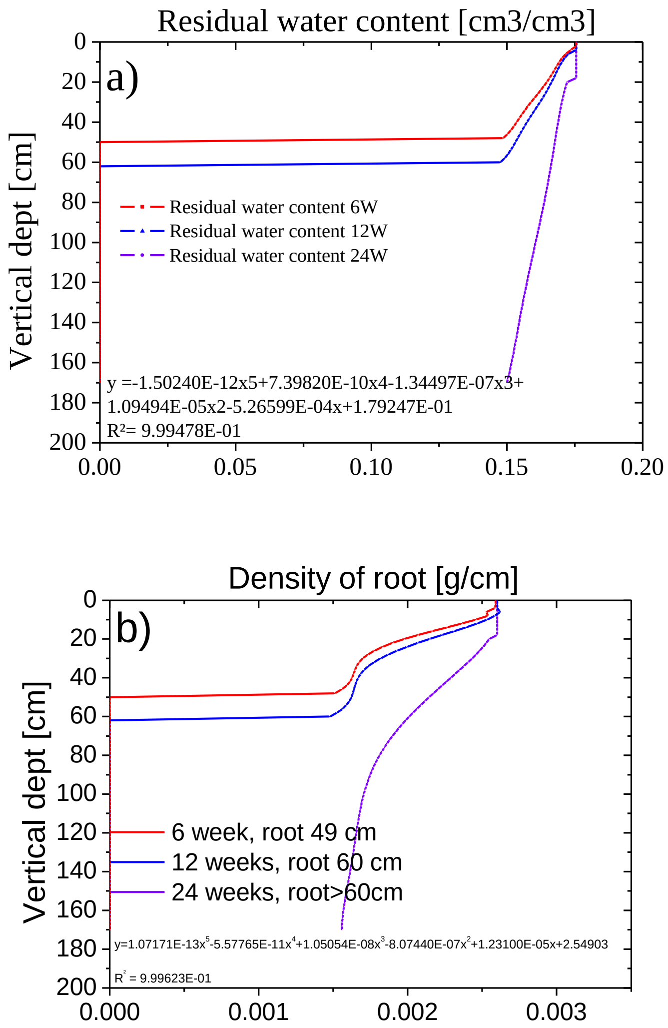


Figure 6-2(a) -The residual water content (Qr) is increased within increment of the density of root, (b)-The increment of the density of the root in each depth

Using the Ks decided by permeability test of each layer with the respective amount of root density, the permeability is increased by the density of grown root after implanting 6, 12, and 24 weeks, respectively (Figure 6-3).

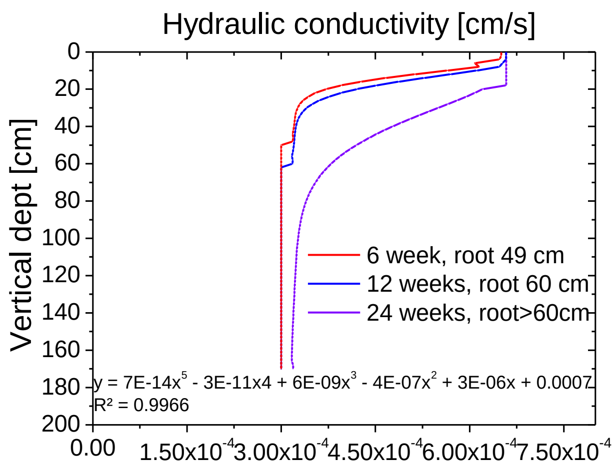
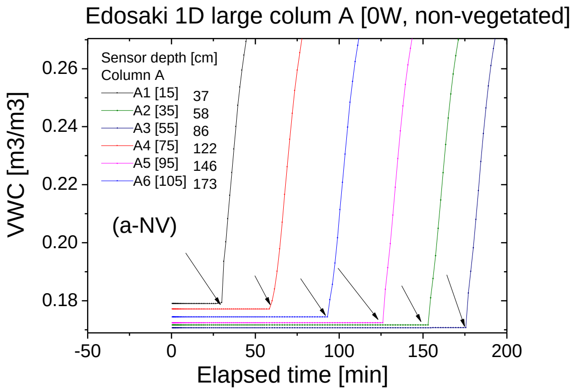
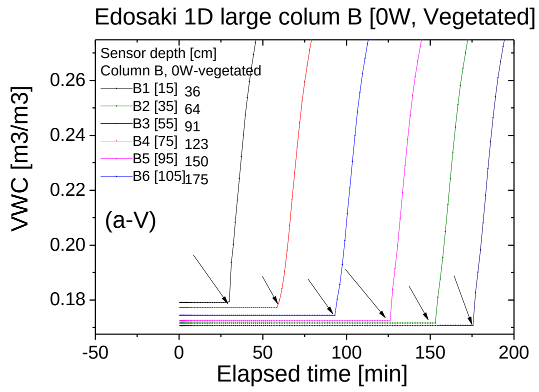
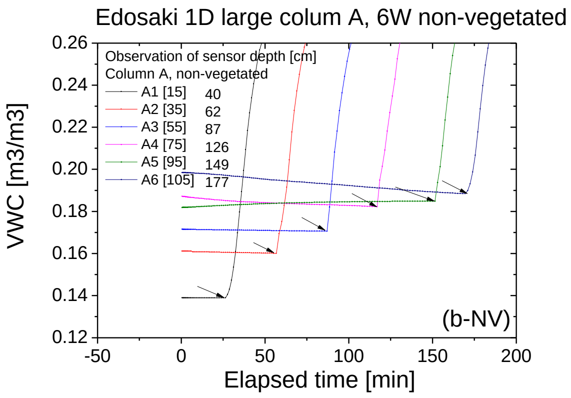


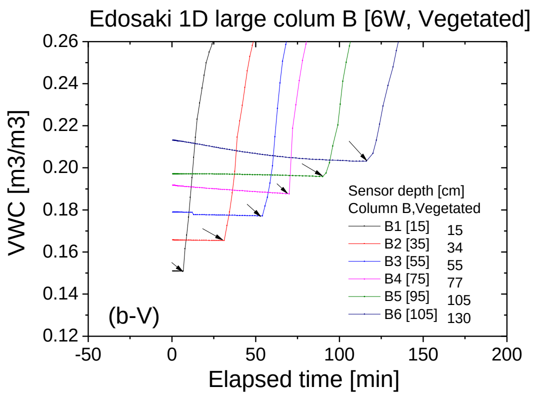
Figure 6-3-Using the Ks decided by permeability test of each layer with the respective amount of root density

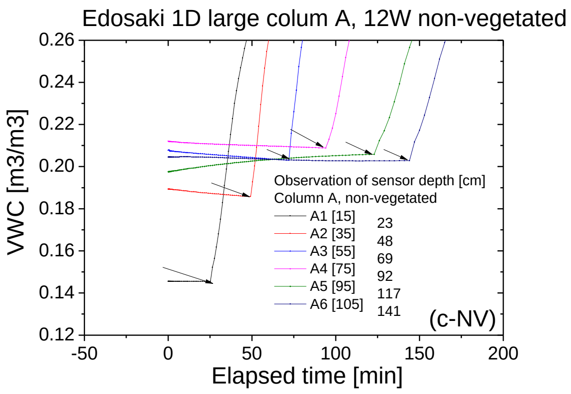
In Figure 6-4 (a-NV);(a-V), the vegetated and non-vegetated columns can be observed at the beginning of time (0W); (b-NV),(b-V) show the vegetated and non-vegetated columns at 6 weeks; (c-NV),(c-V) exhibit the vegetated and non-vegetated columns at 12 weeks and (d-NV),(d-V) present the vegetated and non-vegetated columns at 24 weeks in these plots were zoomed out to show on the pickup point in each depth layers [15 , 35, 55, 75, 95 and 105 cm], when rainfall start before the wetting process, the infiltration is taken some time before starting the initial volumetric water content. The results of the delay time analysis are compared between non-vegetated and vegetated column at 0 week, 6 weeks, 12 weeks and 24 weeks. The results show that delay time for infiltration was reduced by 43% by vegetation.

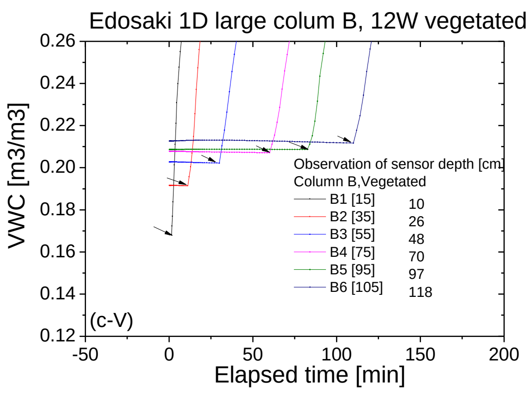

Edosaki 1D large colum A [0W, non-vegetated]
Sensor depth [cm]
Column A
A1 [15] 37
A2 [35] 58
A3 [55] 86
A4 [75] 122
A5 [95] 146
A6 [105] 173
(a-NV)
VWC [m3/m3]
Elapsed time [min]


Edosaki 1D large colum B [0W, Vegetated]
Sensor depth [cm]
Column B, 0W-vegetated
B1 [15] 36
B2 [35] 64
B3 [55] 91
B4 [75] 123
B5 [95] 150
B6 [105] 175
(a-V)
VWC [m3/m3]
Elapsed time [min]


Edosaki 1D large colum A, 6W non-vegetated
Observation of sensor depth [cm]
Column A, non-vegetated
A1 [15] 40
A2 [35] 62
A3 [55] 87
A4 [75] 126
A5 [95] 149
A6 [105] 177
(b-NV)
VWC [m3/m3]
Elapsed time [min]


Edosaki 1D large colum B [6W, Vegetated]
Sensor depth [cm]
Column B,Vegetated
B1 [15] 15
B2 [35] 34
B3 [55] 55
B4 [75] 77
B5 [95] 105
B6 [105] 130
(b-V)
VWC [m3/m3]
Elapsed time [min]


Edosaki 1D large colum A, 12W non-vegetated
Observation of sensor depth [cm]
Column A, non-vegetated
A1 [15] 23
A2 [35] 48
A3 [55] 69
A4 [75] 92
A5 [95] 117
A6 [105] 141
(c-NV)
VWC [m3/m3]
Elapsed time [min]


Edosaki 1D large colum B, 12W vegetated
Observation of sensor depth [cm]
Column B,Vegetated
B1 [15] 10
B2 [35] 26
B3 [55] 48
B4 [75] 70
B5 [95] 97
B6 [105] 118
(c-V)
VWC [m3/m3]
Elapsed time [min]

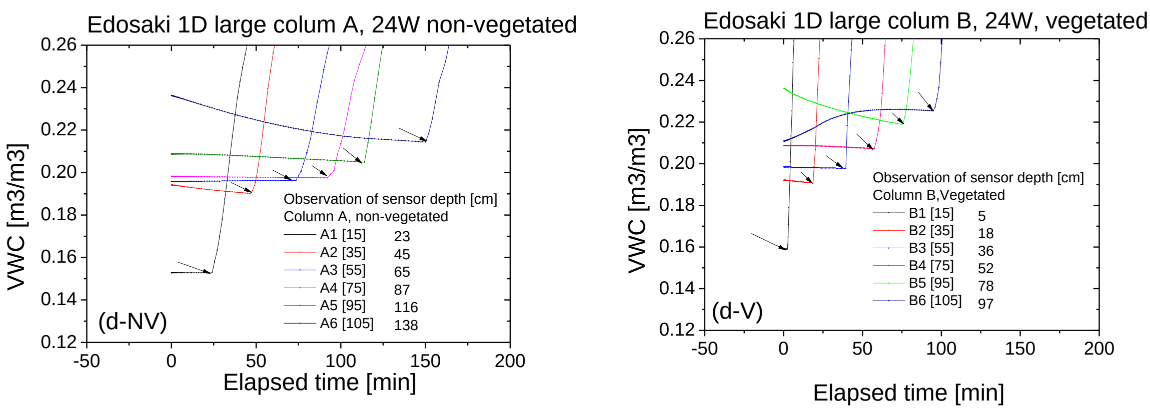
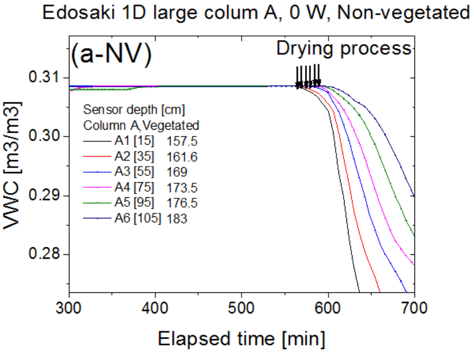
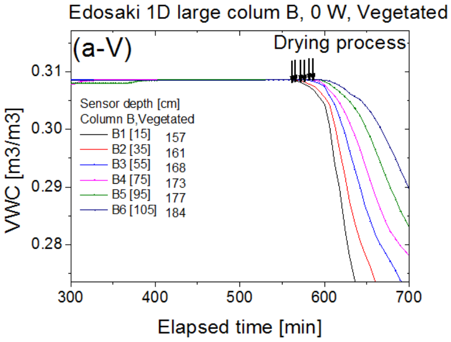
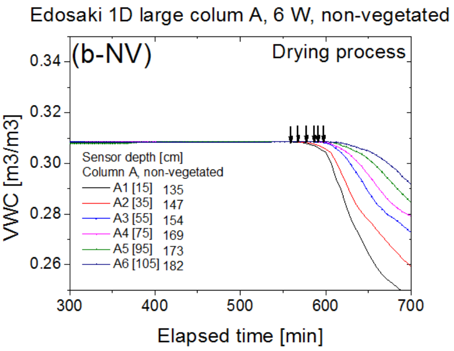


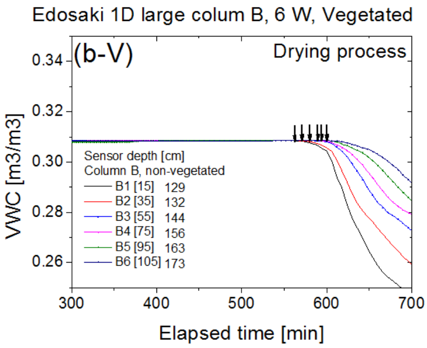
Figure 6-4-The Model test and the volumetric water content (VWC) were simulated by hydrus at the depth 15 cm, 35 cm, 55cm, 75 cm, 95 cm, and 105 cm.

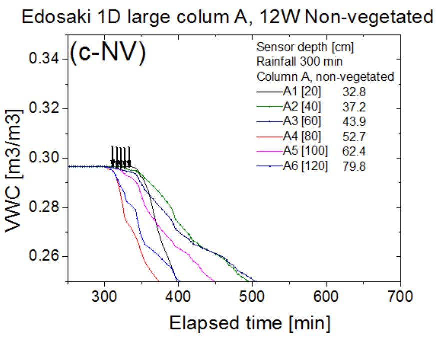
The results of the hydrus and the summary of the delay time before wetting process can be observed in Figure 6-5: (a-NV);(a-V) vegetated and non-vegetated columns at 0 week, (b-NV);(b-V) vegetated and non-vegetated columns at 6 weeks, (c-NV);(c-V) vegetated and non-vegetated columns ayt 12 weeks and (d-NV);(d-V) vegetated and non-vegetated columns at 24 weeks in these plots were zoomed out to show on the pickup point in each depth layers [15 , 35, 55, 75, 95 and 105 cm], after rainfall stop before the drying process, the drainage process is taken some time before starting the drying. The results of the delay time analysis are summarized between non-vegetated and vegetated column at 0 week, 6 weeks, 12 weeks and 24 weeks. The results have agreed with the results from the delay analysis before the wetting process by experiment data.

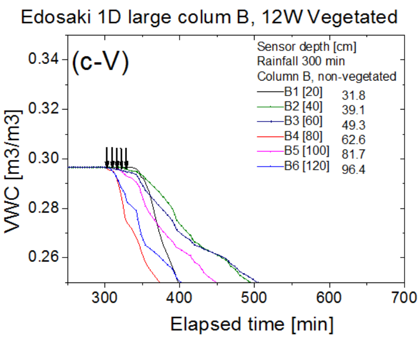

Edosaki 1D large colum A, 0 W, Non-vegetated
(a-NV)
Drying process
Sensor depth [cm]
Column A,Vegetated
A1 [15] 157.5
A2 [35] 161.6
A3 [55] 169
A4 [75] 173.5
A5 [95] 176.5
A6 [105] 183
VWC [m3/m3]
Elapsed time [min]


Edosaki 1D large colum B, 0 W, Vegetated
(a-V)
Drying process
Sensor depth [cm]
Column B,Vegetated
B1 [15] 157
B2 [35] 161
B3 [55] 168
B4 [75] 173
B5 [95] 177
B6 [105] 184
VWC [m3/m3]
Elapsed time [min]


Edosaki 1D large colum A, 6 W, non-vegetated
(b-NV)
Drying process
Sensor depth [cm]
Column A, non-vegetated
A1 [15] 135
A2 [35] 147
A3 [55] 154
A4 [75] 169
A5 [95] 173
A6 [105] 182
VWC [m3/m3]
Elapsed time [min]


Edosaki 1D large colum B, 6 W, Vegetated
(b-V)
Drying process
Sensor depth [cm]
Column B, non-vegetated
B1 [15] 129
B2 [35] 132
B3 [55] 144
B4 [75] 156
B5 [95] 163
B6 [105] 173
VWC [m3/m3]
Elapsed time [min]


Edosaki 1D large colum A, 12W Non-vegetated
(c-NV)
Sensor depth [cm]
Rainfall 300 min
Column A, non-vegetated
A1 [20] 32.8
A2 [40] 37.2
A3 [60] 43.9
A4 [80] 52.7
A5 [100] 62.4
A6 [120] 79.8
VWC [m3/m3]
Elapsed time [min]


Edosaki 1D large colum B, 12W Vegetated
(c-V)
Sensor depth [cm]
Rainfall 300 min
Column B, non-vegetated
B1 [20] 31.8
B2 [40] 39.1
B3 [60] 49.3
B4 [80] 62.6
B5 [100] 81.7
B6 [120] 96.4
VWC [m3/m3]
Elapsed time [min]

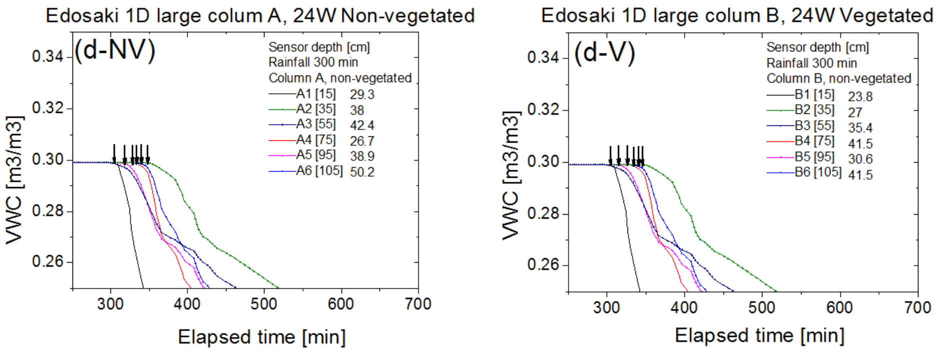


Figure 6-5- (a-NV)(a-V); (b-NV),(b-V); (c-NV),(c-V) and (d-NV), (d-V) the relation of the volumetric water content and elapsed time between non-vegetated and vegetated column at 0, 6, 12 and 24 weeks. These results from the giving rainfall tests 30mm/hr. and 60 mm/hrs. and the volumetric water contents were simulated by the hydrus at the depth 15 cm, 35cm, 55 cm, 75 cm, 95 cm, and 105 cm.

Figure 6-6 (a) is a summary of the delay time before the wetting process and Figure 6-6 (b) is a summary of the delay time before drying process (all cases, estimated by HYDRUS). The results of the delay time analyses were compared between non-vegetated and vegetated column at 0 week, 6 weeks, 12 weeks and 24 weeks. The results show that delay time for infiltration was reduced by the introduction of vegetation: 43% for Edosaki 1D large column test, by 33%, for Kunigami 1D short column test, and by 59% for Edosaki 1D short column test.

The results have agreed with the results from the delay analysis before the wetting process by experiment data.

Figure 6-7 (a) is a summary of the delay time before the wetting process and Figure 6-7 (b) is a summary of the delay time before drying process [all cases, estimated by HYDRUS]. The results of the delay time analyses were compared between non-vegetated and vegetated column at 0 week, 6 weeks, 12 weeks and 24 weeks. The results show that delay time for infiltration was reduced by the introduction of vegetation: 43% for Edosaki 1D large column test, by 33%, for Kunigami 1D short column test, and by 59% for Edosaki 1D short column test.

The results have agreed with the results from the delay analysis before the wetting process by experiment data.

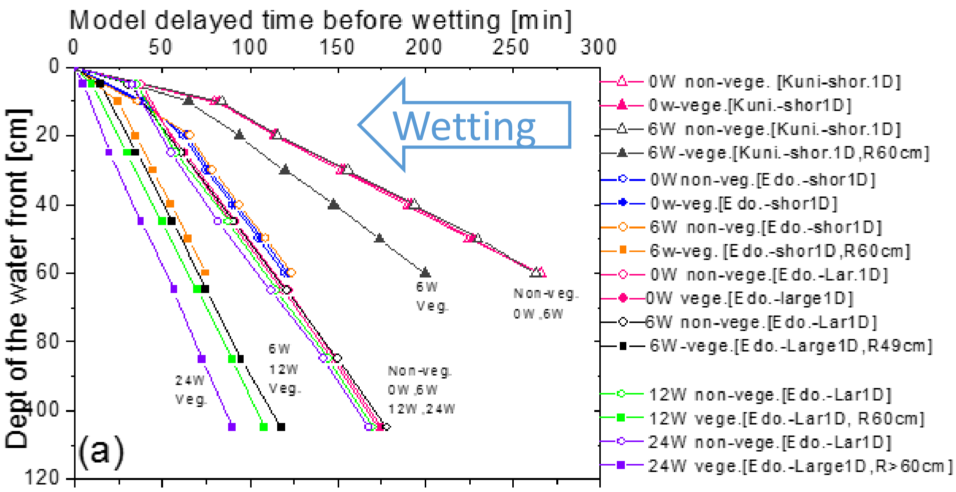


Figure 6-6 (a)-Summary of the wetting process.

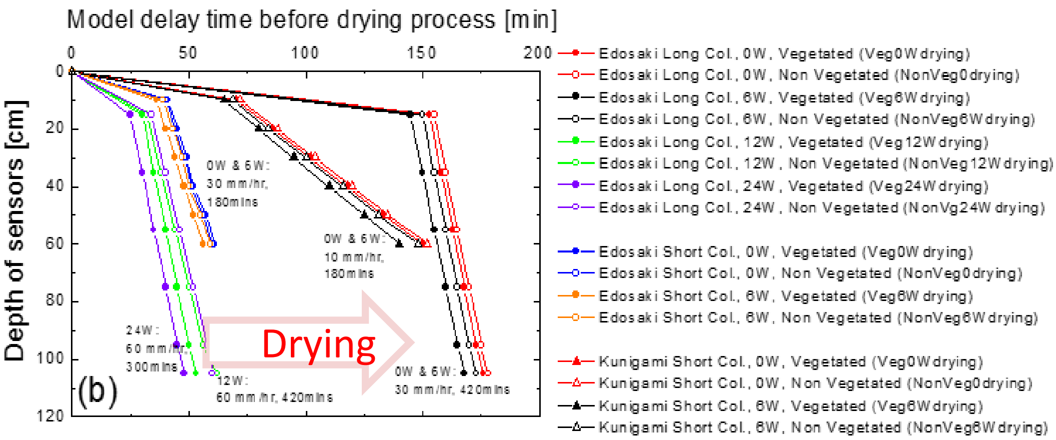


Figure 6.6(b)-Summary of drying process

6.4 Results and analysis by the Hydrus 1D

Figures 6.5(a) has shown the summary of the delay time before wetting process and Figure 6.5(b) reveals the summary of the delay time before drying process by hydrus1D [all cases]. The results of the delay time analysis by hydrus 1D are compared between non-vegetated and vegetated column at 0 week, 6 weeks, 12 weeks and 24 weeks.

In Figure 6.5(a), the results show that delay time for wetting was reduced by the introduction of vegetation: by 43% for Edosaki 1D large column test, by 33% for Kunigami 1D short column test, and by 59% for Edosaki 1D short column test. The results have agreed with the results from the delay analysis before the wetting process by experiment data.

In Figure 6.5(b) it can be seen that the delay time analysis by modelling and real tests of delay time for drying are as follows:

- Kunigami sand 1D short column test: the water drying was reduced by the introduction of vegetation 3.8 %.
- Edosaki sand 1D short column test: The results show that on the vegetated one dimensional short columns, after covering with root network of 6W, the water infiltration the water drying was reduced by the introduction of vegetation 5%.
- Edosaki sand 1D long column test sand: The results show that on the vegetated one dimensional long columns, after covering by root networks of 6W, 12W, and 24W, the water infiltration was effective by roots and positively increased water infiltration on the ground slope after 12W and 24W, the water drying was reduced by introduction of vegetation 25 %.
- Above results have analyzed by the Hydrus 1D has agreed with the result from experiments data.

Figure 6-7 represents each case of the delay time, before the wetting and drying processes. The data obtained from the tests was plotted along with the results from the simulation for different root ages. The comparison at the wetting process stage is also presented. It can be observed that they curves are consistent.

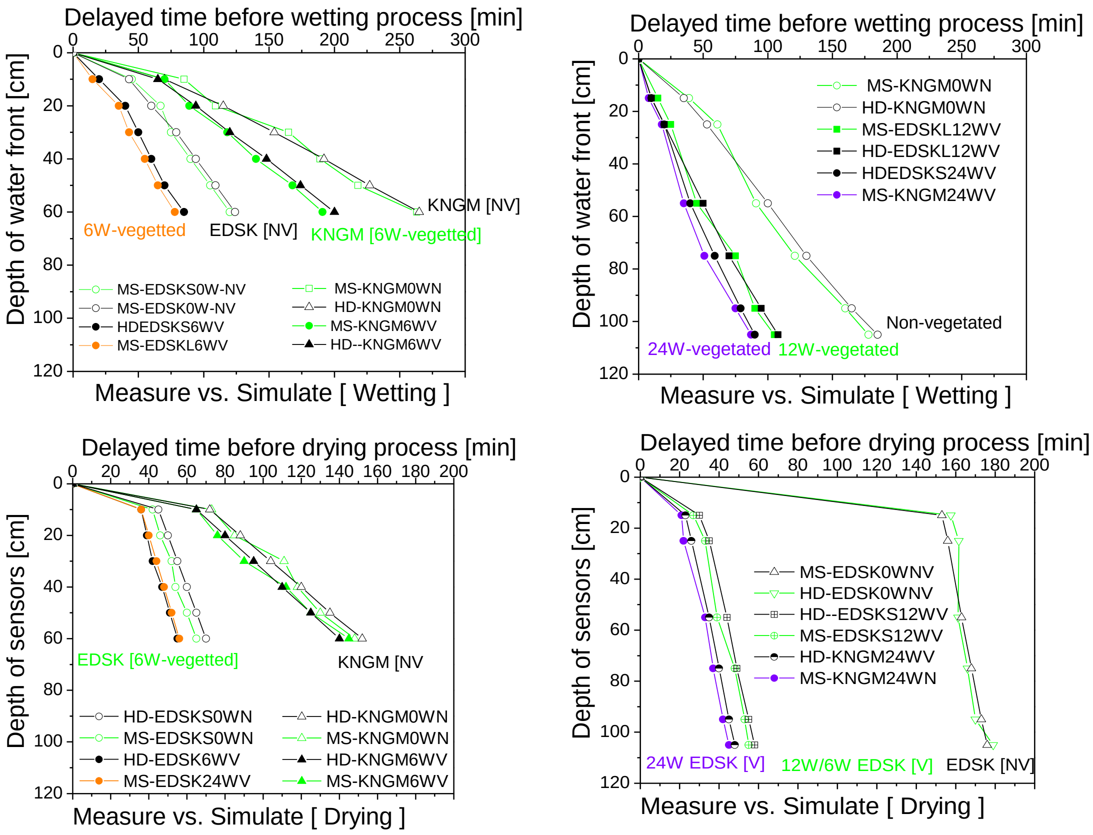


Figure 6-7 Summary of the wetting -drying [Measured vs. Simulate]

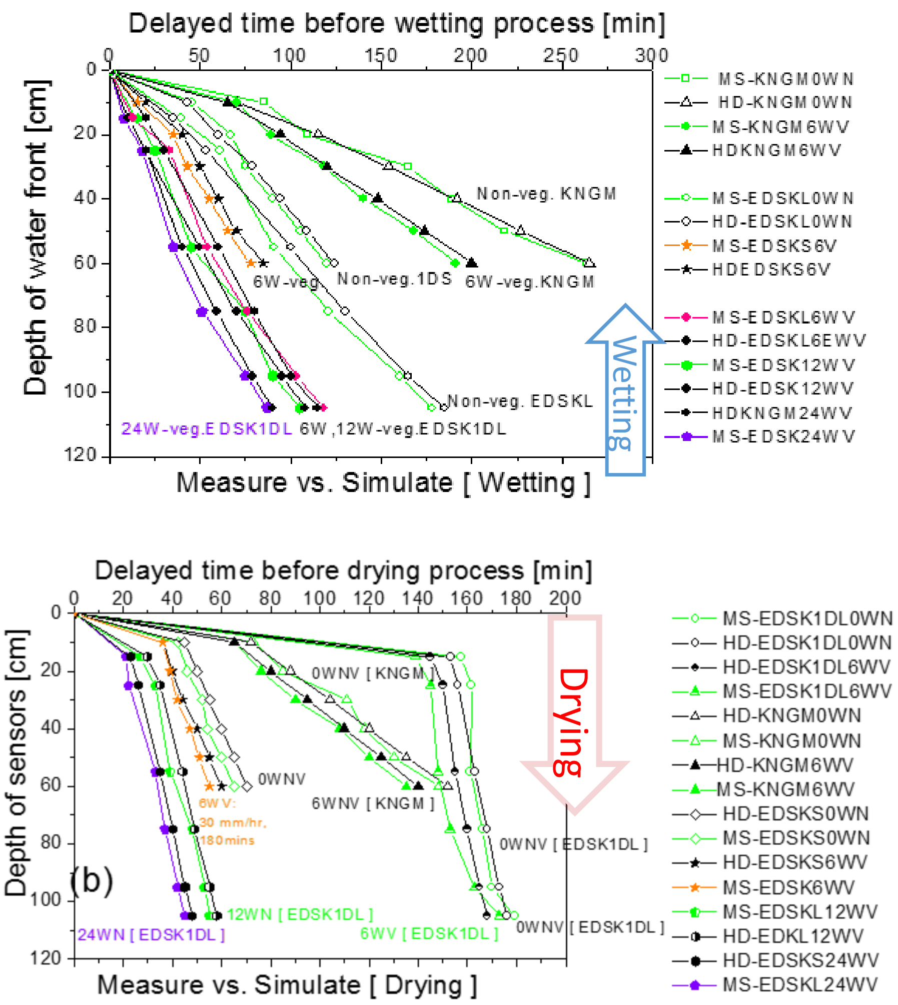


Figure 6-8(a)- Summary of the wetting process: the comparison between measured and simulated delay time are plotted together. Figure 6.6(b)-Summary of the drying process, the comparison between measured and simulated delay time are plotted together.

Figure 6-8 (a) represents the summary of the delay time, before the wetting and drying processes for comparison between measured and simulated, data obtained for delay time have been plotted together. The results are consistent among simulation and tests. Figure 6.8 (b) shows the summary of the delay time before drying process, using the measured and simulated data for all cases. The results of the comparison between measured and simulated delay time were plotted together also at the drying process stage. Again some consistency can be observed.

The main objective of experiments was to observe the water infiltration into the vegetated soils, with the introduction of vetiver vegetation and experiments were conducted extensively under laboratory conditions and in real field situation at IIS, to study and analyze the delay time on both wetting and drying processes, for different types of soils such as Kunigami Edosaki, and field IIS-soils.

Vegetated root networks of Vetiver grass of different ages (6W, 12 W and 24 W) were deployed for conducting experiments (laboratory and field conditions).Conducted experiments of infiltration were compared with non-vegetated soils of similar conditions. It could be concluded that water infiltration increased with the introduction of root networks; furthermore, the older the age of a root network, the higher the increase of infiltration of water to the soils.

6.5 Conclusion remarks

6.5.1 Numerical analysis by using the HYDRUS1D

Effects of root on the material properties were considered in Hydrus 1D by changing residual water contents and the hydraulic conductivities depending on the root density. The results clearly indicated that the delay time for infiltration was considerably reduced by the introduction of vegetation: 50 % for Edosaki 1D large column test, 33% for Kunigami 1D short column test, and 59% for Edosaki 1D short column test.

Delayed time for drainage was reduced by the introduction of vegetation: 30% and 5% for Edosaki sand, and for Kunigami soil respectively.

The results from both analyses (experiments and modelling) showed that delay time for infiltration was reduced by the vegetation during the wetting process. It was observed that the growth of roots accelerates infiltration of rainwater into the ground slope probably due to generation of water paths.

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CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusion

The use of vegetated ground is one of the ecological measures that has been developed and expanded in the last two decades. The concept is soil stabilization through networks of roots and plants, in order to prevent slopes from eroding and collapsing. The major advantages are the reinforcement caused by the tensile strength provided by the root, prevention of scouring by water flow restriction on the slope surface, and evapotranspiration of moisture content from the ground slope.

Volumetric water content is the most important factor affecting the stability of soils and slopes against heavy rainfall events. The instability and the consequent failure of soil-slopes on roads and railways, which are often caused by prolonged heavy rainfall, can lead to human casualties and to economic losses due to the interruption of the transportation system.

In order to mitigate and improve the methodology to assess slope stability, the rainfall intensity is used as the dominant index to evaluate the probability of failure events in an area. Nevertheless, every slope has individual hydraulic characteristics and its probability of failure is different from other slopes even under the same rainfall conditions. Some ground slopes may absorb a lot of water quickly after rainfall start, while some ground slopes may show quick drainage after the end of the rain. Such distinct properties can be evaluated by comparing the time histories of moisture contents along with rainfall records.

In this study, a method was proposed to evaluate the hydraulic properties of vegetated ground based on monitoring data of moisture contents. The experimental program included the following tests: 1) Hydraulic conductivities tests on saturated vegetated and non-vegetated soil, 2) One-dimensional column model tests in the laboratory for vegetated and non-vegetated soil, 3) Field measurement of water infiltration and drainage in vegetated and non-vegetated ground, and 4) Simulation of the results by using a numerical analysis software (HYDRUS 1D).

The following conclusions were obtained from the results of experiment and modeling:

- **Permeability tests**

The first tests on hydraulic conductivity were carried out using a none-vegetated soil sample and 3 more experiments were conducted with vegetated soil samples after vetiver were implanted in the following ratios of week per weight of roots: 1 week/ 1.80 g, 2 weeks/2.10 g, 4 weeks/2.35 g and 6 weeks/3.52 g. The objective was to observe the water infiltration into the vegetated soils. The above results of the experiment have shown that with 0.003g/cm3 of root density, the hydraulic conductivity was increased by 2 times for the permeable Edosaki sand and by 2.3 times for the less permeable Kunigami soil. Their increasing ratio is similar to each other.

- **Laboratory of measurement of 1D column model tests**

There is a reduction in delay time for water infiltration into the ground slope, probably due to the generation of water pathways along the surface of the root. The results of the 1D column test clearly indicated that the delay time for infiltration was reduced by the introduction of vegetation: 43 % for Edosaki sand, 33% for Kunigami soil, and 57% for Edosaki 1D.

The results indicated that time for drying was clearly reduced by the introduction of vegetation: 30 % for Edosaki 1D large column test, 5% for Kunigami 1D short column test, and 8% for Edosaki 1D short column test.

- **Site model tests**

The observations and the results of tests of delay time on wetting and drying process are as follows:

Vegetated-zone: The results show that on the vegetated zone, after covering with root network of 7 months, the water wetting was reduced by the introduction of vegetation 26 %. And the water drying was reduced by the introduction of vegetation 3%.

- **Numerical analysis by using the HYDRUS1D**

Effects of root on the material properties were considered in the Hydrus 1D by changing residual water contents and the hydraulic conductivities depending on the root density. The results clearly indicated that the delay time for infiltration was considerably reduced by the introduction of vegetation: 50 % for Edosaki 1D large column test, 33% for Kunigami 1D short column test, and 59% for Edosaki 1D short column test.

Delayed time for drainage was reduced by the introduction of vegetation: 30% and 58% for Edosaki sand, and for Kunigami soil respectively.

The results from both analyses [Model &Experiment] are consistent and well harmonized and show delayed time for infiltration was reduced by the vegetation during the wetting process and drying process.

The results from both analysis showed that the delay time for infiltration was reduced by the vegetation during the wetting process. It was seen that the grown root accelerates infiltration of rainwater into the ground slope probably due to generating water path along the surface of the root.

Vetiver, a fast growing grass, possesses some unique features of both grass and trees by having large, rapid growing, deep penetrating, reinforcing roots that can offer both erosion prevention and control of the shallow movement of surface earth mass. Therefore the use of vetiver for erosion control and prevention of shallow failure of highway and riverbank slopes, is a low-cost technique which can be practiced.

7.2 Conclusion and Remarks

- Numerical analysis: Effects of root on the material properties were considered in the Hydrus 1D model by
    - "Changing residual water content depending on the root density."
    - "Changing hydraulic conductivity depending on the root density "

- The results from both the analyses [Model &Experiment] are consistent and well harmonized and show delayed time for infiltration was reduced by the vegetation during the wetting process and drying process.

7.3 Recommendation

- The study of the water movement through vegetated ground has not been widely studied by researchers around the world; different techniques and methods have been developed and very important conclusions have been achieved. In this study, the measurement of water content were conducted by 1D column laboratory test and site model with vegetated and non-vegetated ground, resulted in a good technique to observe the hydrological behavior and understand how the root effects on the water infiltration subjected to artificial rainfall. However, the research and simulation analysis was done through 1D analysis and is missing horizontal flow parameters, therefore, the two and three dimensional analysis are required to conduct the stability analysis.

- It is required to carry out measurements of the saturated hydraulic conductivity function, for dead root conditions.
- In order to conduct vegetated ground stability analysis not only moisture content and pore water pressure distributions must be considered, but also the effect of mechanical reinforcements provided by the roots located at the slope's surface or on the top soils.
- Performing laboratory vegetated ground model tests under layered soils to analyze the effects of changes in permeability on hydrological response and failure mechanism is also required.
- To conduct vegetated ground model tests at different configurations to observe the effects of morphological aspects on water redistribution at slope's surface and identify the most susceptible areas where water ponding can occur.
- To carry out experiments at different initial water contents and rainfall intensities in order to determine the failure thresholds in terms of antecedent rainfall (related to initial water content) and rainfall intensity-duration.
- To keep using the moisture content and deformations throughout the ground model to define the main controlling parameters on rainwater distributions and failure initiation.
- The method used for the installation of grass cover on sandy ground
- Models was effective for the grass growing; however, other planting methods as seeding can be used by placing a thin layer of organic material which will act as support during the early stage of seeds growing.