SOIL-ROOTS PERFORMANCE OF PENNISETUM SETACEUM ‘RUBRUM’ ON MECHANICAL SOIL STRENGTH

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Dedicated to my beloved father and my late mother, Mariah Othman, May Allah (SWT) forgive all her sins and may He make Jannatul Firdaus to be her final abode

(Ameen)

And

All my family members, teachers right from childhood up to now and friends
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ABSTRACT

The potential of *Pennisetum setaceum* ‘Rubrum’ root in soil reinforcement was investigated. This African native perennial bunchgrass has been introduced in many parts of the world as an ornamental plant and for soil stabilization. The traditional civil engineering techniques such as concreting of welded wire walls for slope stabilization may not be sustainable in the long term due to high initial capital cost. It also looks harsh and unnatural to the road users. Alternatively, vegetation can be used together with inert structure as a way of reducing the visual impact of civil engineering works. Hence, the study is aimed towards the establishment of a flowery plant that able to perform decent soil-root shear strength reinforcement. *P. setaceum* ‘Rubrum’ has been planted at the field plots at RECESS. A series of laboratory direct shear tests was performed on rooted and non-rooted samples at 100, 200 and 300 mm soil depth, every month throughout the seven months of study period. The roots tensile strength was determined using an Instron Universal Testing Machine (Model 3369). Plant morphological data such as shoot biomass, root density and plant height were also measured. The direct shear test results show that shear strength of rooted sample of *P. setaceum* ‘Rubrum’ increases with time for all depths, with the highest increment of 441% over the control sample, that belong to one of rooted soil sample of month 7 at 300 mm soil depth. The increment is due to high root tensile strength (43.68 kPa ± 3 kPa) and root density (9.36 kg/m³). In term of average peak shear stress, month 7 was highest at all depth. Its shear stress values were 307 ± 82 kPa (100 mm), 181 ± 42 kPa (200 mm) and 179 ± 41 kPa (300 mm). Whereas, root tensile strength decreased with increasing diameter of roots following the power function with the highest average tensile strength of 50 ± 2 MPa (month 6). The results of this paper improve the knowledge about biotechnical characteristics of root systems of *P. setaceum* ‘Rubrum’ and indicate that this species could potentially serve as soil reinforcement.
ABSTRAK

Kajian pada akar spesies rumput *Pennisetum setaceum* ‘Rubrum’ yang berpotensi dalam pengukuhan tanah telah dijalankan. Tumbuhan rumput lebat yang berasal dari Afrika ini telah diperkenalkan ke serata pelusuk dunia sebagai tumbuhan hiasan dan juga sebagai penstabil tanah cerun. Kaedah tradisional kejuruteraan awam bagi penstabilan cerun seperti tembok penahan konkrit mungkin tidak lestari bagi jangka masa panjang kerana kos permulaan tinggi. Struktur itu juga tampak buruk dan tidak mesra alam kepada pengguna jalan raya. Sebagai alternatif, tumbuhan boleh digunakan bersama-sama dengan struktur tersebut bagi mengurangkan kesan pemandangan konkrit yang terhasil oleh struktur kejuruteraan awam. Maka, kajian ini bertujuan untuk mewujudkan suatu tumbuhan berbunga yang dapat menghasilkan pengukuhan kekuatan akar-tanah. *P. setaceum* ‘Rubrum’ telah ditanam di plot tanah padang RECESS. Beberapa siri ujian “daya ricih terus” telah dijalankan pada sampel tanah berakar dan tanpa akar pada kedalaman 100, 200 dan 300 mm setiap bulan sepanjang tujuh bulan tempoh kajian. Kekuatan regangan akar ditentukan menggunakan mesin Ujian Universal Instron (Model 3369). Data morfologi tumbuhan seperti biojisim pucuk, ketumpatan akar dan tinggi tumbuhan juga diukur. Keputusan “ujian ricih terus” menunjukkan kekuatan ricih tanah berakar bagi *P. setaceum* ‘Rubrum’ meningkat seiring dengan masa bagi semua kedalaman tanah, dengan peningkatan tertinggi sebanyak 441 % berbanding sampel kawalan, diperolehi oleh salah satu daripada sampel berakar bulan 7 pada lapisan 300 mm. Peningkatan ini disebabkan oleh daya regangan akar yang tinggi (43.68 kPa ± 3 kPa) dan ketumpatan akar yang tinggi (9.36 kg/m³). Bagi purata daya ricih tanah, bulan 7 adalah tertinggi bagi semua lapisan. Daya ricihnya ialah 307 ± 82 kPa (100 mm), 181 ± 42 kPa (200 mm) dan 179 ± 41 kPa (300 mm). Sementara itu, kekuatan regangan akar semakin menurun apabila diameter akar meningkat, mematuhi fungsi kuasa dengan purata kekuatan regangan tertingginya ialah 50 ± 2 MPa (bulan 6). Dapatkan kajian ini meningkatkan lagi pengetahuan tentang ciri-ciri bioteknikal sistem akar
bagi *P. setaceum* ‘Rubrum’ dan menunjukkan spesies ini berpotensi dalam mengukuhkan tanah.
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<td>%</td>
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<tr>
<td>&lt;</td>
<td>Less than</td>
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<tr>
<td>&gt;</td>
<td>Greater than</td>
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<tr>
<td>±</td>
<td>Plus-minus (indicates range value or tolerance)</td>
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<tr>
<td>√</td>
<td>Square root</td>
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<td>°C</td>
<td>Degree Celsius</td>
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<td>$C_c$</td>
<td>Coefficients of curvature</td>
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<td>cm</td>
<td>Centimetre</td>
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<td>$C_u$</td>
<td>Values of uniformity</td>
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<td>Gram</td>
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<td>g</td>
<td>acceleration due to gravity (10 ms$^{-2}$)</td>
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<td>ha</td>
<td>Hectare</td>
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<tr>
<td>$I_p$</td>
<td>Plasticity index</td>
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<tr>
<td>kg</td>
<td>Kilogram</td>
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<tr>
<td>kN</td>
<td>Kilonewton</td>
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<td>kPa</td>
<td>Kilopascal</td>
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<tr>
<td>m</td>
<td>Mass</td>
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<td>$m$</td>
<td>Metre</td>
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<td>Mg</td>
<td>Megagram</td>
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<td>min</td>
<td>Minute</td>
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mm - Milimetre
MPa - Megapascal
N - Nitrogen
N - Newton
N - North
n - Number of observations or replicates (statistics)
n/a - Not available
p - P-value (statistics)
R²/ r² - Coefficient of determination
s - Second
Tₜ - Tensile stress
tₚ - Time to failure
V - Volume
w - Moisture content
wₐ - Liquid limit
wₚ - Plastic limit
Δx - Horizontal displacement
μm - Micrometre
ρ - Density (pronounce as ‘Rho’)
σ - Normal stress (pronounce as ‘Sigma’)
τ - Shear stress (pronounce as ‘Tau’)
ASTM - American Society for Testing and Materials
BS - Bristish Standard
BSCS - British Soil Classification System for engineering purposes
BSI - The British Standards Institution
C4 - 4-carbon molecule
CCD - Charge coupled device
CPYRWMA - Choctawhatchee, Pea and Yellow Rivers Watershed Management Authority
DSIR - Department of Scientific and Industrial Research
e.g. - for example (from latin 'exempli gratia')
et al. - et alia/ et aliii (used after group of names, avoid a long list names)
FAO - Food and Agriculture Organization of the United Nations
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<td>Fibre Bundle Model</td>
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<td>FOS</td>
<td>Factor of Safety</td>
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<tr>
<td>GIPS</td>
<td>Geran Insentif Penyelidik Siswaizah</td>
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<tr>
<td>Hons</td>
<td>Honours (used after the name of a university degree)</td>
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<td>Inc.</td>
<td>Incorporated (used after the name of a company in the US)</td>
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<td>JKR</td>
<td>Jabatan Kerja Raya (Public Works Department)</td>
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<tr>
<td>km</td>
<td>Kilometre</td>
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<tr>
<td>KPT</td>
<td>Kementerian Pendidikan Tinggi</td>
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<tr>
<td>LCD</td>
<td>Liquid Crystal Display</td>
</tr>
<tr>
<td>Ltd.</td>
<td>Limited (used after the name of a British company or business)</td>
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<td>Majlis Amanah Rakyat (Council of Trust for the Bumiputra)</td>
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<td>MARDI</td>
<td>Malaysian Agricultural Research and Development Institute</td>
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<td>MAHA</td>
<td>Malaysia Agriculture, Horticulture and Agrotourism Show</td>
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<td>MDR</td>
<td>Multi Disciplinary Research</td>
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<td>MSE</td>
<td>Mechanically Stabilized Earth</td>
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<tr>
<td>NPK</td>
<td>Nitrogen, Phosphorus and Potassium</td>
</tr>
<tr>
<td>ORICCC</td>
<td>Office for Research, Innovation, Commercialization and Consultancy Management</td>
</tr>
<tr>
<td>PMR</td>
<td>Penilaian Menengah Rendah (Lower Secondary Assessment)</td>
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<td>RAR</td>
<td>Root area ratio</td>
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<td>RD</td>
<td>Root density</td>
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<td>RECESS</td>
<td>Research Centre for Soft Soil</td>
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<td>RLD</td>
<td>Root length density</td>
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<td>Sdn. Bhd.</td>
<td>Sendirian Berhad (used after the name of a company in Malaysia)</td>
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<td>SERAS</td>
<td>Scientific, Engineering, Response &amp; Analytical Services</td>
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<td>Species</td>
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<td>SPAC</td>
<td>Soil-plant-atmosphere continuum</td>
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<td>spp.</td>
<td>Species (refer to all species in that given genus)</td>
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<td>Terminal Bersepadu Selatan</td>
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<td>TMI</td>
<td>Testing Machine, Inc.</td>
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<td>TVNI</td>
<td>The Vetiver Network International</td>
</tr>
<tr>
<td>UK</td>
<td>United Kingdom</td>
</tr>
<tr>
<td>US/USA</td>
<td>United States of America</td>
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<tr>
<td>USCS</td>
<td>- Unified Soil Classification System</td>
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<td>USDA</td>
<td>- United States Department of Agriculture Forest Service</td>
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<td>UTHM</td>
<td>- Universiti Tun Hussein Onn Malaysia</td>
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CHAPTER 1

INTRODUCTION

1.1 Research background

The planet Earth has an erratic surface and landslides occur frequently. During the early times, humans have tried to select relatively stable ground to make a settlement. As population increases and human life becomes more urbanized, there is a need for terraces and corridors to be created to make room for buildings and infrastructures such as quays, canals, railways and roads. Hence, man-made slopes also known as cut and fill slopes have to be formed to facilitate such developments (Cheng & Lau, 2014). For example, in the modernizing of Malaysia’s routes, many expressways were built to link many major cities and towns in western Peninsular Malaysia. Many slopes have to be formed, therefore it requires protection from the erosion due to rainfall and runoff. The solution is to have the vetiver hedgerows planted on the slope of major highways in Malaysia such as the Kuala Lumpur-Karak, East-West, North-South and Cameron Highland highways since 1993. This vetiver grass (Chrysopogon zizanioides) can grow very fast, in some applications rooting depth can reach 3 – 4 m in the first year if planted correctly (Truong, Van & Pinners, 2008). Some of the cut slopes were up to 150 m in vertical height in areas where annual rainfall exceeds 3000 mm. In the 1990s, following, the extensive research into vetiver root strength by Diti Hengchaovanich, a geotechnical engineer of Thailand, he has successfully used this vetiver hedgerows system in the stabilization of those major highways in Malaysia (Truong, 2004).

According to Osuagwu (2012), the use of grasses, trees and other plants to protect slopes from erosion, shallow landslides and improve the geotechnical properties of soil is termed as ‘soil bioengineering’. It is considered as a practical alternative to more traditional methods of slope stabilization such as soil nailing and
geosynthetic reinforcement. This bioengineering is now a well-known practice in many parts of the world particularly in Europe, since it has been widely investigated and discussed starting in the 1960s (Comino & Druetta, 2010).

Nowadays, it is highly demanded to incorporate the use of vegetation in restoring the stability of hillslope especially to solve the problem associated with shallow slope failure in both natural and man-made slope (Abdullah, Osman & Ali, 2011). Based on a manual for maintenance and service of unpaved roads outlined by CPYRWMA (2000), the most efficient and cost-effective method of stabilizing banks and slopes is grass seeding. The grass will reduce water movement and allow more infiltration. It will effectively hold soil particles in place and more importantly reducing sedimentation. Surface completely covered slope with grass will be more stable because the roots grip the soil on the slopes and prevent it from sliding. Above ground, the shoots can grow up to a few meters and when planted together near each other, it will form a solid vegetative barrier that retards water flow, filters and traps sediment in run-off water (Truong & Loch, 2004).

On the other hand, slope revegetation could be an economical and environmentally friendly solution to enhance and remediate unstable soils. With an increase in awareness of the environment in which human lives together with all other living things, sustainable and ecologically friendly solutions like this are being sought after, in order to solve problems in engineering (Loades, 2010). Even though soil bioengineering technique has been regarded as one way to alleviate landslide and erosion problems, this process of revegetation is severely time consuming. Hence, in order to avoid further damage to environment, properties and more importantly, life, the right propagation density and plant species, preferably the native one should be considered (Osman, Ali & Barakbah, 2009).

Research carried out by Petrone & Preti (2010) gave emphasized on the use of indigenous plants for riverbank protection and its effect on economic efficiency. The research that took place in the humid tropics of Nicaragua proved that the use of local species not only successful in environmental restoration, even in a hardship area (by maximizing the contribution of the local labor force and minimizing the use of mechanical equipment), but also economically sustainable. Nonetheless, not much research was conducted to determine the appropriate plants, particularly grass species that has a marked adaptability to stabilize slope embankment and offering an
aesthetically flowery appearance. Therefore, this study is initiated in order to provide a technical understanding on these particular issues.

1.2 Problem statement

The use of conventional structures such as concrete gravity wall, tie-back wall and rock buttress to stabilize the slope sometimes is objected due to its stark, harsh and unnatural appearance. Moreover, the structures are costly (Gray & Sotir, 1992). The alternative solution for the cut and fill stabilization is soil bioengineering techniques. It provides attractive, cost-effective and environmentally compatible ways to protect slopes against superficial erosion and shallow mass movement (Gray & Sotir, 1996).

Traditional civil engineering techniques known as ‘grey solutions’, such as concreting of welded wire walls for slope stabilization, that may not be sustainable in the long term due to high initial capital expenditure and more importantly increasing maintenance requirements overtime (Morgan & Rickson, 1995). Besides that, the concrete itself is noted as material that impervious to water resulting in significant increases in surface run off following rain events. With low residence times for water on the surface, drainage channels and rivers can become over-burdened with water resulting in flooding (Loades, 2010).

Therefore, in civil engineering, vegetation is can be used as a way of reducing the visual impact of civil engineering works and improving the quality of the landscape. This can be illustrated by having a beautiful scenery of flowering plants growing along the highways, creating a vibrant roadway and preventing eyesore to the drivers. Vegetation able to perform an important engineering function because of its direct influence both at the surface and on the soil, protecting and restraining the soil, and at the depth, increasing the strength and competence of the soil mass (Coppin & Richards, 2007).

According to Morgan & Rickson (1995), carefully selected and implemented bioengineering techniques are bound to be more sustainable over time as vegetation is self-regenerating and able to respond dynamically and naturally to changing site conditions, ideally without compromising or losing the engineering properties of selected vegetation.

The economic differentials between conventional, grey solutions and the use of vegetation may be significant in areas where the availability of products such as
concrete, sheet piling, rip-rap and gabions is severely restricted, as in inaccessible areas of developing countries. The current studies found that bioengineering techniques have been used in developing countries such as Nepal and Nicaragua where experience has shown the conventional methods of slope stabilization are prohibitively expensive on implementation and in maintenance, as well as being inappropriate to the local technology and expertise used to combat slope instability of the area (Petrone & Preti, 2010).

According to Osman & Barakbah (2006), it is aware that the documentation of plant contribution to slope stability is extensive in most part of the developed country, but it is lacking in the developing world. Slope problems vary between different geographical regions. Due to this variability, the solutions are also different and have to be specifically tailored. Moreover, there is a severe lack of empirical data regarding the attribution of plant cover on slope stability in Malaysia (Osman & Barakbah, 2006). Hence, it is essential to establish various data on soil-roots mechanical strength of potential flowery plant towards soil reinforcement.

1.3 Aim and objectives

Based on the problems elaborated, the research aims towards the establishment of a flowery plant that able to perform a decent soil-root shear strength reinforcement for 7 months of planting period. The objectives of this study are stated as below:

i) To analyse the soil-roots shear strength performance of a flowery plant throughout the 7 months of planting period.

ii) To determine the root tensile strength of single root specimen related to its diameter over the 7 months of planting period.

iii) To examine the relationship between plant morphological data and shear stress development at different planting period.

1.4 Scope of research

The study was carried out at a field of Research Centre for Soft Soil (RECESS), Universiti Tun Hussein Onn Malaysia (UTHM) for period of 7 months. The mass
planting of studied species was carried out at the site that within the reach of researcher, hence the selection of field study on laterite fills located inside the university is reasonable and for the ease of the study.

The research was limited to:

i) The field of RECESS used to grow the studied species is made up of laterite soil as platform fills on top of layer of clay. The topography of the field area is relatively flat with the original ground about 1.35 m to 1.80 m above the mean sea level. It is situated on area which has water table of 0.5 – 0.65 meter from the ground surface (RECESS, 2017).

ii) The flowery plant was chosen based on its vigorous, cheap and flowery in Malaysia’s climatic condition. For those criteria listed, the plant used in this research is *Pennisetum setaceum* ‘Rubrum’ with common name known as ‘purple fountain grass’.

iii) The mode of planting is monoculture where only one species is allowed to be grown in the field, rather than mix-culture system.

iv) In contrast to usual practice in investigating soil-root reinforcement, the plants used in this study were grown in a field rather than laboratory designated plots.

v) The phenomenon being discussed will circulate around the problem of superficial landslides which means it is less than 1 meter deep landslide and also known as miniature debris flows (Burylo, Hudek & Rey, 2011).

vi) It should be noted at the outset that this research confines itself primarily to methods and techniques for protecting upland slopes against superficial erosion and mass movement. Upland slopes stated herein include natural slopes, embankment fills, highway and railroad cuts, landfill slopes, gullies and ravines. Streambank or riverbank, coastal dune and bluffs stabilization are not addressed (Gray & Sotir, 1996). Superficial erosion is often ascertainable in coarse grained soils, compared to deep slides that often occur rather in fine grained soil (Frei, 2009). Mass movement as described by Oostwoud Wijdenes & Ergenzinger (1998) is miniature debris flows, consist of a mixture
of coarse marl fragments within a silty matrix, moving down slope as slides, gravity and fluid driven flow

vii) Direct shear test was conducted based on BS1377-7:1990, using small shear box apparatus (60 mm x 60 mm) in the laboratory (laboratory test) rather than in-situ test (field test) that usually make use of larger shear box. Small shear box is used for determining the angle of shearing of cohesionless soils and the drained peak and residual shear strength of cohesive soil. Meanwhile, large shear box is used for determining the similar properties of gravelly soils or on large block samples. It is also due the availability of the direct shear apparatus at RECESS.

viii) Determination of root tensile strength based upon a single root, being pulled up vertically using Universal Testing Machine (Instron, Model 3369).

ix) Assessment on soil-root reinforcement is carried out for planting period of 7 months.

x) Several basic geotechnical and plant morphological testing are conducted.

xi) The study was limited to empirical data (direct comparison of shear stress gained by rooted and non-rooted soil) rather than theories/ soil reinforcement model such Wu’s model or FBM model. Hence the soil-roots shear strength and root tensile strength will not be computed as one in this study as can be found in those two models. However notes about those models have been briefly discussed in Section 2.4.1.1. No slope stability analysis to determine factor of safety (FOS) required in the study.

xii) The study only focus on the mechanical effects of the root rather than hydrological effects. This is due to the time contraint and large parameters will be required if hydrological data such as precipitation, potential evoptranspiration, frequency of rain events, soil loss, run off and canopy cover etc. are employed in the study.
1.5 Significant of research

Biotechnical and soil bioengineering stabilization provide attractive, cost-effective and environmentally compatible ways to protect slopes against superficial erosion and shallow mass movement. The research will bring value to practitioners in such diverse fields as geotechnical engineering, geology, soil science, forestry, environmental horticulture and landscape architecture (Gray & Sotir, 1996).

The use of soil bioengineering techniques are believed able to promote and sustain the life of indigenous vegetation species, reduce costs and employ the local labour force (Petrone & Preti, 2010). However, much information about the below ground functions and properties of the various types of vegetation that is relevance to the civil/ geotechnical/ environmental engineers need to be known. The challenge was mainly due to the difficulties in extracting whole root systems, and the problems of testing plant roots both in situ and in the laboratory for their strength and other mechanical properties. The lack of precise information on plant root properties has possibly discouraged the use of soil bioengineering in civil engineering works, with civil engineers preferring exact numbers to enable quantification for design to take place. Thus this study plays an important role in the efforts to enrich and fulfill the knowledge of vegetation used in civil engineering structures in the country and indirectly promoting sustainable approach to the construction works.

According to research undertaken by Loades (2010), with an increased understanding of the fundamental concepts on root systems, a practitioner interested in soil reinforcement by roots will be able to better identify technologies and predict their impact on soil stability. Engineering applications for this research could include:

i) River bank management
ii) Engineered embankments
iii) Flood defence
iv) River catchment management
v) Sport surface technology
Hopefully, this study would complement similar studies revolved around topic of soil bio- and eco-engineering, soil erosion control, slope stability and land restoration.
CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Landslides are a widespread erosional process occurred in highland regions that includes a wide range of ground movements such as rockfalls, deep failure of slopes and shallow debris flow. These geotechnical problems occured due to steep slopes, high weathering rates exacerbated by severe climatic conditions or lack of vegetation (Burylo, Hudek & Rey, 2011). Thus, attention has nowadays been drawn to soil bioengineering using vegetation as the environment-friendly method to mitigate the landslide.

This chapter will discuss more details about the term of soil bioengineering, and examples of its application on slopes as well as their effects towards the slope stability. The effects can be divided into hydrological and mechanical factors, which can be beneficial or adverse to the slope stability (Coppin & Richards, 1990). Besides, root system and architecture can either promote or dissipate soil water pressure, thus they may either enhance or decrease the potential of shallow landslides (Ghestem, Sidle & Stokes 2011). More importantly, soil and root strength are interrelated, for example root system changes are being affected by different soils and treatments. Compaction of soil may also impede the root growth and alter root architecture (Loades, 2010).

2.2 Soil bioengineering definiton

In the past decades, the searching for ecologically correct technologies for environmental restoration has become very important. Many researchers has urged to
accommodate ecological approaches to what was formally done through rigid engineering (Holanda & Rocha, 2011). Mitsch & Jørgensen (2003) brought the idea of “ecological engineering” that involves creating and restoring sustainable ecosystems that have value to both humans and nature. The authors stated that, it combines basic and applied science for the restoration, design and construction of aquatic and terrestrial ecosystems.

Meanwhile, “soil bioengineering”, or biotechnical slope protection, has been defined variously as “the use of mechanical elements (or structures) in combination with biological elements (or plants) to arrest and prevent slope failures and erosion” (Gray & Leiser, 1982). Similarly, Campbell, Shaw, Sewell & Wong (2008) stated the meaning as the use of living vegetation, either alone or in conjunction with non-living plant material and civil engineering structures, to stabilize slopes and/or reduce erosion. In the case of upland slope protection and erosion reduction, the term means combination of mechanical, biological, and ecological concepts to arrest and prevent shallow slope failures and erosion (Gray & Sotir, 1992).

Until recently, many practitioners have coined the terms soil bio and eco-engineering, but confusion still exists as to the exact definition of each. It appears that the term bioengineering was first used as the translation from the German word ‘Ingenieurbiologie’, created in 1951 by V. Kruegner when referring to projects using both the physical laws of ‘hard’ engineering and the biological attributes of living vegetation, which described the work that encompassed both engineering and biology (Stokes, Sotir, Chen & Ghestem, 2010). Over time in North America, it became clear that the word ‘bioengineering,’ which also referred to medical works, was confusing. In 1981, after many discussions with Dr. Schiechtl and other European practitioners, R. Sotir developed the new terminology ‘soil bioengineering’ for North America. This terminology has also been accepted in other parts of the world including Hong Kong and Malaysia (Stokes et al., 2010).

The differences between soil bioengineering and eco-engineering are largely due to their effectiveness over time and space. In soil bioengineering, from the first moment of installation, no erosion should occur, as this would be considered part of the original criteria and may be alleviated by the angular arrangement and density of the installed measures (Stokes et al., 2010). Still, Stokes et al. (2010) emphasized that in eco-engineering, civil engineering techniques are not used, although local
organic material at the site, e.g. logs and stumps, may be positioned to prevent soil runoff.

### 2.3 Soil bioengineering stabilization

In this section, two approaches to soil bioengineering techniques are presented: vegetative system and vegetative systems combined with simple structures. Both approaches are discussed cursorily, aided by suitable figures. The vegetative systems are hydroseeding, ground covers, live staking, live fascines, brushlayering and Vetiver grass hedgerows. The second approach is the conjunctive use of plant and inert structures such as vegetated cribwall, vegetated geotextiles structure, precast concrete cellular blocks, vegetated cellular grids and coil rolls. These techniques able to improve the appearance and performance of structure (Sotir & Gray, 1995).

#### 2.3.1 Hydroseeding

Hydroseeding or hydromulching is a technique in which seeds and nutrients are sprayed over the ground as a slurry (Bache & MacAskill, 1984). It is the most common method to stabilize natural hill, cut and fill slope (Florineth & Gerstgraser, 1996). Hydroseeding is used on steep slopes which have a smooth surface and mild climate, mainly in forests. Seed of grass/ herb, organic fertilizer, mulch and an algae product as glue are mixed in a special barrel with water and pumped out onto the slope (Figure 2.1). It is advisable to fasten a jute mesh on the slope when it comes to very steep slope, so that it can fix the hydroseed (Florineth & Gerstgraser, 1996).

#### 2.3.2 Ground cover

A dense herbaceous or grass cover comprises one of the best defenses against soil erosion. For many installations vegetation alone will provide adequate long-term erosion protection (Gray & Sotir, 1996). In this case, the cover system is leguminous plant named Calopo (Calopogonium mucunoides). It is also known as “wild ground nut” and “kacang asu” in English and Bahasa Indonesia respectively. It can reach several meters in length and form a dense, vigorous, creeping and tangled mass of
foliage, 30-50 cm deep (Figure 2.2). The root system is dense and shallow, at most 50 cm deep (FAO, 2011). This creeper plant is mainly used as cover crop, alone or in mixture with other legumes (e.g. *Centrocoma pubescens, Pueraria phaseoloides*), especially in rubber, oil palm or in young forest plantations (Figure 2.3). Calopo is a pioneer species, it provides soil protection against erosion, reduces soil temperature, improves soil fertility and controls weeds (Cook et al., 2005). It was introduced in Indonesia and Malaysia as a cover crop and became naturalized. It is considered a weed in some regions (US Forest Service, 2011).

![Figure 2.1: Hydroseeding with a hydroseeder (Schiechtl & Stern, 1996)](image)

### 2.3.3 Live staking

Live staking involves the insertion and tamping of live, rootable vegetative cuttings perpendicularly into the ground (Figure 2.4). The live stake will root and leaf out if correctly prepared and placed (Figure 2.5). Live stakes can be placed in rows across a slope to help control shallow mass movement. They can also be tamped through and used in conjunction with jute or coir netting. The cuttings are usually ½ to 1 ½ inches in diameter and 2 to 3 feet long. The materials must have side branches cleanly removed and the bark intact (Gray & Sotir, 1996). This system of stakes creates a living root mat that stabilizes the soil by reinforcing and binding soil particles together and by extracting excess soil moisture (Sotir & Gray, 1995).
2.3.4 Live fascines

Live fascines are long bundles of branch cuttings bound together into sausage-like structures, which are placed in shallow trenches parallel to the slope contour (Figure 2.6). The bundles are tied together with twine and anchored in the trench with wooden stakes and/or live stakes, as shown in Figure 2.7 (Gray & Sotir, 1996). Live fascines serve to dissipate the energy of downward moving water by trapping debris and providing a series of benches on which grasses, seedlings, and transplants establish more easily. Portions of the live fascines also root and become part of the stabilizing cover.

![Figure 2.2: Calopo’s trifoliate leaves (US Forest Service, 2011)](image1)

![Figure 2.3: Calopo is grown at slope along the Jalan Felda Aring, Kelantan](image2)

![Figure 2.4: Schematic diagram of an established growing live stake installation (Sotir & Gray, 1995)](image3)

![Figure 2.5: Healthy, growing live stakes (DesCamp, 2004)](image4)
2.3.5 Brushlayering

In the case of brushlayering, live branches or shoots of such woody species as shrub willow, dogwood or privet are placed in successive layers with the stems generally oriented perpendicular to the slope contour, as shown in Figure 2.8. Live branch cuttings are placed in small benches excavated into the slope. The benches can range from 2 to 3 feet wide. The portions of the brush that protrude from the slope face assist in retarding runoff and reducing surface erosion. Brushlayering can improve soil stability to depths of 4 to 5 feet (Sotir & Gray, 1995). It works better on fill as opposed to cut slope because much longer stems can be used in the former method. Usually, branches up to 12 feet in length can be used on fill slope brushlayering installations (Gray & Sotir, 1996). After one year, vegetation cover has become established (Figure 2.9).
2.3.6 Vetiver grass hedgerows

Vetiver (*Chrysopogon zizanioides*) is a non fertile, non-invasive Indian clump grass cultivated for centuries for essential oil (TVNI, 2015). The grass works best when planted in hedgerows on contour with the plants spaced approximately 15 cm apart as shown in Figure 2.10 (Gray & Sotir, 1996). To produce quality hedgerows, quality planting materials must be used which must always begin with mature and active tillers cultivated from nursery. Vetiver grass cultivar aged 4 months is suitable for transplanting. Vetiver hedgerows shall never be planted from cut-root slip. Only container plants shall be used to ensure the success of the planting (Yoon, 1994). This vetiver hedgerows have been proven to stabilize some of the major highway slopes in Malaysia such as the Kuala Lumpur-Karak, East-West, North-South and Cameron Highland highways since 1993 as shown in Figure 2.11 (Truong, 2004).

![Figure 2.10: Vetiver hedgerows after 1 month of planting at East – West Highway, Malaysia (Yoon, 1997)](image1)

![Figure 2.11: The same vetiver hedgerows after 11 months of planting (Yoon, 1997)](image2)

2.3.7 Vegetated crib wall

A vegetated crib wall consists of a hollow, box like interlocking arrangement of structural beams (Figure 2.12). In conventional cribwalls, the structural members are fabricated from concrete, wood logs and dimensional timbers. This live crib walls is an example of combination vegetative system and inert structure. The vegetation provides an attractives screen or landscaping touch on the face of the crib wall (Figure 2.13). In the live wooden crib wall, the structure is filled with a suitable backfill material and layers of live branch cuttings. For the concrete crib walls, the
frontal spaces between the stretchers in walls provides opening through which vegetative cuttings or rooted plant can be inserted (Gray & Sotir, 1996).

Figure 2.12: Concrete crib wall during construction (Schiechtl & Stern, 1996)  Figure 2.13: Open-front concrete crib wall with plantings in openings (Sotir & Gray, 1995)

2.3.8 Vegetated geogrids

A vegetated geogrid installation consists of live cut branches (brushlayers) interspersed between layers of soil and wrapped in natural or synthetic geotextile materials, as shown in Figure 2.14. The brush is placed in a crisscross or overlapping pattern so that the tips of the branches protrude just beyond the face of the fill. The foliage growing on the face of the fill will retard runoff velocity and filter the sediment (Figure 2.15). Vegetated geogrid structures are constructed in much the same way as a conventional mechanically stabilized earth (MSE) structural fill. However, the stems that extend back into slope are living and root along their lengths and act as horizontal slope drains (Gray & Sotir, 1996).

2.3.9 Precast concrete cellular blocks

Precast concrete cellular blocks are placed on the slope surface, similar to a simple grating (Figure 2.16). They are fixed with iron pegs or anchors. The voids of the blocks are filled with topsoil which is seeded. However the grassing effect could be very variable. The blocks with larger apertures would facilitate better grass establishment compared to the small one (Figure 2.17). After filling the blocks with
soil, exposed concrete is unsightly for some time. These precast blocks provide immediate stabilising effect to the slope (Schiechtl & Stern, 1996).

Figure 2.14: Schematic diagram of an established geogrids wall (Gray & Sotir, 1996)

Figure 2.15: The willows are well established on geotextile reinforced slope (Schiechtl & Stern, 1996)

Figure 2.16: Vegetated precast concrete cellular blocks at km 54, Jalan Gua Musang – Cameron Highland

Figure 2.17: Small apertures of cellular blocks causing improper grassing effect (Schiechtl & Stern, 1996)

2.3.10 Vegetated cellular grids

A cellular grid is essentially a lattice like array of structural members that is fastened or anchored to a slope as shown in Figure 2.18. The structural members may be either concrete, timber or a three dimensional expandable polymeric web. The polymeric web usually manufactured from polyethylene or polyester strips (Figure 2.19). The spaces within the lattice or honeycomb array are planted with suitable vegetation. The purpose of installing the structure is to facilitate the establishment of
vegetation on steep, barren slope. It does not require the importance of select backfill and cribfill (Gray & Sotir, 1996).

**Figure 2.18**: Installation of vegetated expendable honeycomb cellular grid on a slope at Jalan Kemaman – Dungun, Kijal, Terengganu

**Figure 2.19**: Empty cellular grids that expand into a large honeycomb-like array (Terrafix Geosynthetics Inc, 2015)

### 2.3.11 Coil rolls

Coirlogs or coil-rolls are cylindrical shape erosion control product which is made of 100% compressed biodegradable coconut fibers, wrapped in a polymer exterior netting to form a bioengineering solution known as the Coconut Coir Logs (Figure 2.20). This flexible structure provides protection for slope embankment and toe, ensures stabilization on stream bank, enhances vegetation establishment while acting as silt check and sediment control tool (Fibromat, 2016). Coil rolls are used to prevent loss of nutrients from the soil due to water run-off and supply the shrub with enough nutrients to grow. They are arranged horizontally on the slope surface, parallel to the contour (Figure 2.21). Organic fertilizer in the bags that are placed on top of the berms will seeps slowly during the rain to provide continuous nutrients supply to the growing plant while apart of it will retain in the coil rolls (JKR, 2011).

### 2.4 Effects of vegetation on slope stability

The importance of vegetation in the role of improving soil stability has been recognized for a long time (Morgan, 2005). There are two mechanisms of plant that influence the stability of slope, namely hydrological and mechanical. Hydrological mechanism is associated with hydrologic cycle that is interrelated with plant roles
While mechanical mechanism occurred due to physical interactions between plant shoots and its ambient surrounding or roots system and slope soil (Figure 2.22). It is realized that, both hydrological and mechanical effects can be adverse or beneficial to slope stability (Alfred, 2006; Ghestem et al., 2011). However, the most important part of the vegetation is the root. It increases the resistance of the soil by modifying its mechanical and hydrological properties (Gray & Sotir, 1996).

Figure 2.20: Coil rolls are arranged horizontally parallel to the contour (JKR, 2011)

Figure 2.21: Coir rolls installed on a slope at km 21, Jalan Gua Musang – Cameron Highland (JKR, 2011)

Figure 2.22: Mechanical effects of vegetation on slope stability (Coppin & Richards, 1990)
2.4.1 Mechanical effects

2.4.1.1 Root reinforcement

The most apparent way in which vegetation stabilizes soil is through root reinforcement. It occurs when the tap and sinker roots penetrate down through the soil mantle and mechanically anchor into the firmer underlying strata (Ronald, 1985). Roots embedded in soil form a composite material consisting of fibres of relatively high tensile strength and adhesion within a matrix of lower tensile strength. The shear strength of the soil is therefore enhanced by the root matrix (Ali & Osman, 2008). This is analogous to the reinforced soil system, where a soil mass is stabilized by the inclusion of metallic, synthetic or natural materials. The shear strength of the rooted soil mass is enhanced due to the presence of a root matrix. Root reinforcement of soil provides relief of local stress by transferring load to regions of lower stress, through the interaction of semi-continuous root systems (Farshchi, 2009).

A lot of works on slopes demonstrated that when compared with non-root permeated soils, even low root density can provide substantial increase in shear strength and the magnitude additional apparent cohesion varies with the distribution of the roots within the soil and with the tensile strength of the individual roots (Wu, Mckinnell & Swanston, 1979; Abernethy & Rutherfurd, 2001; Ali & Osman, 2008).

Currently, there are two theoretical slope stability models incorporating the soil-roots strength parameters, namely Wu’s Model and Fibre Bundle Model (FBM). The first model was developed by Tien H. Wu in 1976 and used extensively for the last 30 years (Stokes et al., 2010). This model of additional cohesion taking into account the contribution of roots and it assumes that all roots grow vertically and act as loaded piles such that tension is transferred to them instantaneously as the soil is sheared (De Baets et al., 2008). Various limitations with the model have led to the development and use of a new model called the Fibre Bundle Model (FBM) (Pollen & Simon, 2005). The second model argues that all roots crossing the shear plane will break at the same time as claimed by Wu’s model. It is because, the shear surface may propagate progressively through the soil mass and some roots pull out rather than break. These effects often result in an overestimation of root cohesion (Docker & Hubble, 2008). Hence, the second model predicts soil-root reinforcement better than the the first model (Loades et al., 2010).
2.4.1.2 Root tensile strength

Root tensile strength is an important factor to consider when choosing suitable species for reinforcing soil on unstable slopes. Tensile strength has been found to increase with decreasing root diameter. It is defined as “the maximum force per unit area required to cause a material to break” (Genet et al., 2005). Not only is root tensile strength important when considering soil reinforcement, but it can also affect plant anchorage. In herbaceous species, plants must withstand grazing pressure, whereby uprooting occurs in tension, therefore a higher root tensile strength will enable the plant to remain anchored in the soil (Ennos & Fitter, 1992).

Wide variations in root tensile strength have been reported in the literature. Kindly refer Section 2.12: Review of root tensile strength of some species, for the details review of the root tensile strength of numerous species recorded by other researchers. In addition, the comparison of tensile strength values between various species has been mentioned in Section 4.4.8, in form of table and graphs.

The root tensile strengths appear to depend on species and site factors such as local environment, season, root diameter and orientation (Gray & Sotir, 1996). Study by Lindström & Rune (1999) showed that root resistance to failure in tension can be influenced by the mode of planting e.g. naturally regenerated Scots pine (Pinus sylvestris L.) had stronger roots than those of planted pines. The time of year has also been found to affect tensile strength as roots being stronger in winter than in summer, due to the decrease in water content (Turmanina, 1965). Tensile strength usually decreases with increasing root size (Loades, 2010; Osman, Abdullah, & Abdullah, 2011; Zainordin et al., 2015) and this phenomenon has been attributed to differences in root structure, with smaller roots possessing more cellulose per dry mass than larger roots (Commandeur & Pyles, 1991).

2.4.1.3 Root area ratio (RAR)

Root area ratio (RAR) is defined as the area of roots in relation to the area of soil (Loades, 2010). It is calculated in order to measure root distribution (Abernethy & Rutherfurd, 2001), also very important to be used as one of the parameters in determination of additional cohesion of rooted soil in Wu’s root reinforcement
theoretical model (Wu et al., 1979). RAR has a high variability with species, site condition and depth. It has been used as an index of root density by many authors (De Baets et al., 2008; Comino & Marengo, 2010; Burylo et al., 2011). It was reported that the upsurge in the RAR causing the increase of soil reinforcement (Loades et al., 2010). Thus, many authors suggested to use RAR as a part of slope stability characterization in their research (Avani, Lateh & Bibalani, 2013).

There is exponential reduction in root area quantity with distance away from the tree stem at all depth and as well as decrease in their maximum lateral extends with depth (Genet et al., 2005). Abdi et al., (2010) analyzed the RAR in ironwood (Parrotia persica) and found that root density normally decreases with depth according to an exponential function. Maximum RAR values were located within the first 0.1 m layer. Furthermore, Naghdí et al., (2013) studied study the effect of alder (Alnus subcordata) roots on hillslope stability. The results indicated that the root density, number of roots and RAR decreased with increasing depth. The maximum RAR values were located in the upper layers only. Sometimes, root density that is calculated as roots dry weight over a volume of soil is used to estimate the root area ratio (RAR). Similarly, the pattern of result shows root density also decreased significantly with increasing depth (Genet et al., 2008).

2.4.1.4 Anchorage, arching and buttressing

Vegetation particularly from woody plants able to influence slope stability through buttressing and soil arching of the trunks of trees growing in slopes. Arching occurs when soil attempts to move through and around a row of trees firmly embedded in an unyielding soil layer (Bache & MacAskill, 1984). The embedded stems also act as buttress piles or abutments, restraining soil movement from trunks, thereby counteracting the down-slope shear stress (Gray & Leiser, 1982).

The taproot and the sinker roots of many tree species penetrate into the deeper soil layers and anchor them against down-slope movement. The trunks and the principal roots acts in the same manner as toe stabilizing piles, further restraining the down-hill movement of soil. The magnitude of the arching effects is influenced by spacing, diameter, embedment of trees, thickness and inclination of the yielding stratum of slope as well as shear strength properties of soil. Whereas trees that are
sufficiently close together, the soil between the unbuttressed parts of the slope may gain strength by arching (Coppin & Richards, 1990).

2.4.1.5 Surcharging

Surcharge is the effect of the additional weight on a slope resulting from the presence of vegetation and it is normally considered only for trees, since the weight of grasses and most herbs and shrubs are comparatively small. Surcharge could have adverse effects, although it can be beneficial depending on the slope geometry, the distribution of vegetation cover and the properties of the soil. This surcharge induces a downslope stress, which reduces stability and a normal stress to the slope, which increases the slope resistance to movement (Gray & Leiser, 1982). However, some researchers also discovered that increase in normal load had increased the shear strength of soil, implying the additional load by vegetation contributed in improving the slope stability (Abdullah et al., 2011; Docker & Hubble, 2008).

Surcharge at the top of slope can lead to reduction of overall stability, whereas it can add to stability when applied at the bottom of the slope. This is proven by a study carried out by (Ali, Farshchi, Mu’azu & Rees (2012), which determined the factor of safety (FOS) based on various tree positions on slope. They discovered that the tree located at the toe of slope had the highest FOS value compared to when is located at the crest or middle of the slope. Another study shows that in an infinite slope, surcharge is beneficial when cohesion is low, groundwater level is high, soil angle of internal friction is high and slope angle is small (Coppin & Richards, 1990).

2.4.1.6 Wind loading

Wind loading is usually only significant when the wind speed is stronger than 11m/s. Both the up- or down-hill wind loadings can destabilize the slope especially in larger trees with shallow roots. The forces induced in vegetation by wind can sufficient to disturbed upper soil layer thus, initiate landslips. An up-hill wind if sufficiently strong can cause a toppling of a tree and impart a destabilizing moment to the slope and a greater possible destabilizing effect can result from increased water infiltration through the scar created by an uprooted tree (Coppin & Richards, 1990).
This wind loading effect is best described by a study on soil-roots system of Makino bamboo towards slope stability by Lin, Huang & Lin (2010). In 2004, continuous attacks of two typhoons; Typhoons Mindulle on 2\textsuperscript{nd} July and Aere on 25\textsuperscript{th} August in central Taiwan causing a large area of slopeland covered with Makino bamboo collapsed and eroded. The typhoons has strong wind velocity ranged from 30 – 48 m/s. It can be speculated that the tension cracks widespread over the slope surface due to the wind loading acting on the bamboo stems and the sequential rainwater infiltration is the dominating factor in the collapse failure of slopeland. Moreover, the shallow root depth (0.8 - 1.0 m) and large growth height (over 10 m) of Makino bamboo became extremely unfavorable to the slope stability.

\subsection*{2.5 The root system}

While it has been proven that the vegetation is able to improve soil stability through both its above-ground and below-ground biomass, few studies have focussed on the significance of the root system. The root system is particularly important when the above-ground vegetation is absent for some time e.g. after harvest, grazing, fire or outside the growing period of the crop (Hudek, 2013).

The development of the rooting system is influenced by environmental and genetic factors such as water availability (rainfall and/or irrigation), temperature, seasons and altitude, soil moisture, structure, texture, depth and slope, tillage, organic content and nutrients input, micro- and macro-organisms activity, lignin and cellulose content, plant age, density and competition (Genet \textit{et al.}, 2005; Osman & Barakbah, 2006; Fan & Su, 2008; Preti, Dani & Laio, 2010).

Coppin & Richards (1990) properly explained that the root systems vary from very fine fibrous systems through branched systems to a vertical taproot. All plants have a mat of surface roots as to collect nutrients and which grow in and around the surface soil layers because this is where mineral nutrients are generally available. Deeper roots are used for anchorage and for absorbing water. Large taproots are often associated with the storage of food for over-wintering plants, especially where the above-ground parts die back substantially. The taproots are thus perennial structures whereas fine fibrous roots are subject to annual cycles of decay and renewal.
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