Nature Based Landslide Risk Management Project in Sri Lanka

Guidance Document

Use of Nature-based Solutions for Site-specific Landslide Risk Mitigation

NBLRM

September 2020

NBLRM

NATURE BASED LANDSLIDE RISK MANAGEMENT PROJECT IN SRI LANKA

USE OF NATURE-BASED SOLUTIONS FOR SITE-SPECIFIC LANDSLIDE RISK MITIGATION

Guidance Document

2020

Citation

ADPC 2020. Guidance Document on Use of Nature-Based Solutions for Site-specific Landslide Risk Mitigation, Nature Based Landslide Risk Management Project in Sri Lanka.

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ISBN 978-624-5298-03-7

Published by: Asian Disaster Preparedness Center, Room No. 4-101/4-102, Block 4, BMICH, Bauddhaloka Mawatha, Colombo 07

Printed in Moratuwa, Sri Lanka by ES Print Solutions

This document has been developed under Nature Based Landslide Risk Management Project in Sri Lanka funded by the World Bank (Grant no. 7191576).

FOREWORD

With landslides becoming increasingly frequent in Sri Lanka, importance of undertaking risk mitigation interventions is growing. In the past Sri Lanka has largely relied on engineering solutions on landslide risk management and the application of nature-based and hybrid (nature-based solutions in combination with conventional engineering solutions) approaches for landslide risk management has been limited. It has been demonstrated in many countries in Asia that risk-informed nature-based solutions can be effective in reducing the occurrence and associated impacts of such landslides.

This "Guidance Document on Use of Nature-based Solutions for Site Specific Landslide Risk Mitigation" is an outcome of the World Bank funded Nature Based Landslide Risk Management Project in Sri Lanka. The project is implemented by National Building Research Organization (NBRO) with technical assistance from Asian Disaster Preparedness Center (ADPC), Thailand. This Analytics and Advisory Services project aims at raising awareness on the subject and deepening knowledge within the country on the role of nature-based solutions for landslide risk management. It is also expected to apply this knowledge in a number of pilot demonstration sites under the ongoing Climate Resilience Improvement Project (CRIP) funded by the World Bank.

This document is expected to serve as a Guidance Document on application of nature-based as well as hybrid solutions. Some of the good practices of bio-engineering for stabilization of vulnerable slopes and reducing the erosion potential is also included in the document. It forms a part of the project outcomes and developed with the purpose of providing guidance to NBRO, relevant local authorities, other practitioners to design, implement and monitor nature-based solutions for landslide and erosion risk reduction under a range of physical conditions. The nature-based and especially hybrid solutions presented in this guide are chosen specifically to Sri Lanka's need for landslide risk reduction. In addition, it is expected that the vegetation cover may make the appearance of slopes as natural as possible, and help in creating not only safer but also more visually acceptable and ecologically sustainable slopes.

This manual is written for the use by engineers, geologists, town planners, land use planners etc. who will be directly involved in structural mitigation work for reducing landslide risks. Often, they struggle to obtain the services of agricultural engineers, agronomists, botanists, etc. when they wish to integrate nature-based solutions as a part of mitigation project designs. It is not possible to replace the technical advice of experts in the subject through a Guidance Document of this nature and it is not intended. It is our expectation that this document will provide those involved in designing landslide risk mitigation projects with understanding and technical guidance in application of bio-engineering measures in slope stabilization.

We have taken initiative to hand over copies of 1st draft of the guidance document during NBRO symposium 2019 December and provided in our web site for wider circulation. However, in our view, this work is still in progress and hence we wish to make a sincere request to users to provide comments on the content and make appropriate suggestions with the view to improve it in future. All such contributions are gratefully appreciated and acknowledged.

I wish to thank all who have provided inputs and made contributions in various ways. We are indebted to the World Bank for providing financial assistance for undertaking a pilot project on Nature Based Solutions for Landslide Risk Management in Sri Lanka and it is our sincere hope that we will be able to improve on the content with support of everybody involved in landslide risk management in future and finalize the same.

Eng. (Dr.) Asiri Karunawardena
Director General
National Building Research Organization, Sri Lanka
September 2020

MESSAGE FROM ADPC

Nature-based Solutions (NbS) for landslide risk mitigation are emerging as an environmental friendly, economically viable and sustainable solutions in many Asian countries, e.g. Nepal, India, Hong Kong and Thailand. NbS make use of ecosystem services and natural processes to address different types of societal and environmental challenges arising natural hazards such as landslides. The scientific community consider them as alternatives or complements to conventional engineering or “gray” solutions. Moreover, NbS have the potential to promote people centric approaches in enhancing the resilience of vulnerable communities.

In view of the above, the World Bank launched the Analytics and Advisory Services project in Sri Lanka on Nature-based Landslide Risk Management in partnership with National Building Research Organization (NBRO), the mandated agency for landslide risk management in Sri Lanka. Asian Disaster Preparedness Center (ADPC) had the privilege in providing implementation and technical guidance for project execution.

This Guidance Document emanating from the project provides information covering a wide range of different aspects of NbS and their applications at site-specific level for landslide risk mitigation in Sri Lanka. I strongly believe that this Guidance Document will immensely benefit Sri Lanka, and beyond, in managing the landslide risk in an efficient and effective manner by enabling sustainable development in landslide prone areas in the country as well as in the Asian region.

Finally, I wish to express my sincere gratitude to the World Bank for their financial assistance which enabled a smooth execution of the project. My sincere thank goes to the Director General of NBRO and its staff and also to ADPC’s team members in the successful implementation of this project.

Mr. Hans Guttman
Executive Director
Asian Disaster Preparedness Center, Thailand
September 2020

ACRONYMS

ADPC	: Asian Disaster Preparedness Center
CRIP	: Climate Resilience Improvement Project
DEM	: Digital Elevation Model
DRM	: Disaster Risk Management
DRR	: Disaster Risk Reduction
FoS	: Factor of Safety
GIS	: Geographic Information System
GOSL	: Government of Sri Lanka
GPR	: Ground Probing Radar
IUCN	: International Union for Conservation of Nature
JICA	: Japan International Cooperation Agency
LHMP	: Landslide Hazard Mapping Project
NbS	: Nature-based Solutions
NBRO	: National Building Research Organization
UNDP	: United Nations Development Program
WB	: World Bank

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CHAPTER 01

INTRODUCTION

NBLRM

Chapter 1 INTRODUCTION

1.1. General

The central Sri Lanka consist of a mountainous terrain. It is popularly known as the central highlands, due to its topography and highly fractured and folded nature of basement rock. It is overlain by residual soil and colluvium as well a weathered rock layer of varying thickness and responsible for creating a significant susceptibility, vulnerability to landslides and resultant increased risk. This is seen from the past major devastating events with higher loss of lives, damage to infrastructure, destruction of property, impacts on livelihood and local economy. During the recent years, considering ever increasing risk environment, the Government of Sri Lanka, has made several commitments, while endorsing the Global Frameworks such as the Sendai Framework of Action for DRR (SFDRR) 2015-2030, UN Sustainable development Goals (SDGs), 2015 Paris Climate Conference (COP21), World Humanitarian Summit 2016 etc. and places high importance towards disaster risk reduction for sustainable development.

As witnessed through recently occurred natural disasters, it is evident that Sri Lanka is becoming one of the hotspots for natural disasters within South Asian sub-region. In addition to landslides, floods, droughts, cyclones and high wind events have claimed high number of human losses, whereas the impact created annually to national economy and civil society due to them is enormous. All those are climate induced events and global climate change may have some influence in positive and negative variations in weather in particular in the monsoon calendar. Sri Lanka is dependent on two monsoon periods and early monsoon onset tends to bring abundant rainfall whereas delayed onset is almost never associated with better than average rainfall. Although the total rainfall over the entire monsoon season may not show significant differences it is those peaks that seems to be creating floods, landslides and droughts.

During the monsoon season, there are often peak periods, when there is hardly any rainfall or short duration high rainfall events. These periods tend to be random but seems to be are responsible for above mentioned disaster events. Other factors influencing the monsoon pattern of the country, is the impact of El Niño and its counterpart La Niña. When there are the warming and cooling events associated with the Indian and Atlantic oceans, there seems to be a role played by El Niño in changing the monsoon variations. When such events, in particular the climate induced events, impact communities and ecosystems that are already under significant stress from other development pressures, the consequences can be severe. Moreover, many of the poor segments of the country rely predominantly on climate sensitive livelihoods such as agriculture, livestock, fisheries etc. and they will have low capacity to adapt to the impacts of climate change, and climate induced hazard events.

Among such disaster events, landslides have become one of the most devastating disaster events in the country, that cause human deaths, property losses and damages to infrastructure and lifelines frequently. Landslides are seen to have greater and adverse economic impacts in urban centers in the hill country where there is a higher density of human settlements and infrastructure facilities.

1.2. Types of slope failures and landslides

The term "landslide" describes a wide variety of processes that result in the downward and outward movement of slope-forming materials including rock, soil, artificial fill or a combination of these. The materials may move by falling, toppling, sliding, spreading or flowing. Although landslides are primarily associated with mountainous regions, they can also occur in areas of general low relief. In low-relief areas, landslides occur as cut and fill failures (roadway and building excavations), river bluff failures, lateral spreading landslides, collapse of mine-waste piles (especially coal) and a wide variety of slope failures associated with quarries and open-pit mines (United States Geological Survey 2004). Landslides occur in a variety of environments, characterized by either steep or gentle slope gradients: from mountain ranges to coastal cliffs or even underwater, in which case they are called submarine landslides. Gravity is the primary driving force for a landslide to occur, but there are other factors affecting slope stability, which produce specific conditions that make a slope prone to failure.

Many of the existing classifications on landslides are done in considering specific mechanics of slope failure and the material types involved. Hungr *et al.,* (2013) indicated that the system of landslide classification devised by late D. J. Varnes in 1978 is the most widely used system globally. Hungr *et al.,* (2013) provides an update for "The Varnes classification of landslide types". They use type of material as the primary criteria. This classification provides 32 types of different landslides (Table 1.1).

Table 1-1 Summary of the proposed new version of the Varnes classification system. The words in italics are placeholders (use only one) (Hungr *et al.*, 2013)

Type of movement	Rock	Soil
Fall	1. *Rock/ice* fall [a]	2. Boulder/debris/silt fall [a]
Topple	3. Rock block topple [a] 4. Rock flexural topple	5. Gravel/sand/silt topple [a]
Slide	6. Rock rotational slide 7. Rock planar slide [a] 8. Rock wedge slide [a] 9. Rock compound slide 10. Rock irregular slide [a]	11. *Clay/silt* rotational slide 12. *Clay/silt* planar slide 13. Gravel/sand/debris slide [a] 14. *Clay/ silt* compound slide
Spread	15. Rock slope spread	16. *Sand/silt* liquefaction spread [a] 17. Sensitive clay spread [a]
Flow	18. *Rock/ice* avalanche [a]	19. Sand/silt/debris dry flow 20. Sand/silt/debris flow slide [a] 21. Sensitive clay flow slide [a] 22. Debris flow [a] 23. Mud flow [a] 24. Debris flood 25. Debris avalanche [a] 26. Earth flow 27. Peat flow

Type of movement	Rock	Soil
Slope deformation	28. Mountain slope deformation 29. Rock slope deformation	30. Soil Slope deformation 31. Soil creep 32. Solifluction

[a] Movement types that usually reach extremely rapid velocities as defined by Cruden and Varnes. The other landslide types are most often (but not always) extremely slow to very rapid.

1.3. Types of movement observed in landslides

Falls

Falls are abrupt movements of masses of geologic materials that become detached from steep slopes or cliffs. Movement occurs by free fall, bouncing and rolling. Depending on the type of earth material involved, the result can be a rock fall, soil fall, debris fall, earth fall so on. All types of falls are promoted by undercutting, differential weathering, excavation or stream erosion.

Topple

A topple is a block of rock that tilts or rotates forward on a pivot or hinge point and then separates from main mass, falling to the slope below, and subsequently bouncing or rolling down the slope.

Slides

Although many types of mass movements are included in the term of "landslides", the more restrictive use of the term refers to movement of soil or rock along a distinct surface of rupture which separates the slide material from more stable underlying material. The two major types of landslides are rotational slides and translational slides.

Rotational slide

Rotational slide is one in which the surface of rupture is curved concavely upward (spoon shaped) and the slide movement is more or less rotational about an axis that is parallel to the contour of the slope. A "slump "is an example of a small rotational slide.

Translational slide

In a translational slide, the mass moves out, or down and outward along a relatively planar surface and has little rotational movement or backward tilting. The mass commonly slides out on top of the original ground surface. Such slides may progress over great distances if conditions are right. Slide material may range from loose unconsolidated soils to extensive slabs of rock.

Lateral Spreads

Lateral spreads are a result of nearly horizontal movement of geologic materials and are distinctive because they usually occur on very gentle slopes. The failure is caused by liquefaction, the process whereby saturated, loose, cohesion less sediments (usually sands and silts) are transformed from a solid in to a liquefied state or plastic flow of subjacent material. Failure is usually triggered by rapid ground motion such as that experienced during earthquakes or by slow chemical changes in the pre water and mineral constituents.

Creep

Creep is the imperceptibly slow, steady downward movement of slope-forming soil or rock. Creep is indicated by curved tree trunks, bent fences and small soil ripples or terracettes.

Debris flow

A debris flow is a form of rapid movement in which loose soils, rocks and organic matter combine with entrained air and water to form a slurry that then flows downslope. Debris flow areas are usually associated with steep gullies. Individual debris flow areas can usually be identified by the presence of debris fans at the termini of the drainage basins.

Debris avalanche

A debris avalanche is a variety of very rapid to extremely rapid debris flow.

Earthflow

Earthflows have a characteristic "hourglass" shape. A bowl of depression forms at the head where the unstable material collects and flows out. The central area is narrow and usually becomes wider as it reaches the valley floor. Flows generally occur in fine grained materials or clay-bearing rocks on moderate slopes and with saturated conditions.

Mudflow

Mudflow is an earthflow that consists of material that is wet enough to flow rapidly and that contains at least 50% sand, silt and clay sized particles.

Lahar

A lahar is a mudflow or debris flow that originates on the slope of a volcano. Lahars are usually triggered by such things as heavy rainfall eroding volcanic deposits, sudden melting of snow due to heat from volcanic vents or lakes dammed by volcanic eruption.

1.4. Common types of landslides and slope failures observed in Sri Lanka

According to National Building Research Organization (NBRO) of the 65,000 sq. km of land extent of Sri Lanka an area of nearly 20,000 sq. km, encompassing 10 Districts are prone to landslides. It is about 30 % of the land area of the country spared in to districts such as Badulla, Nuwara Eliya, Kandy, Matale, Ratnapura, Kegalle, Kalutara, Galle, Matara and Hambantota. In addition, some parts of Kurunegala district also has shown some vulnerability. In 2016, landslides resulted in the loss of around least 50 lives and affected almost 4000 families. Landslides also destroyed over 110 houses in 2016 and caused a loss in income for over a million people dependent on agriculture, trade and industries. In May 2017, 35 major landslides occurred causing most number of deaths out of all the disaster events recorded within the country.

The mode of failure of reported landslides, depends on the material type, the structure of the material (bedding, joints, and the orientation of these planes of weakness), and the topography and slope gradient. Different modes of failure within soil formations can also combine in to complex failure mechanisms. Soils tend to fail in rotational slides along the radius of the sphere with the lowest factor of safety. They can also fail along planes of weakness, such as the interface between rock and soil. In addition, part of Rock formations also tends to fail along pre-existing planes of weakness such as joints or bedding planes.

There is no proper classification of landslide types proposed for Sri Lanka but different failure modes such as falls, slides, creeps, debris flows and lateral spreads within sub-soil mass as well as topples within rock masses are found to be common. Among them, most common types of landslides seem to be the debris flows and minor cutting failures along the main road network. There are also shallow as well as deep seated landslides as well as raid and slow-moving landslides, witnessed in different parts of Sri Lanka.

Figure 1-1 Debris Flow - Landslide at Aranayake (a) and landslide at Meeriyabadda (b) (Dulanjalee, 2018)

Figure 1-2 Failure of cut slope about 7 m in height in close proximity to the railway line in Ihalakotte – Balana (Mampitiyaarachchi, *et al.*, 2018)

Figure 1-3 Location with rockfall threat. Kandy - Mahiyangana – Padiyathalawa road between culverts 55/3 and 55/6 (Source: http://nbro.gov.lk/)

1.5. Factors triggering landslides in Sri Lanka

A landslide trigger decreases the factor of safety to less than one. When the factor of safety is less than one, driving forces are greater than resisting forces, and failure will occur. Triggers include both natural and human-caused events. Human induced triggers include removal of the toe of the landslide through excavation, loading of the head of the landslide (addition of mass), and artificial vibration. Natural triggers include toe removal through erosion, changes in water pressure, and earthquakes. Any of these potential triggers can also combine to cause failure.

Precipitation

An increase in precipitation will increase the ground saturation which will raise the ground water table on one hand and on the other hand reduce the shear strength of the soil mass and increase the weight of the soil mass.

Weathering

Weathering is the natural processes of rock deterioration which produces weak material that can be susceptible to land sliding. It is caused by the chemical action of air, water, plants, bacteria etc. and the physical action brought on by changes in temperature (expansion and shrinkage), the freeze-thaw cycle etc.

Drawdown of water levels

Rapid lowering of water levels in coastal areas or along river banks due to tides or river discharge fluctuations can cause underwater land sliding. The process in which weak river banks are unsupported as the water level drops which is known as "drawdown" is often seen as a main disaster in countries such as Bangladesh, Lao PDR, Cambodia as the farmer community is deprived of lager chunk of farm land annually.

Rapid sedimentation

Rivers supply very large amounts of sediment to deltas in lakes and coastal areas. The rapidly deposited sediments are frequently under consolidated and have excess pore-water pressure and low strengths. Such delta sediments are often prone to underwater land sliding.

Human interventions

Human interventions triggering landslides are mainly associated with construction, changes of slope, and changes in surface water and ground water regimes. Changes of the slope often result from terracing for agriculture, cut and fill construction for roads, school or hospital buildings, house construction etc. If the activities are not designed properly by professional engineers in most cases such construction can increase the slope angle, decrease the lateral pressure, and load the head of a potential landslide. Changes in irrigation or surface runoff can cause changes in surface drainage and contribute to increase in ground water table. The ground water table can be also increased due to lawn watering, waste water effluent release, leaking water pipes, swimming pools, ponds etc. A high ground water level result in increased pore water pressure and decreased shear strength, thus facilitating slope failure.

Artificial vibration

Blasting carried out in rock quarrying can destabilize adjoining mountains and slopes clos by the quarry.

1.6. Landslide Hazard Zonation Mapping Project (LHMP) implemented by NBRO

NBRO implemented Landslide Hazard Mapping Project (LHMP), is continuing since 1990. The LHMP was initially funded by the UNDP and since 1996, the program has been funded by the government of Sri Lanka (GOSL). As an outcome of the LHMP, it is expected to produces hazard maps. Such project outcome helps to identify spatial distribution of landslide hazard and at present maps are available in 1:50,000 scale and 1: 10,000 scale. While 1:50,000 scale maps are available for Badulla, Nuwara Eliya, Kegalle, Ratnapura, Kandy, Matale, Kalutara, Galle, Matara and Monaragala districts, 1:10,000 scale maps are available for selected areas of above districts. Currently the mapping team is engaged in developing hazard maps in selected areas of Kurunagala, Nuwara Eliya and Matale districts.

The maps produced by the Landslide Hazard Mapping Project (LHMP) are currently being used in issuance of landslide early warning, reconnaissance study for suitability of land for development planning, detail landslide investigation work leading to landslide risk assessment, issuance of Landslide Risk Assessment Reports, and identification & prioritization of potentially dangerous sites for mitigation. The maps are also used in national and regional level planning by various institutions. Most of these maps are available for downloading free of cost in PDF format in the NBRO website (www.nbro.gov.lk)

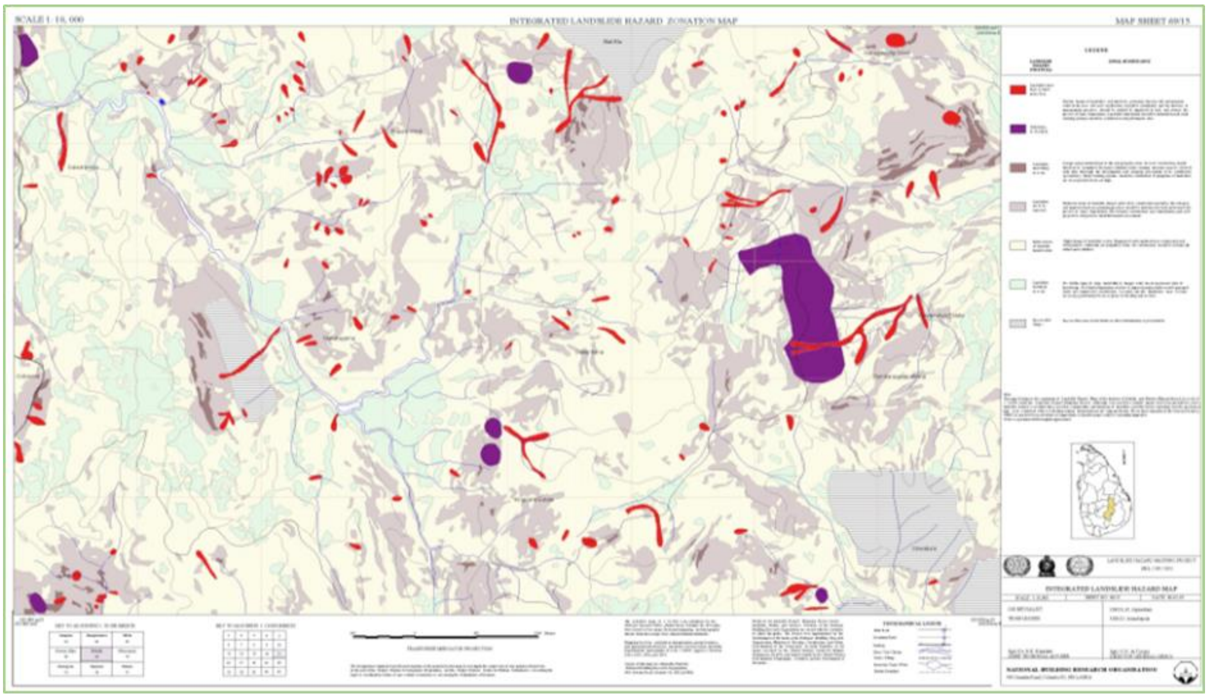


Figure 1-4 Sample of 1:10,000 LHZ Maps: Badulla District - Sheet No.6915

1.7. Nature-based Solutions (NbS)

In literature, there are many definitions for Nature-based Solutions. In this guidance document the definition put forward by "Natural Hazards – Nature-based Solutions" platform was adopted as it seems to be easily understandable by a general reader. The above web platform was developed by the World Bank, Global Facility for Disaster Reduction and Recovery (GFDRR) and Deltares. The URL link of the platform is https://naturebasedsolutions.org/.

Definition

Nature-based Solutions (NbS) are interventions which make use of natural processes and ecosystem services to address hazards such as floods, erosion and landslides. NbS can be completely "Green" (consisting of only ecosystem elements) or "Hybrid" (combination of ecosystem elements and conventional engineering measures).

Importance of NbS are highlighted in international agreements such as Sendai Framework for Disaster Risk Reduction (2015-2030) as an effective and sustainable technique to reduce disaster risk.

Arec-Mojica et. al. (2019) mentioned that NbS should not be considered as a single approach but an umbrella term for various ecosystem-based approaches. They further indicated thirteen different NbS approaches (Fig. 1.5) in reducing the risk of landslides after referring 55 NbS publications from two peer-reviewed bibliographic databases Scopus and Science Direct.

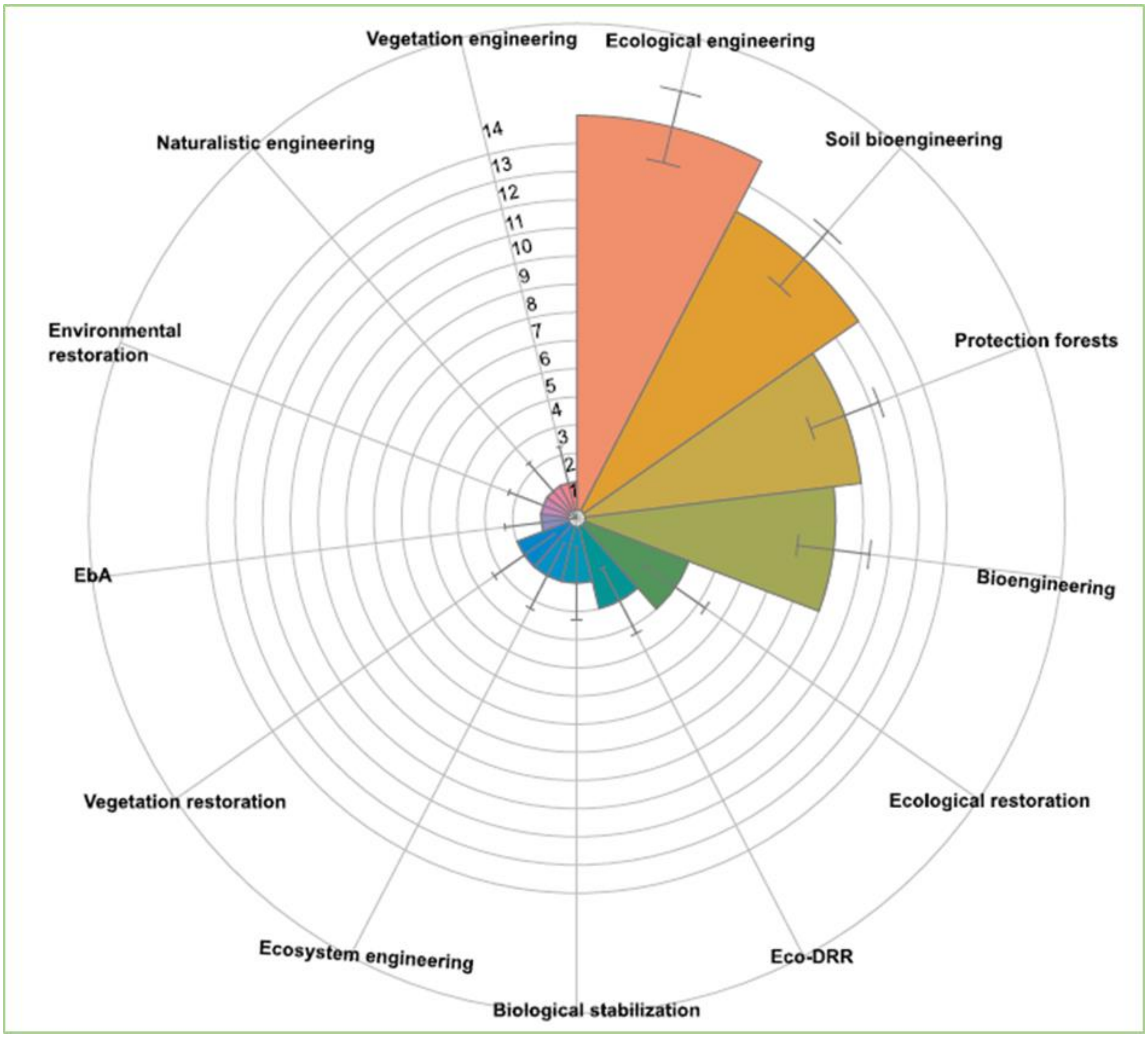


Figure 1-5 Different NbS approaches (Arec-Mojica *et al.*, 2019)

According to Figure 1.5, the most frequently mentioned NbS approaches were Ecological Engineering, Soil bioengineering and Protection forests. The authors had found several variants of similar concepts such as soil bioengineering, vegetation restoration and environmental restoration. They further mentioned that this type of different terminologies within the main NbS concepts are used by specific research communities or in connection with different natural hazards.

Nature-based Solutions are further defined by International Union for Conservation for Nature (IUCN) as “actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits”.

IUCN has proposed 8 principles of relevance to nature-based solutions (NbS), which are highlighted below:

1. Embrace nature conservation norms (and principles);

2. Can be implemented alone or in an integrated manner with other solutions to societal challenges (e.g. technological and engineering solutions);
3. Are determined by site-specific natural and cultural contexts that include traditional, local and scientific knowledge;
4. Produce societal benefits in a fair and equitable way, in a manner that promotes transparency and broad participation;
5. Maintain biological and cultural diversity and the ability of ecosystems to evolve over time;
6. Are applied at a landscape scale;
7. Recognize and address the trade-offs between the production of a few immediate economic benefits for development, and future options for the production of the full range of ecosystems services; and
8. Is an integral part of the overall design of policies, and measures or actions, designed to address specific challenge?

1.8. Integration of NbS in landslide risk mitigation and management

It is important to see how NbS approaches could be accommodated with the traditional measures initiated in Sri Lanka for managing landslide risk. The Landslide susceptibility maps described under section 1.6 above, when overlain with feature maps containing all exposure elements at risk (Population, housing, critical facilities, infrastructure, lifelines etc.), provides an indication of various at-risk elements located in a given area. That will provide exposure (in quantitative term) to landslide hazard with different degree of susceptibility (such as very high, high, medium, low). Depending on the degree of vulnerability of such exposure elements, the level of risk can be defined. The actions that are needed for reducing the risk has to be determined subsequently and there are two major decisions that can be taken in terms of reducing the existing landslide risk.

- Living with existing risk, with introduction of appropriate measures to reduce landslide risk.
- Safer Land use planning through the measures for reducing the exposure having undertaken various interventions including resettlement/relocation of vulnerable elements

Landslide susceptibility maps already developed by NBRO provides 04 hazard categories and delineation of such hazard categories spatially, can be done through prior conduct of landslide hazard assessment. Depending on the susceptibility/proneness to landslide hazard, among them 02 categories of land, has a high probability of occurrence of landslides where risk cannot be managed only through preparedness measures. Other two zones indicated as a modest level of landslides hazard and landslides not likely to occur need to be screened further for delineating the potential safe areas, where risk could be managed through preparedness measures.

The concept of safer land use planning is mostly applicable for areas, where the landslide susceptibility is very high, and high. There are several factors that need to be considered at each level of hazard potential. For example, when the susceptibility is very high and other options are not feasible and not cost effective, such areas could be subjected to resettlement to avoid exposure to potential landslides in future. However, the studies show that relocation of vulnerable families living in high landslide risk areas, need to be executed with careful consideration of socio-economic context in addition to other factors.

The Figure 1.6, presents the schematic diagram, indicating the possible options for landslide DRR. The general approach for living with risk is to create a safer environment through undertaking appropriate measures including preparedness and mitigation measures and enhancing the capacity for responding to landslide disaster situations. All risk mitigation measures could be categorized as structural, non-structural (including risk transfer) measures. The schematic diagram shows the possibility of integrating Green Nature-based solutions as one of the possible standalone practice or practice that can be applied in combination with other engineering measures or as a Hybrid approach for landslide hazard risk mitigation. The methodology, selection criteria, landscape design and application details related to nature-based solutions for landslide risk management is described in the following chapters.

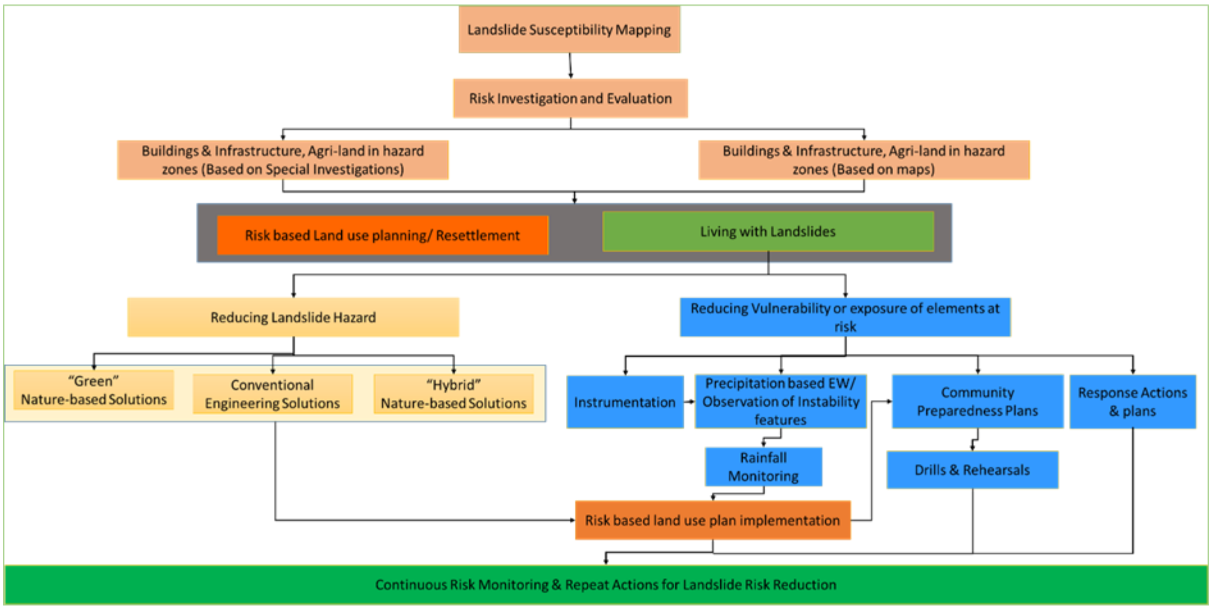


Figure 1-6 Schematic diagram for integrating Green/Nature based solutions as one of the possible standalone practices or in combination with other engineering measures as a hybrid approach for landslide risk management

CHAPTER 02

CLASSIFICATION OF MITIGATION MEASURES

NBLRM

Chapter 2 CLASSIFICATION OF MITIGATION MEASURES

2.1 Framework for landslide risk management

Until recently, disaster risk was perceived as a direct consequence of natural hazards. Gradually, disaster risk has come to be understood as a compound event, which lies at the intersection of hazards, exposure, and vulnerability of the exposed elements. At present it is a common understanding that with the influence of climate and global environmental changes, even the natural component of hazards is being altered by anthropogenic activities, changing hazard susceptibility, coverage, frequency, and severity.

The triggers of disaster events, associated with earthquakes, tropical cyclones, and most types of landslides, are rapid events. However, in most cases, disaster risk accumulation is slow and continuous over time. The UNISDR defines risk as the expected number of losses due to occurrence of a disaster event. This recognizes that disaster risk result from a series of independent components, associated with hazard type (which vary in frequency, intensity, duration, rapidity of onset type) and number of exposed elements (assets, population, environmental features); the vulnerability of the exposed elements (arising from various physical /structural, social, economic, and environmental factors). An increase in exposure, induced by population and economic growth and vulnerability due to above mentioned socio-economic and physical factors, are identified as main factors inflating future disaster risk. The SAFELAND Project that has been implemented in Europe for Mitigating landslides in vulnerable countries has proposed a framework for landslide risk management provided in Figure 2.1 below.

It summarizes the sequential approach for landslide risk management (Fell *et al.*, 2005; Hungr *et al.*, 2005 as cited in Safe Land, 2012). It is widely used internationally and has been adopted as the reference framework in the "Guidelines for landslide susceptibility, hazard and risk zoning for land use planning" published by Fell *et al.* on behalf of the JTC-1 Joint Technical Committee on Landslides and Engineered Slopes (Safe Land, 2012).

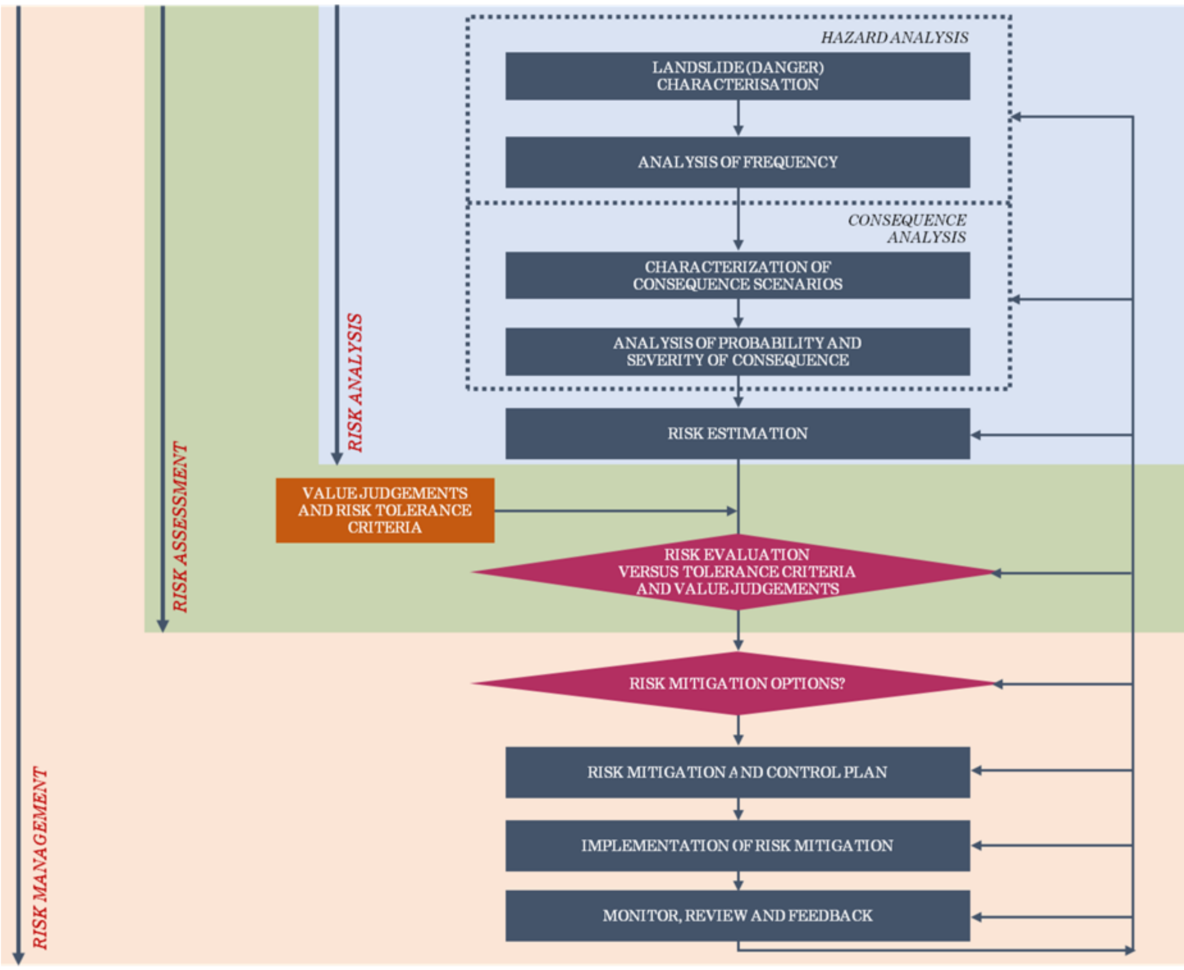


Figure 2-1 Framework for landslide risk management (Fell *et al.* as cited in Safe Land, 2012)

2.2 Risk transfer mitigation measures for different landslide types

As shown in Figure 2.1, the evaluation, implementation and control of mitigation measures fall within this framework and in fact complete and complement the risk analysis and risk assessment stages of the process and it is therefore useful to relate the classification of mitigation measures to the same principles and criteria used in the rest of the process.

Within the general domain of the mitigation measures classified here as

- "stabilization", i.e. reduction of hazard, it is possible to consider a further subdivision in relation to the triggering factors and mechanisms that each technique addresses. Other somehow related, widely used, classifications of stabilization measures include distinctions between:
- "active" and "passive" stabilization measures (Picarelli and Urcioli; Evangelista et al., as cited in Safe Land, 2012), in relation to whether the mitigation measures "actively" pursue an improvement of the stability of slope, or they "passively" intercept the run out when movement actually occurs, protecting the elements at risk.
- "hard" and "soft" stabilization measures (Parry et al. as cited in Safe Land, 2012), where "hard" is normally used to describe structural techniques that are visually obvious, while "soft" is normally used to describe techniques that are visually less intrusive and which improve the strength or other properties of the ground, such as its drainage capability. The terms "hard" and "soft" can

also be used in relation to the relative stiffness of the stabilization works and the surrounding soil, which results in the overall behavior of the stabilized slope being modelled as an equivalent continuum or as distinct materials. The terms “hard” and “soft” can also be used in direct analogy with the terms “structural” and “nonstructural”, with the same meaning of hardware and software, depending on whether the mitigation measure addresses tangible, material or intangible, “immaterial” aspects of the risk.

- “preventive” and “remedial” stabilization measures (Parry *et al.* as cited in Safe Land, 2012), relating to their relevance to different stages of movement (see Leroueil, as cited in Safe Land, 2012).

2.3 General approach for mitigation of landslides

Table 2-1 General classification of mitigation measures (Safe Land, 2012)

Classification		**Component of risk addressed**	**Brief description**	**Notes and other terms used**
STRUCTURAL	Stabilization	Hazard (H)	engineering works to reduce the probability of occurrence of landsliding	Preventive, remedial, hard, soft, active stabilization
	Control	Vulnerability (V)	engineering works to protect, reinforce, isolate the elements at risk from the influence of landsliding	Preventive, hard, soft, passive stabilization
NON-STRUCTURAL	Avoidance	Elements (E)	temporary and/or permanent reduction of exposure through: warning systems and emergency evacuation or safe sheltering, land-use planning and/or relocation of existing facilities	Direct temporary and/or permanent reduction of the number and/or value of elements at risk. Monitoring and warning or alarm systems and associated civil protection procedures, often described as reducing vulnerability, in actual fact operate through temporary, selective avoidance.
	Tolerance	Elements (E)	Awareness, acceptance and/or sharing of risk	Indirect reduction of the number and/or value of elements at risk

2.4 Criteria for selection of mitigation measures

The selection of the most appropriate mitigation measures to be adopted in specific situations must consider the following aspects:

- factors which determine the hazard, in terms of the type, rate, depth and the probability of occurrence of the movement or landslide, such as, for example:
  - the physical characteristics of the geosystem, including the stratigraphy and the mechanical characteristics of the materials, the hydrological (surface water) and the hydrogeological (groundwater) regime;
  - the morphology of the area;

- the actual or potential causative processes affecting the geosystem, which can determine the occurrence of movement or landslides;

- factors which affect the nature and quantification of risk for a given hazard, such as the presence and vulnerability of elements at risk, both in the potentially unstable area and in areas which may be affected by the run-out;
- factors which affect the actual feasibility of specific mitigation measures, such as, for example:
  - the phase and rate of movement at the time of implementation;
  - the morphology of the area in relation to accessibility and safety of workers and the public;
  - environmental constraints, such as the impact on the archeological, historical and visual/landscape value of the locale;
  - preexisting structures and infrastructure that may be affected, directly or indirectly;
  - capital and operating cost, including maintenance.

2.5 Mitigation measures at site-specific Level

Mitigation measures which aim to reduce the hazard must reduce the probability of triggering of the landslide(s) which the specific measure is intended to address. This type of mitigation measures is sometimes referred to as “stabilization”. The factors which determine the triggering of movements are:

a) decrease in shear strength $\Sigma\tau_r$
b) increase in driving shear stress $\Sigma\tau_d$

The most common causative processes are listed in Table 2.2 (adapted from Leroueil, 2001). Combinations of (a) and (b) often act simultaneously as a direct result of external processes, as in the case of basal erosion or excavations, which can cause both an increase in τ_d, through increased slope angle and/or height, or a decrease in τ_r, through a reduction in total and effective stress.

Table 2-2 Triggering factors with examples of common causative processes (adapted from Leroueil, as cited in Safe Land, 2012)

Triggering factor	Common causative processes
Decrease in shear strength τ_r	- Infiltration due to rainfall, snowmelt, irrigation, leakage from utilities - Construction activities, e.g. pile diving - Weathering (rebound/swelling, physical, chemical) - Fatigue and excess pore pressure due to cyclic loading
Increase in driving shear stress τ_d	- Erosion or excavation at the toe - Surcharging at the top - Rapid drawdown - Fall of rock onto the slope and other impulsive loading - Earthquake
Note: Many processes affect both τ_d and τ_r; association to one or the other in the table is indicative only	

In order to reduce the probability of triggering, mitigation measures which aim to reduce the hazard of landslides occurring must act in the system in the opposite direction, by:

A. increasing the resisting forces; and/or
B. decreasing the driving forces.

While this could provide a first step in the classification of this type of mitigation measures, it is more convenient to classify them on the basis of the physical process involved. In particular, it is here recommended to distinguish between the classes indicated in Table 2.3.

Table 2-3 Landslide Hazard Mitigation Measures (adapted from Popescu & Sasahara, as cited in Safe Land, 2012)

Physical Process	Brief Description
Surface protection; control of surface erosion	• Vegetation (hydroseeding, turfing, trees/bushes) & Nbs • Fascines/brush. • Geosynthetics. • Substitution; drainage blanket • beach replenishment; rip-rap. • Dentition
Modifying the geometry and/or mass distribution	• Removal of material from the area driving the landslide (with possible substitution by lightweight fill). • Addition of material to the area maintaining stability, with or without gravity, catilever, crib/cellular and/or reinforced soil walls. • Reduction of the general slope angle. • Scaling (removal of loose/unstable blocks/boulders).
Modifying surface water regime – surface drainage	• Diversion channels • Check dams • Surface drains (ditches, piping) to divert water from flowing onto the slide area. • Sealing tension cracks. • Impermeabilization. (*) • Vegetation. (*) • Nbs Note (*): associated with control of surface erosion
Modifying groundwater regime – deep drainage	• Shallow or deep trenches filled with coarse grained free-draining geomaterials and geosynthetics • Sub-horizontal drains • Vertical small diameter wells; self-draining (where they provide relief to artesian pressures or underdrainage to a perched acquifer) or drained by siphoning, electropneumatic or electromechanical pumps • Vertical medium diameter wells with gravity drainage through a base collector • Caissons (large diameter wells), with or without secondary sub-horizontal drains and gravity drainage • Drainage tunnels, galleries, adits, with or without secondary sub-horizontal or sub-vertical drains and/or as gravity outlet for wells drilled from the surface
Modifying the mechanical characteristics of	• Substitution • Compaction • Deep mixing with lime and/or cement

Physical Process	Brief Description
the unstable mass	• Permeation or pressure grouting with cementitiuous or chemical binders • Jet grouting • Modification of the groundwater chemistry
Transfer of loads to more competent strata	• Shear keys: counterforts, piles; barrettes (diaphragm walls); caissons • Anchors: soil nails; dowels, rock bolts; multistrand anchors (with or without facing consisting of plates, nets, reinforced shotcrete) • Anchored walls (combination of anchors and shear keys)

Some of the causative factors, mentioned above that cause a high level of hazard in a region may be different from one site to another, while some other factors due to fundamental natural conditions are not changeable. Inappropriate land use and drainage are two factors that can be changed.

A region of sloping ground with bare land subjected to severe surface erosion, shallow landslides or slope destabilization, slumping the ground etc. can be improved by introduction of surface drainage improvement measures with enhancement of sub-surface layers through bio-engineering measures utilizing vegetation types with a deep root system and good surface covering foliage. The ratings assigned for land use pattern and drainage will change for the better leading to a reduced hazard rating.

2.6 NbS for landslide risk mitigation

Different NbS categories which can be applied in landslide risk mitigation can be found in the web tool box developed by Norwegian Geotechnical Institute (NGI). This Landslide Risk Mitigation tool box can be accessed via www.larimit.com. Table 2.4 lists out the NbS categories applicable in landslide risk mitigation.

Table 2-4 NbS mitigation measures

Category - Physical process	NbS measure
Surface protection and erosion control - Living Approach	Hydroseeding Turfing Tree bushes direct/ pit planting (live transplanting) Live/ inert fascines and straw wattles Bush mattresses Bush layering Live Stakes (live poles) Live smiles
Surface protection and erosion control - Combined Living/ Not living Approach	Geotextile (Rolled Erosion Control Proucts) Drainage Blankets Beach replenishment/ nourishment Rip-rap Rock dentition
Modifying the surface water regime -	Terracing

Category - Physical process	NbS measure
surface drainage	
Modifying the surface water regime - surface drainage	Vegetation - hydrological effects Live pole drains Live/ rock check dams
Modifying the mechanical characteristics of the unstable mass	Vegetation - mechanical effects
Transfer of loads to more competent strata	Soil nail and root technology (SNART) - Hybrid
Retaining structures to improve slope stability	Vegetated gabions (Hybrid) Live crib walls Vegetated slope gratings
Passive control works for dissipating the energy of a landslide	Afforestation Live gully breaks

Information relevant to each of the above measures are described in (https://www.larimit.com/mitigation_measures/).

Main thematic areas available are:

- Description of the method,
- Advantages/ Disadvantages,
- Design methods,
- Suggested period of installation,
- Materials,
- Functional suitability depending on site specific characteristics

Examples of NbS in Sri Lanka

Some examples of such mitigation measures from several sites in Sri Lanka are provided below as Figure 2.2, 2.3, and 2.4

Figure 2-2 Slope protected with berm drains, cascade drains and surface protecting measure

[Different surface protecting measures; shotcreting and vegetation had to be used based on the prevailing conditions]

Figure 2-3 Nail heads connected by high tensile strength steel mesh and vegetation introduced by hydro-seeding with the help of coir mesh

Figure 2-4 Different surfacing options

[Full face shotcreting or/and application of bio-engineering after connecting nail heads with beams]

CHAPTER 03

ROLE OF PLANTS IN IMPROVING SLOPE STABILITY AND MINIMIZING SOIL EROSION

NBLRM

Chapter 3 ROLE OF PLANTS IN IMPROVING SLOPE STABILITY AND MINIMIZING SOIL EROSION

3.1 Importance of a nature-based landslide risk management strategy

With landslides becoming increasingly frequent in Sri Lanka, importance of undertaking risk mitigation interventions is growing. In the past Sri Lanka has largely relied on engineering solutions on landslide risk management and the application of nature-based and hybrid (engineering in combination with nature based) approaches for landslide risk management is still limited. It has been demonstrated in many countries in Asia that the risk-informed nature-based solutions can be effective in reducing the occurrence and impact of such landslides.

The application of appropriate technologies in the sustainable management, conservation, and restoration of ecosystem to reduce disaster risk is an important aspect of natural resource management. A landslide is a natural phenomenon that can trigger a disaster if it occurs at an unexpected time or space. Management of landslides, and, particularly, protection against landslides, is conventionally treated as a resource-intensive activity. However, historical development of vegetation and nature-based techniques in erosion control have evolved to a broader context of bioengineering.

It is well known that vegetation plays an important role in protecting natural and artificial earth systems against shallow-seated landslides, surface erosion, and shallow mass-wasting in projects such as cut and fill slope stabilization, earth embankment protection, and small gully repair treatment.

Soil bioengineering is the use of plant material, living or dead, to alleviate environmental problems, such as shallow rapid landslides or eroding slopes and stream banks (Lewis et al., 2001). In bioengineering systems, plants are important structural components, rather than just aesthetic features. The bioengineering approach to slope stabilization requires a true partnership between engineering geologists, maintenance personnel, civil engineers, and landscape architects.

The application of bioengineering for slope stabilization and protection is now used world-wide as a nature-based, economical, and eco-friendly approach. In recent years, bioengineering solutions have effectively been implemented in many Asian countries, such as Nepal (Dhital *et al.*, 2013), Pakistan (Faiz *et al.*, 2015), India (Singh, 2010), and Sri Lanka (Bandara & Jayasingha, 2018; Balasuriya *et al.*, 2018). However, nature-based bioengineering solutions are often unique to particular ecosystems, thereby limiting their repeatability. Moreover, the selection and use of appropriate plants and vegetation for bioengineering applications have been overlooked due to the unavailability of proper selection criteria.

However, it should be noted that not all types of landslide can be mitigated through bio-engineering techniques alone. In deep-seated landslides, for example, factors such as the level of ground water table, the requirement of toe supports, and the direction of surface water outflow should be determined with care to minimize the landslide risk. Hence, it is better to plan a solution using both geo-technical and bio-engineering inputs, which can be defined as *hybrid approaches*.

3.2 Bioengineering and biotechnical stabilization techniques

The terms *soil bioengineering and soil biotechnical techniques* are used in concurrence. Soil bioengineering is a technique that uses plants and plant material alone, whereas biotechnical techniques use plants in conjunction with more traditional engineering measures and structures to stabilize slopes (Gray & Sotir, 1996) and are currently employed to alleviate shallow, rapid landslides and eroding stream banks (Lewis *et al.*, 2001). In addition to engineering, ecological, and economic benefits, both bioengineering and biotechnical techniques contribute to sustainable development practices as they enhance the aesthetics of the environment and reduce the ecological impacts of construction, maintenance, and operations (Fay *et al.*, 2012).

In soil bioengineering systems, plants (grasses and shrubs, especially deep-rooted species) are an important structural component in reducing the risk of slope erosion (Jiang, 2004). Soil bioengineering measures are designed to aid or enhance the reestablishment of vegetation (United States Department of Agriculture [USDA], 1992). The general perspective is that properly designed and installed vegetative portions of systems should become self-repairing, with only minor maintenance to maintain healthy and vigorous vegetation. Soil bioengineering frequently mimics nature by using locally available materials and minimal heavy equipment, and is an inexpensive way to treat slope stabilization (Lewis *et al.*, 2001).

The selection of plants or vegetation for bioengineering applications should consider the views of several disciplines and is often a collaborative exercise between soil scientists, hydrologists, botanists, engineering geologists, maintenance personnel, civil engineers, and landscape architects (Lewis *et al.*, 2001). The role of vegetation in protecting the soil from erosion has long been recognized (Morgan, 2005). The effectiveness of plants for erosion control, slope protection, and landslide prevention depends on the plant architecture and mechanical properties. Some plants will be more suitable than others for erosion control, but may be less effective against slope failures and landslides. Thus, the selection of suitable plant species to achieve the desired objective requires a careful balance of considerations. For each field site and each set of objectives, different factors should be considered.

Vegetation play an essential part in every eco-system and Fay *et al.* (2012) explains that soil bioengineering has several main functions such as:

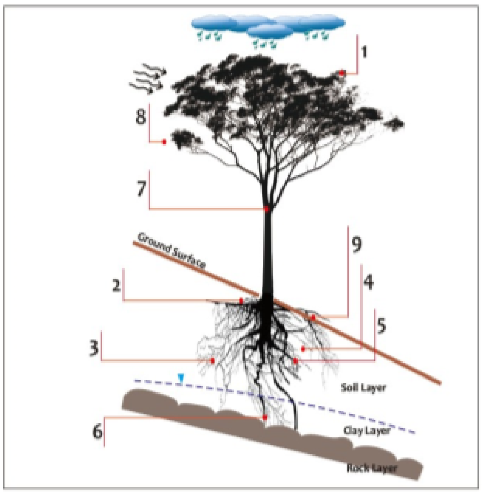
- Catching Material: When material moving down the slope (due to erosion or shallow sliding) the catching is done by the stems of vegetation. Movement can cause due to gravity alone or with the aid of water
- Armoring the slope against surface erosion due to run-off of water or rain splash. If a continuous vegetation cover can be made available it is easy to fulfil this requirement.
- Supporting the slope by propping from the base. The support is higher when there are more mature and larger grown up plants.
- Reinforcement by improving the shear strength of the sub-surface soil layer as a result of root system. But the qualitative assessment show that the reinforcement effect will depend on the root system.
- Drainage of soil mass: If the vegetation cover can contribute in draining excess water from the slope, it can avoid slumping of saturated surface material. This will depend on the distribution

and configuration of the plants over the surface and the effects of vegetation on the pore water pressure.

- Limiting the extent of the slope failure: since plant roots can hold the surface together it can prevent shallow failures.

3.3 Role of vegetation in bioengineering

The role of vegetation is to stabilize the slope with mechanical reinforcement of soils through roots as mechanical aspects and through the hydrological impact of the reduction of soil water content through transpiration and interception of precipitation (Ziemer, 1981; Greenway, 1987; Mulyono *et al.*, 2018). The hydrological and mechanical aspects of the vegetative contribution are shown in Figure. 3.1.



Number	Hydrological Mechanism	
1	Foliage intercepts rainfall, causing adsorptive and evaporative losses that reduce precipitation to infiltrate.	(+)
2	Roots and stems increase the roughness of the ground surface and soil permeability, thereby expanding the infiltration capacity.	(-)
3	The roots absorb water from the soil, which is released in to the atmosphere through transpiration mechanism that cause the pore water to decrease.	(+)
4	Depletion of soil moisture by the root adsorption may encourage the soil to crack, thus increasing the infiltration capacity.	(-)
	Mechanical Mechanism	
5	Roots reinforce the soil, increasing soil shear strength.	(+)
6	Vegetation roots anchor to the deep soil layer, providing support to the upslope soil mantle through buttering and arching.	(+)
7	The weight of vegetation increases the normal and downhill force components.	(+)
8	Plants exposed to the wind transmit dynamic forces to the hill.	(-)
9	Roots bind soil particles and reduce their susceptibility to erosion.	(+)

Figure 3-1 Hydromechanical effects of vegetation on slope stability (adapted from Mulyono *et al.*, 2018)

Plant evapotranspiration mechanisms serve as rainfall holders by maintaining the negative pore water pressure on the ground (Greenway, 1987). The higher the density of the canopy and leaf area, the greater the ability to catch rainfall (water interception) and interception reduces and delays rainfall to the soil surface (Mulyono *et al.*, 2018).

Shear stress, transferred in the ground into tensile resistance in the roots, carries out the mechanical soil reinforcement by the roots. Root condition also has a role in holding the soil layer. Fibrous roots help the plant hold the soil more strongly (Danjon *et al.*, 2008). In addition to plant root characteristics (Collison and Pollen, 2005), the magnitude of overall soil shear strength is also influenced by general soil conditions (moisture, clay fraction, porosity). A tree's roots will increase the soil shear strength via the tensile strength of its own roots and provide slope-shearing resistance during or after heavy rainfall on shallow landslides (Fan and Su, 2008).

The interaction between vegetation and soil does not always benefit the system because some interactions adversely affect stability. For instance, an increase in ground surface roughness by vegetation reduces the overland flow velocity, thus increasing infiltration. The infiltration process results in the presence of perched water on the boundaries of two differently permeable materials, which can increase the soil pore-water pressure and provide additional forces to soil mass movement

(Danjon *et al.*, 2008). Increased infiltration of water into the soil through the scar created by an uprooted or decayed tree can then lower the resistance of the whole soil. The wind pressure on a tree could also produce a destabilizing effect if the tree is not well anchored and can eventually cause slope failure (Li and Eddleman, 2002). Roots provide a better connection between soil particles in the soil body (tensile force on the surface), which results in cementation forces in the mass of the soil.

The growth habits of native plant species can greatly influence slope stability because each species has a unique rooting pattern and tensile strength. For instance, grass roots are very fibrous and abundant in the surface horizon, adding surface stability when grass cover is high. Grass and forb roots, however, add very little soil strength at deeper depths because their roots are not as strong and do not penetrate as deeply as tree roots (Gray and Leiser, 1982). Alternatively, the roots of shrub and tree species are long and deep, with relatively high tensile strength. The main advantage of tree and shrub species is their long vertical roots (taproots) that can cross failure planes and bind the soil strata together.

The sole purpose of plant establishment is not to limit the roles played by live plants. For example, biotechnical slope stabilization techniques use vegetative cuttings from easy-to-root species (e.g., *Gliricidia sepium*) to structurally reinforce the soil. As these materials root, they add further stabilization to slopes through interconnecting root systems and soil moisture withdrawal. Biotechnical slope stabilization practices include stake planting, pole planting, joint planting, brush layers, and branch packing.

Some of the beneficial and negative effects of vegetation on Slopes is provided below:

Table 3-1 Summary of the beneficial and negative effects of vegetation on slopes (Howell, 1999a)

Mechanical Mechanisms	**Effect**
Stems and trunks trap materials that are moving down the slope.	Good
Roots bind soil particles to the ground surface and reduce their susceptibility to erosion.	Good
Roots penetrating through the soil cause it to resist deformation.	Good
Woody roots bind fragmented rocks together.	Good
Woody roots may open the rock joints due to thickening as they grow.	Bad
The roots cylinder of trees holds up the slope above through buttressing and arching.	Good
Tap roots or near vertical roots Penetrate into the firmer stratum below and pin down the overlaying materials.	Good
Vegetation exposed to wind transmits dynamic forces into the slope.	Bad
Hydrological Mechanisms	**Effect**
Leaves Intercept raindrop before they hit the ground.	Good
Water evaporates from the leaf surface.	Good
Water is stored in the canopy and stems.	Good
Large or localized water droplets fall from the leaves.	Bad
Surface run-off is slowed by stems and grass leaves.	Good
Stems and roots increase the roughness of the ground surface and the permeability of the soil.	Site dependent

Mechanical Mechanisms	Effect
Roots extract moisture from the soil, which is then released to the atmosphere through transpiration.	Weather dependent

3.4 Root traits

A plant trait is defined as a distinct and quantitative feature of a species in terms of plant morphology, physiology, or biomechanics (Stokes *et al*., 2009). In addition to the general and specific qualitative features of plants, there has been an increasing focus on using plant traits as screening criteria to assist engineers in identifying suitable species for slope stabilization. Geotechnical engineers who wish to apply soil bioengineering techniques need to identify relevant plant traits for plant screening and selection in relation to the mechanical strength the system gains through bioengineering. Soil mechanical properties are generally most influenced by (i) the density of roots crossing the shear plane, (ii) the branching density throughout the soil profile, (iii) the total length of coarse roots above the shear plane, and (iv) the total volume of coarse root and fine root density below the shear plane (Mattia *et al*., 2005; De Baets *et al*., 2008; De Baets *et al*., 2009; Stokes *et al*., 2009; Ghestem *et al*., 2014a). During failure, fine, short, and branched roots slip through the soil rather than breaking. Moreover, a plant's hydrologic reinforcement also influences a plant's traits (Ghestem *et al*., 2014a). Simplified screening criteria can be drawn based on the available information on root traits (Figure 3.2).

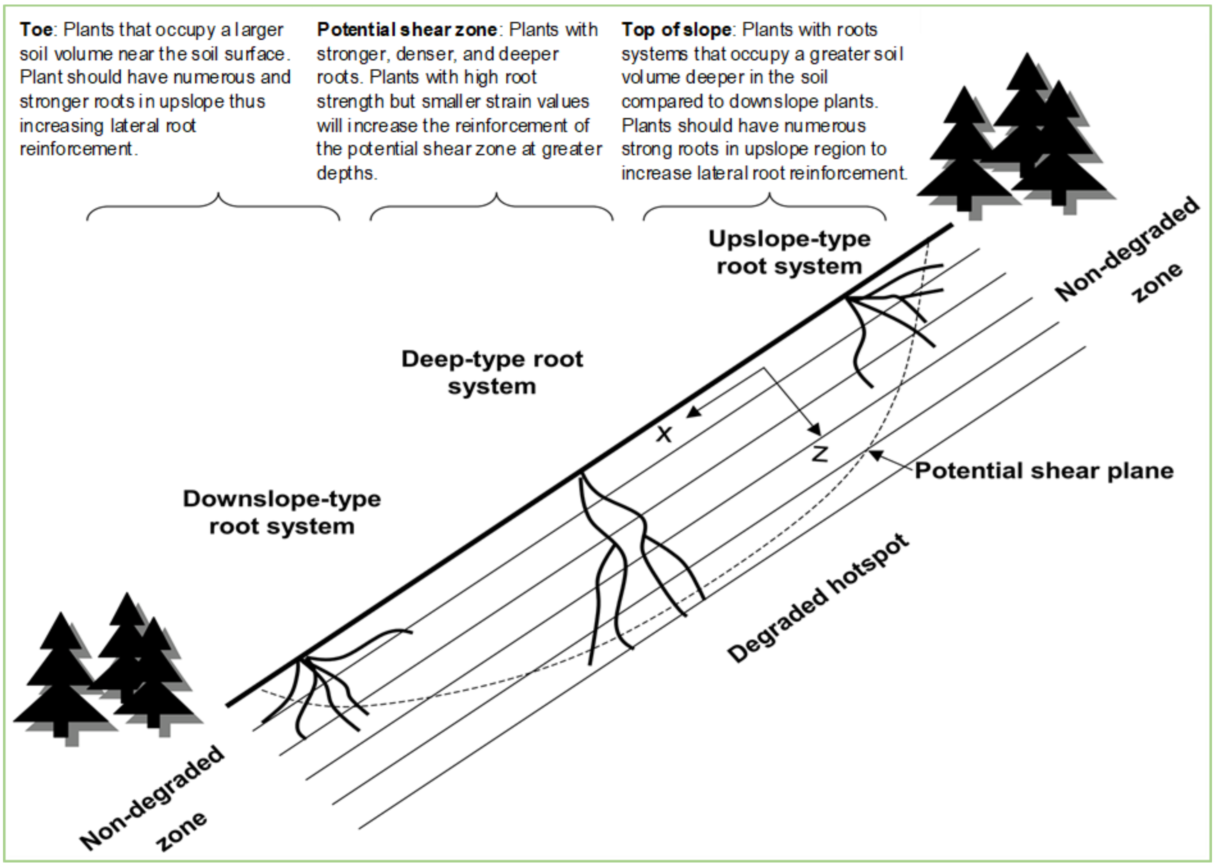


Figure 3-2 Simplified scheme for root trait-based plant species selection for bioengineering (modified after Ghestem *et al*., 2014a, 2014b)

Bio-engineering measures can perform certain engineering functions to support slope stabilization and minimize erosion. However, vegetation cover or plants cannot emulate all the functions offered by engineering solutions as there is a significant limitation in the growth of plant roots in particular the effective depth which could reach only several meters. Therefore, various plant types depending on their bioengineering characteristics can offer various functions that conventional engineering solutions can offer, but has its own limitations. Table 3.2 presents the engineering functions of vegetation as indicated by Howell (1999a):

Table 3-2 Engineering functions of vegetation (Howell, 1999a)

Bio - Engineering Function	**Requirements**	**Examples in Nepal**	**Civil Engineering Equivalent**	**Combination of Both**
Catch eroding materials moving down the slope, as a result of gravity alone or with the aid of water. The stems of the vegetation perform this function.	Strong numerous and flexible stems. Ability to recover from damage.	Micro scale: clumping grasses in contour grass lines. Large scale: Shrubs with many stems, Large bamboos.	Catch walls.	Catch wall with bamboos above
Armour the slope against surface erosion from both run-off and rain splash. To be effective, this requires a continuous cover of low vegetation. Plant with high canopies alone do not armour the slope (the terminal velocity of a rain drop is reached after a fall of only 2 meters, and some canopies generate larger rain drops.)	Dense surface cover of vegetation. Low canopy. Small leaves	Grass lines or a complete grass carpet of clumping or spreading grasses.	Revetments	Vegetated stone pitching
Reinforce the soil by providing a network of roots that increases the soil's resistance to shear. The degree of effective reinforcement depends on the form of the roots and the nature of the soil.	Plants with extensive roots with many bifurcations. Many strong fibrous roots.	Density rooting clumping grasses plated in lines. Some shrubs and trees.	Reinforced earth.	Jute netting with planted grass.
Anchor the surface materials by extending roots through potential failure planes into firmer strata below. If the potential failure is deeper than	Plants with deep roots. Strong, Long, vertically oriented roots.	Shrubs and trees which are deeply rooting.	Soil anchors	Combination of anchors and trees.

Bio - Engineering Function	Requirements	Examples in Nepal	Civil Engineering Equivalent	Combination of Both
about 0.5 meter, this is achieved only by large woody plants with big vertical roots (tap roots)				
Support the soil mass by buttressing and arching. Large heavy vegetation, such as trees, at the base of a slope can provide such support in the form of buttresses; or on a micro scale clumps of grass can buttress small amounts of the soil above them. Across the slope, a lateral effect is created in the form of arching: this is where the soil between buttresses is supported from the side by compression. The buttresses and arches of a building have the same engineering functions.	Extensive, deep and wide-spreading root systems. Many strong fibrous roots.	Large clumping bamboos; most trees	Retaining walls	Retaining wall with bamboos above
Drain excess water from the slope. The planting configuration of the vegetation can enhance drainage, avoiding saturation and slumping of material. Vegetation can also help to reduce pure-water pressure within the slope, by extracting water from the roots and transpiring it out through the leaves.	Plants small enough to be planted in closely-packed lines, Ability to resist scour High leaf area to enhance transportation.	Downslope and diagonal vegetation lines, particularly those using clumping grasses. Most shrubs and trees.	Surface or sub-surface drains.	French drains and angled grass lines.

CHAPTER 04

SITE-SPECIFIC LANDSLIDE RISK ASSESSMENT

NBLRM

Chapter 4 SITE-SPECIFIC LANDSLIDE RISK ASSESSMENT

4.1 Framework for conducting site-specific risk assessments

For sites having landslide threat, location specific technical data (Digital Elevation Model (DEM), geotechnical data, geophysical survey data etc.), socio-economic data, past hazard and loss assessment data, need to be collected as the 1st step. Subsequently, site visits have to be organized for verification of existing data and collection of additional data needed for site-specific susceptibility mapping. The steps that are followed in susceptibility mapping is provided in the flow diagram presented in Figure 4.1. The collected data will be used in development of large scale (preferably 1:2,000) site specific factor maps (soil formations, geology, slope gradient, land use, landform, hydrology etc.), deriving landslide attribute data and integrating them in a GIS environment for developing susceptibility maps. The validation will be done using NBRO landslide inventory for the particular district and undertaking a location specific flow-path analysis for the site.

The collected data in the field and during desk studies mentioned above and flow path assessment data will be used, to demarcate the probable area of influence of the landslide. Detail exposure elements in the shortlisted site including footprints of buildings will be prepared for the demarcated area and socio-economic data will be collected using a questionnaire survey instrument and interviews during transact walk within the area of probable impact. Development of exposure data bases will be carried out for all sites considering following:

- All elements at risk (houses, buildings, infrastructure facilities, lifelines etc.)
- Topography
- Hydrology (all natural and man-made elements) and ecological features
- Soil formations
- Socio-economic data related to populations likely to be exposed

The flow diagram summarizing the framework for site-specific risk assessments is given in Figure 4.1. For the selected site, site-specific repots including maps have to be prepared. In addition to information related to level of landslide susceptibility, the site-specific hazard and risk assessment reports shall contain the details of all exposure elements within the probable impact area, probable loss in case of landslide occurrence, socio-economic impacts etc. Additionally, future climate induced scenarios and its influence to site specific landslide susceptibility also need to be analyzed and included in the site-specific hazard assessment reports for selected sites. That way it is essential to capture the influence of future climate change induced scenarios in landslide susceptibility and provide predictions in site-specific hazard assessment reports for short listed sites.

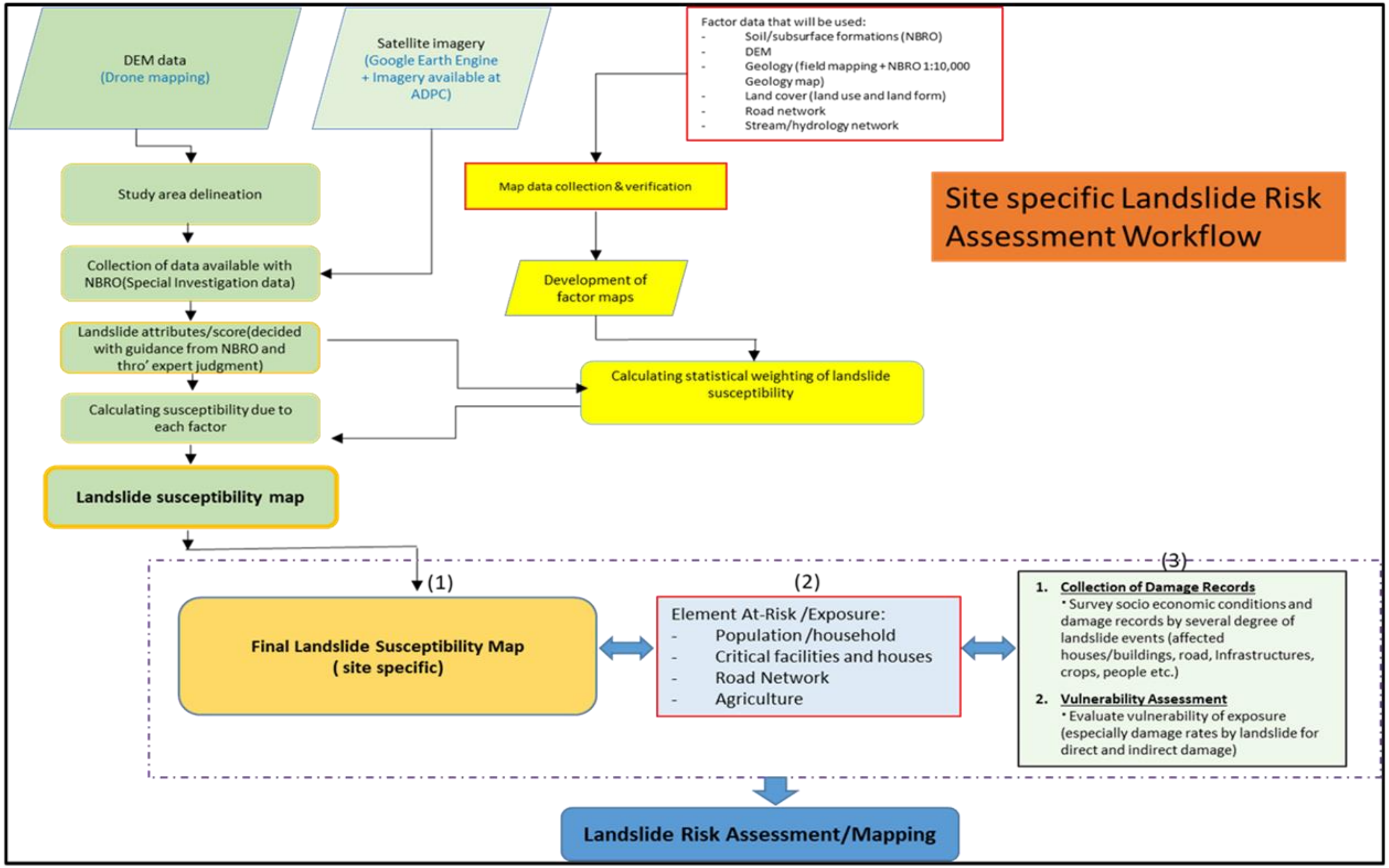


Figure 4-1 Framework for susceptibility mapping and risk evaluation for short listed sites

4.2 Case study: Socio-economic survey of exposure elements at risk

This case study was from two of the selected site under the World Bank funded Nature Based Landslide Risk Management Project in Sri Lanka.

(a) Site at Badulusirima in Badulla

The landslide at Badulusirigama is located within the premises of Uva Wellassa University in Badulla District. With respect to administrative boundaries, the area belongs to Badulla Divisional Secretariat and lies within Rambukpotha and Hindagoda Grama Niladhari Divisions

Figure 4-2 Aerial view of upslope of the landslide and Uva Wellassa University Premises

Table 4-1 Summary of elements at risk

Elements at Risk	Quantity
Total Number of buildings	95
Number of residents/occupants	355
Road length (minor and major roads) (km)	1
Power supply facilities (No. of High-tension line towers)	4
Water supply facilities (Transmission pipe length in m)	400
Vulnerable land extent (total area in sq. km)	0.08

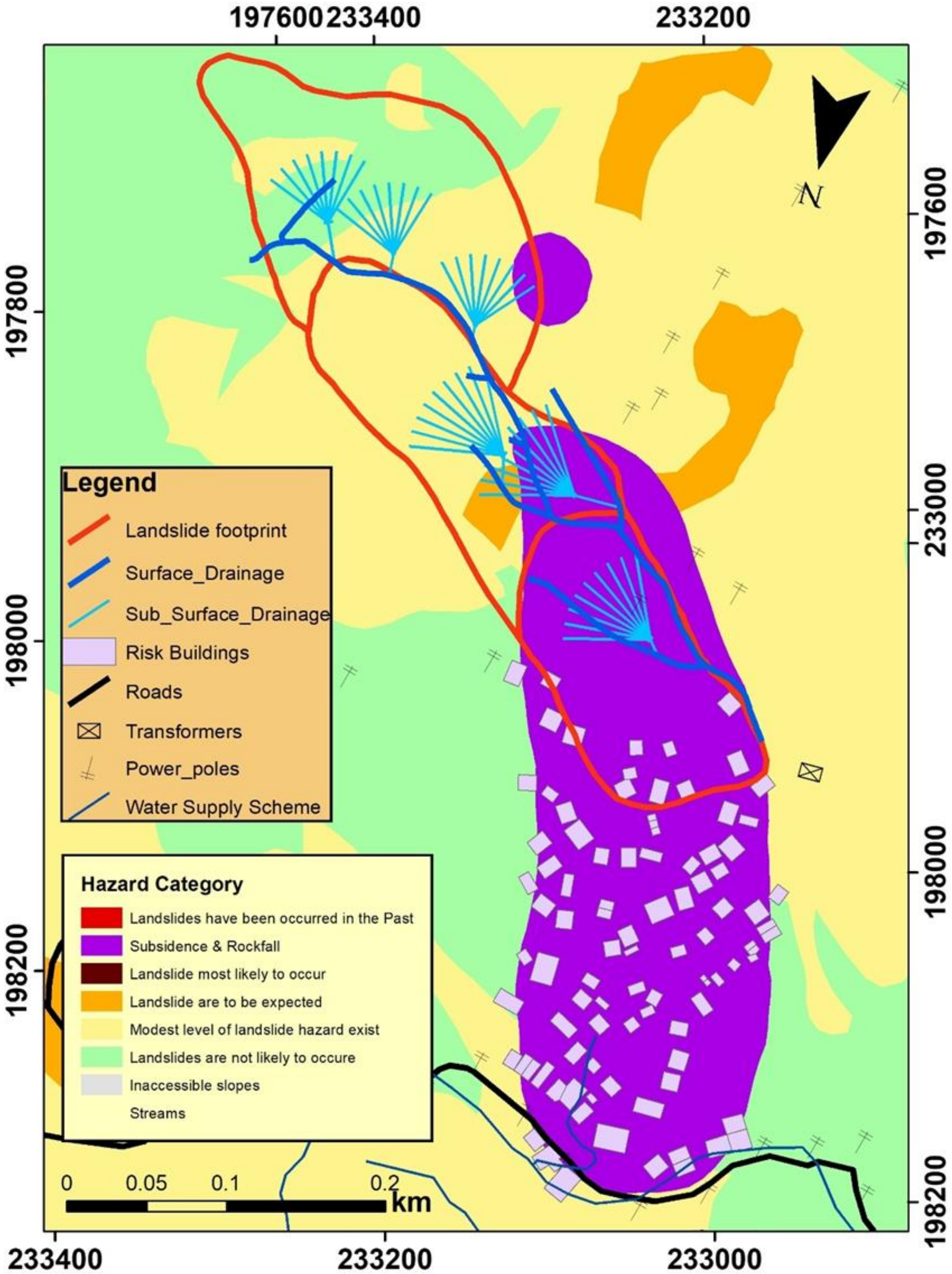


Figure 4-3 Map showing the spatial distribution of elements at risk in the study area overlaid on the landslide hazard zonation map

Main Findings of the building survey

1. Majority of head of households (56%) are male headed. About 73% of the heads are 50 years and older.
2. Major portion of the heads are engaged in Government sector employment.
3. 68% of the housing units are residential while 24% are Line Houses
4. Majority of them have been constructed during the period 1980-1990 where government organizations have acted as designer of the house.

5. Majority of the structures consist of Load Bearing Walls and Small Bricks were the major material of construction.
6. Major portion of the housing units consist of
   - cement floors
   - foundations mainly of rubble works
   - Wood roof structures with asbestos as the roofing material
   - Have a systematic drainage system
7. 69% of the units are located on a terrain with gentle slope while 31% of the units are located on steep slopes.
8. No landslide signs were observed in 58% of housing units, however cracks on buildings, stagnation of water and subsidence were observed in some units.
9. 71% of the respondents reported that they do not receive any instruction on disaster preparedness.
10. Most families prefer to relocate within the current GN division.

(b) Site at Galabada in Ratnapura

The site is located in Ratapura district belonging to Galabada Grama Niladhari Division. The site is owned by Galaboda Tea Estate which is under Hapugastenna Plantation, Finlay group.

According to information gathered from NBRO scientists at Ratnapura district office, the site has shown ground movements since 30 years back. The landslide has a width of around 50-55m and a length of 135m. Large movements were recorded in the year 2014 and 2016.

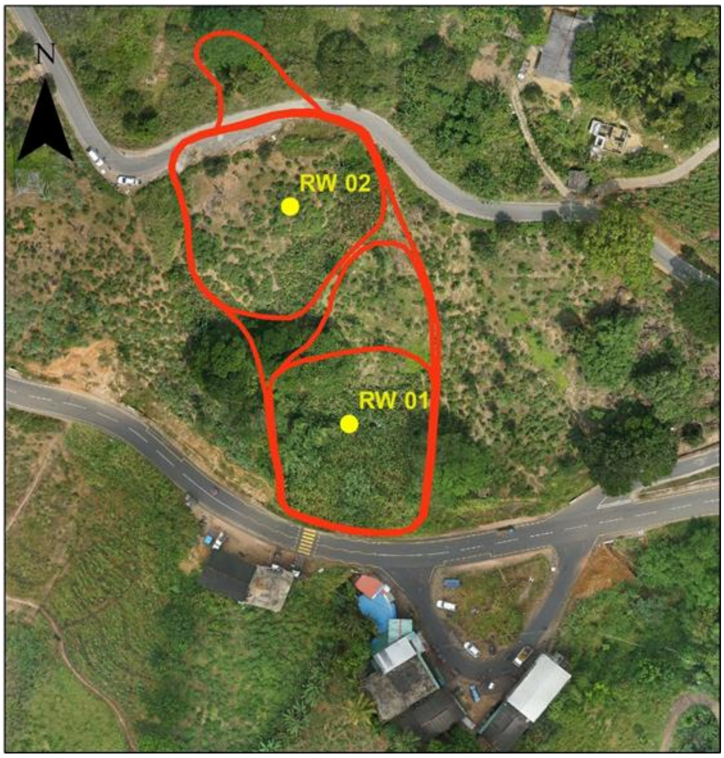


Figure 4-4 Landslide foot print at Galabada

The vulnerable land area to landslide hazard was identified using NBRO Landslide Hazard Zonation Map and after studying the Geotechnical data extracted from the investigation done by JICA in the year 2018. Accordingly, Figure 4.6 shows the land area vulnerable to landslide hazard delineated by a gray color circle. All the elements which falls in the given area were selected. Afterwards an analysis on socioeconomic aspects and physical characteristics of building units was carried out. The necessary data for the analysis were obtained by conducting a house by house questionnaire survey at site. The results generated are presented in following epigraphs.

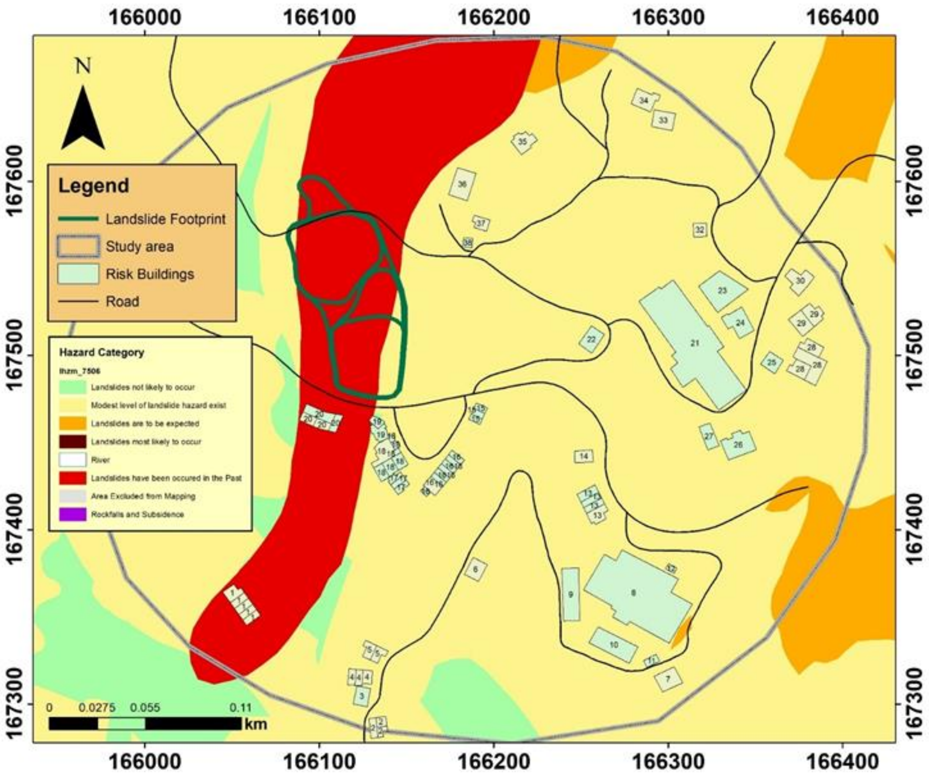


Figure 4-5 Map showing the spatial distribution of elements at risk in the study area overlaid on NBRO landslide hazard zonation map

Table 4-2 Quantitative measure of elements at risk

Elements at Risk	**Quantity**
Total number of building units	73
Number of residential buildings	33
Number of residents/ occupants	117
Number of commercial building units	25
Number of industrial building units	13
Number of building units which house institutions	2
Road length (km) Major Roads Minor Roads	 0.51 2.22
Number of Power supply facilities (High Tension line length in m)	403
Vulnerable land extent (total area in sq. km)	 0.15

Main Findings of the building survey

1. Majority of head of households (75%) are male headed. About 46% of the heads are of 40-50 age group while 39% are 50 years and older.

2. Major portion of the heads are engaged in Private sector employment.
3. 54% of the housing units are Line Houses while 35% are Residential Units.
4. Majority of them have been constructed before year 1990, where mainly masons have acted as the designer of the house.
5. Majority of the structures consist of Load Bearing Walls and Cement Blocks was the major material that had been used in construction.
6. Major portion of the housing units consist of
   - cement floors
   - foundations mainly of rubble works
   - Wood roof structures with asbestos as the roofing material
   - Do not have a systematic drainage system
7. 75% of the units are located on a rolling terrain while the rest on steep slopes.
8. No landslide signs were observed in 68% of housing units, however cracks on buildings were observed in some units.
9. 56% of the respondents reported that they do not receive any instruction on disaster preparedness.
10. Most families prefer to relocate within the current GN division.

CHAPTER 05

APPRAISAL OF POTENTIAL FOR THE APPLICATION OF NbS

NBLRM

Chapter 5 APPRAISAL OF POTENTIAL FOR THE APPLICATION OF NbS

5.1 Principals in application of NbS for landslide risk management

The most common NbS approach used in literature in addressing landslide hazard can be regarded as Soil Bioengineering (Dhital *et al.*, 2013, Gray & Sotir 1996).

Soil bioengineering is the use of plant parts (roots and stems) as main structural and mechanical elements in a slope protection system (Gray & Sotir, 1996). Such techniques are regarded as cost effective and nature friendly practices appropriate for stabilization of slopes mainly in South/ East Asian region of the world.

Bioengineering techniques improve slope stability by increasing the matric suction of the soil via root water uptake together with the evapotranspiration of their canopy. Further, the root network of plants provides mechanical reinforcement to unstable soil mass. Moreover, such techniques contribute to maintain ecological balance of landslide prone areas.

However, it is a well-known fact that nature-based solutions and/or hybrid solutions cannot be applied in every landslide case. Hence, there is a need for a developing a criteria for shortlisting sites in order to select the most appropriate location for implementation of Green NbS and Hybrid Solutions.

5.2 Site selection criteria for the application of NbS

Unstable sites with landslide symptoms must be studied in detail considering the factors such as socio-economic, risk escalating factors and geo-engineering in order to understand the socio-economic conditions, level of risk and the nature of failure mechanism before implementing green NbS and hybrid solutions. Mostly such solutions would be ideal for shallow & slow-moving landslides.

5.2.1 Description of the criteria

Five key factors were utilized in short listing of sites for application of NbS and hybrid solutions. Each of them is assigned with a weightage factor depending on their importance to application of plant species at site with the landslide threat. The priority weight of each factor was assessed quantitatively by using Analytic Hierarchy Process (AHP) developed by T. L. Saaty as recorded by Saaty, (1987) in his study.

The proposed site selection criterion together with weightage assigned to each factor is indicated in Figure 5.1

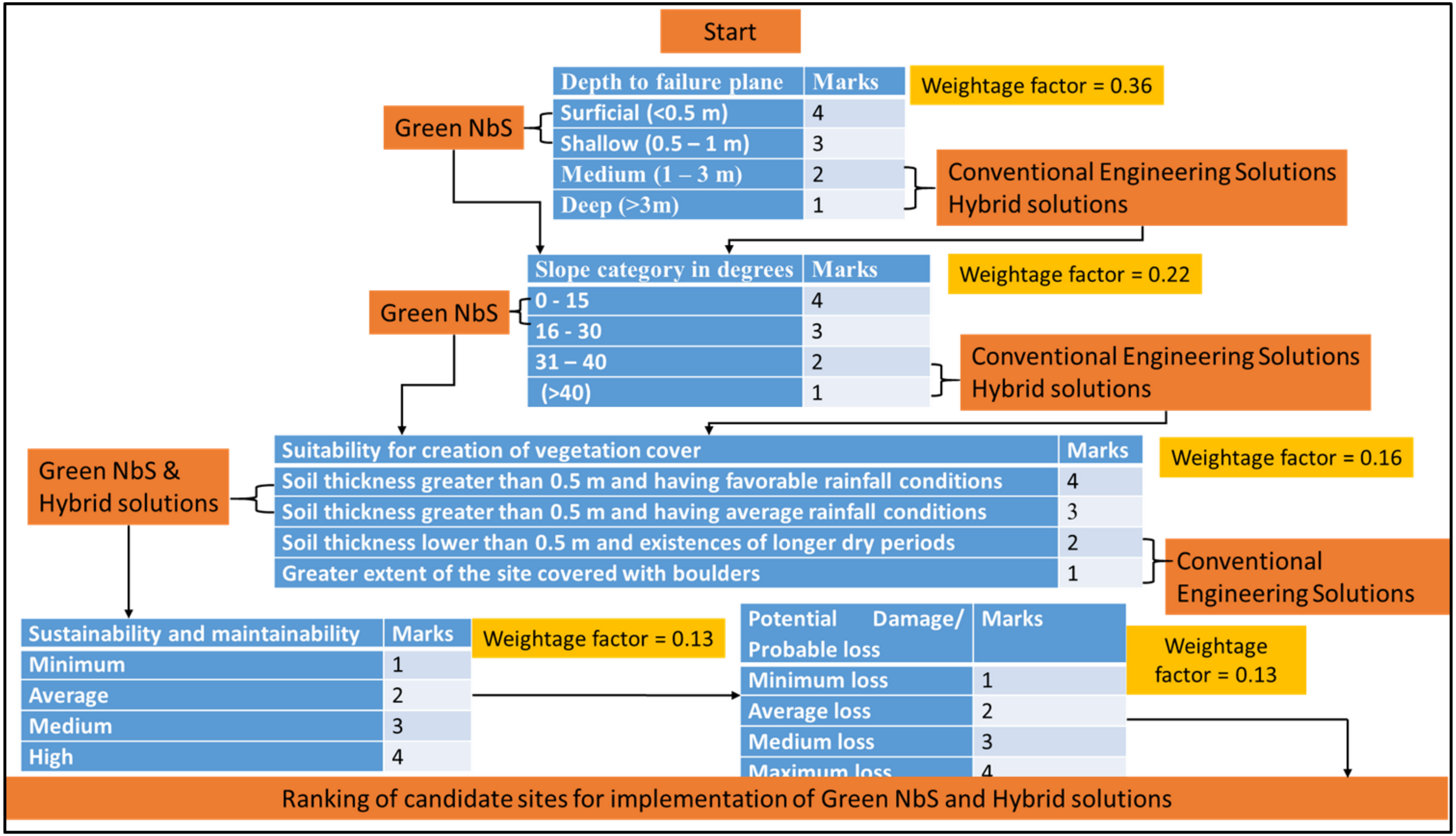


Figure 5-1 Site selection criterion

Depth to failure plane

The criteria have five categories and marks (from 0 to 4) are allocated to each category as shown in the Table 5.1. “Deep” category was given the lowest marks since, implementation of nature- based solutions are not very effective in such sites. However, nature-based solutions can be used to control the soil erosion rate and prevent the gullying effect.

Table 5-1 Scores allocated for depth to failure plane

Depth to failure plane	Marks
Surficial (<0.5 m)	4
Shallow (0.5 - 3 m)	3
Medium (1 - 3 m)	2
Deep (>3 m)	1

Slope range and category (in degrees)

Choi & Cheung (2013) mentioned that in Hong Kong vegetation was used as a slope surface cover in the upgrading of existing man-made slopes which are not steeper than 55 degrees. Further, it must be noted that with the increase of slope angle, the soil thickness tends to decrease which is a unfavorable factor for the growth of vegetation. Hence, considering the factors described above, marks are suggested for each slope category as shown in Table 5.2.

Table 5-2 Marks allocated for slope range

Slope category in degrees	Suggested marks
0 - 15	4
16 - 30	3
31 - 40	2
(>40)	1

Suitability for creating a vegetation cover

Factors such as soil thickness, presence of boulders and the climatic conditions of the present ecosystem are considered when issuing out marks for each category.

Table 5-3 Marks allocated for planting ability

Suitability for creation of vegetation cover	Marks
Soil thickness greater than 0.5 m and having favorable rainfall conditions	4
Soil thickness greater than 0.5 m and having average rainfall conditions	3
Soil thickness greater than 0.5 m and existences of longer dry periods	2
Greater extent of the site covered with boulders and/or soil thickness less than 0.5 m	1

Sustainability/ maintenance challenges

In the implementation of landslide hazard mitigation strategies using vegetation, it is vital to consider sustainability and maintenance challenges. Vegetation must be properly maintained in order for it to make a positive contribution towards slope stability. Therefore, it is better to pay more attention to the possibility of implementing a "build and watch approach" instead of the more common "build and forget approach".

If it involves higher maintenance cost or sustainability due to external factors, then application of vegetation-based techniques are not very conducive, hence, the score given will be very low. Further, the possibilities must be looked into whether an economic benefit can be generated from the proposed landslide prevention measure.

Table 5-4 Marks allocated for sustainability and maintainability

Sustainability and maintainability	Suggested marks
Minimum	1
Average	2
Medium	3
High	4

Probable loss considering the exposure elements at risk within the impact zone/sensitivity considering socio-economic, environmental, cultural aspects

It is important to prioritize the areas where the landslide risk is higher in carrying out hazard mitigation activities. An idea on probable loss in monetary terms considering exposure elements, socio-economic, environmental and cultural aspects is a good indicator to evaluate the magnitude of the risk. Higher the probable loss, greater will be the landslide risk. Marks can be assigned under this factor as given in Table 5.5.

Table 5-5 Marks allocated for sustainability and maintainability

Probable loss	Suggested marks
Minimum loss	1
Average loss	2
Medium loss	3
Maximum loss	4

5.2.2 Derivation of final score for the site

The scores allocated under each sub category must be multiplied by the corresponding weightage factor shown in Figure 5.1. The Final score can then be finalized by taking the weighted average.

$$Final\ Score = \frac{\sum_{i=1}^{n}[W_i * S_i]}{\sum_{i=1}^{n} W_i}$$

n - no. of criteria

W - Weight assigned to each criteria

S - Marks assigned to each criteria

The final score is based on a scale of 4.0. The site with the highest score against a threshold value of 2.0 can be considered as suitable for implementation of NbS and hybrid solutions.

The final score can be categorized into three categories of landslide risk mitigation measures based on the level of appropriateness of nature-based techniques. The different categories are shown in Table 5.6.

Further, the proposed site selection criteria can be used as a tool to rank candidate sites and decide on suitable landslide risk mitigation solutions.

Table 5-6 Different categories of landslide risk mitigation measures

Final score	**Landslide risk mitigation measures**
$4.00 \leq S_{final} < 3.00$	Landslide risk can be mitigated using nature-based techniques alone or together with small scale engineering structures only if required.
$3.00 \leq S_{final} < 2.00$	Landslide risk can be mitigated using hybrid solutions (combination of nature-based techniques and conventional engineering measures).
$S_{final} \leq 2.00$	Landslide risk can be mitigated using large scale engineering structures. Nature-based techniques can be used to control surface erosion and to improve aesthetic appearance.

CHAPTER 06

PLANT SELECTION

NBLRM

Chapter 6 PLANT SELECTION

6.1 Introduction

Plants form the nucleus of bioengineering techniques; thus, the selection of appropriate plants is the first move towards success. Plant trait-based selection is the best approach. First, the architectural features or structure of plant root systems play a significant role in shallow slope stabilization and erosion control (Reubens *et al.*, 2007). Second, the ecological significance, and particularly the compatibility with the surrounding environment, is important. It is well established that native plant species are preferred because they tend to tolerate drought and need little irrigation, fertilizer, pest and disease control, and demand less trimming (Dollhopf *et al.*, 2008). Low plant maintenance creates significant savings in labor, fuel, chemical use, and maintenance equipment costs. Finally, a mixture of compatible plant species is preferred over a single species as plant succession determines long-term ecological sustainability (Fay *et al.*, 2012).

Aboveground plant structure is as important as the belowground root system. The structure of aboveground vegetation plays an important role in stabilizing slopes by intercepting and absorbing water, retaining soil, retarding runoff velocity (by providing a break in the water's path), and by increasing surface roughness, rainwater interception and evapotranspiration (Schor and Gray, 2007). Each type of vegetation serves a critical function. Grasses, or herbaceous cover, protects sloped surfaces from rain and wind erosion. Shrubs, trees, and other vegetation with deeper roots are more effective at preventing shallow soil failures, as their roots and stems provide mechanical reinforcement and restraint and their root uptake and foliage interception modify slope hydrology (Ibid.). Where the main function of structural elements is to allow vegetation to become established and take over the role of slope stabilization, the eventual deterioration of the structures is not a cause for concern (USDA, 1992).

6.2 Rationale and scientific approach

Many types of plant and vegetation can be used to stabilize slopes and landslides, yet the best selection should be site-specific. This chapter provides a basic framework for plant selection for bioengineering solutions; however, the practitioners should be able to critically assess the worksite before making conclusions. Every worksite is unique, and it is critical to understand the site water, soil, and topography, as well as its socio-economic needs, before selecting an appropriate plant type for slope stabilization. To accomplish this, a full site assessment should be completed, one that provides information on the soil types and characteristics and surface and subsurface water conditions, and also takes into consideration short-term and long-term land use planning. Developers should consider using a multidisciplinary team with a diverse knowledge and experience base.

Information gained from the literature review was further developed by additional information from practitioners, scientists, and engineers on the current practices, effective practices, and emerging solutions being used nationally and internationally. Information gained from the literature review and additional sources was incorporated into this report as the body of the text, additional resources, references, current and effective management practices, useful points, photographs, and knowledge and research gaps. The plant manual (Chapter 7) provides a review of existing knowledge in the form of literature, expert interviews, field visits, and preliminary laboratory studies.

6.3 Natural vegetation types in landslide-prone areas of Sri Lanka

The landslide-prone areas of Sri Lanka are generally overlapped with wet and intermediate zones. In the wet zone, the dominant vegetation of the lowlands is tropical evergreen forest, with tall trees, broad foliage, and a dense undergrowth of vines and creepers. Subtropical evergreen forests resembling those of temperate climates flourish in the higher altitudes. Montane vegetation at the highest altitudes tends to be stunted and windswept.

At one time, forests covered almost the entire island but, by the late twentieth century, lands classified as 'forests' or 'forest reserves' covered only one-fifth of the land. The southwestern interior contains the only large remnants of the original forests of the wet zone.

6.4 Root-soil matrix

Roots are strong in tension, whereas soils are strong in compression but weak in tension; thus, the combined effect of soil and roots results in a reinforced soil. When shearing the soil, roots mobilize their tensile strength whereby shear stresses that develop in the soil matrix are transferred to the root fibers via interface friction along the root length (Gray and Barker, 2004) or via the tensile resistance of the roots (Ennos, 1990). There are several ways to assess the increase in soil shear strength: laboratory tensile tests, in-situ shear tests on root-reinforced soils, laboratory testing of root-soil composites, and modelling the root-soil interaction. Under the WB funded Nature Based Landslide Risk Management project, the simple laboratory tensile strength measurement has been adapted as the first step of an experimental series aiming to define parameters incorporating root traits in model simulations.

Strength of plant roots in landslide prone areas

Under the World Bank funded Nature Based Landslide Risk Management project, eleven plant species were selected for the first trial experiment. Then action has been taken to collect the root strengths of eleven plant species, from areas close to the Badulusirigama pilot site, a landslide prone area in Badulla. The root tensile strengths of the collected plant species were measured through laboratory experiments.

For each selected plant species, approximately 10 undamaged roots with an average diameter of 2 to 50 mm, and a minimum root length of 0.15 m were selected. To collect the roots, a few individual, medium-size plants, growing in the same microenvironment (same habitat, similar landscape position), were dug out using the dry excavation method. The roots were manually collected by careful excavation, and also by cutting the roots on exposed profiles (Figure 6.1). After excavation, the roots were individually stored in a plastic bag to preserve their moisture content. The collected root samples were immediately transported to the laboratory; however, the tested roots probably had slightly different moisture contents.

Figure 6-1 Root sample collection for laboratory tests

Root tensile strength tests were conducted in the laboratory using Dynamometer universal tensile and compression test machine (Model LW 6527, WC DILLON & Co Inc, USA) (Fig. 6.2). This device combines three functions: (1) traction force generation, (2) measuring load and displacement, and (3) data acquisition. Clamping is the most critical issue when measuring root strength. Roots with fleshy root epithelia could not be tested due to clamping problems, as the samples slipped without breaking. Also, direct mounting of roots causes grip damage to the roots. In this experiment, we wrapped cotton textile bandage around the griping ends of the roots to increase the grip and to minimize the damage to the roots.

Figure 6-2 Root tensile strength testing using Dynamometer

The initial root length was set to 150 mm. The root diameter was measured at both ends and the middle was measured using Vernier calipers or a micrometer. The elongation at the breaking point, load, and time taken for the test were recorded.

The following formula was used to calculate the tensile strength:

$$T_r = \frac{F_{max}}{\pi\left(\frac{D^2}{4}\right)}$$

where F_{max} is the maximum force (N) needed to break the root and D is the mean root diameter (mm) before the break.

6.5 Planning process

Plant species selection should be considered early in the process of planning the bioengineering solution. The tropical ecosystems host a diverse range of vegetation and plant species due to its variation in both soils and climate. Thus, not only the natural vegetation but also introduced plant species thrive well in tropical environments. However, for practical use, socio-economic stabilization and, long-term ecosystem sustainability of the sites and their surrounding environment, species selection should be made with care. Many widely occurring plants are inappropriate for soil stabilization because they do not protect the soil effectively, are not economical to establish or maintain, or because they are not quickly and easily established. Some plant types grow well in many soil types and climates, but others may require specific soil and/or climatic conditions. Plants that are preferred for some sites may be poor choices for others; some can become troublesome weeds.

In a broader context, the approaches to bioengineering solutions can be classified into two general categories: living and nonliving. The living approach uses live plant materials, while the nonliving approach uses geological, physical, and mechanical means. However, living and nonliving measures are often combined to form a complete system. Unlike many mechanical and physical structural designs, selection of proper plant species to integrate with the system requires numerous studies that are often costly and time-consuming. The need of a proper vegetation and plant selection criteria arises at the planning stage; thus, a comprehensive plant manual will assist planners with practical use.

This section provides a step-by-step description of plant selection for a given situation (Figure 6.3). The approach used in developing the plant manual is a six-step decision-making process and guides users to select appropriate plants for a worksite.

6.6 Aspects of concern

The foremost concern is to consider the plant community succession; in cases where planners wish to regenerate natural vegetation over a long period of time, planting early seral species at the beginning may work. In other cases, where the objective is to limit the number of vegetation to one or few species, it may be necessary to intervene immediately after seeding or planting in order to meet the revegetation objectives of the project. For example, short-term revegetation planning may require site preparation works, enabling particular vegetation to thrive while other species are suppressed. In the meantime, any move against natural succession may require regular intervention, such as the removal of any invasive species before they produce seeds or regenerative parts, gap filling and replanting, and even fertilizer application and pest control. If the plan is to use vegetation or plants that generate income through crop, fodder, wood, or timber harvest, the site could be managed as an agricultural field.

Controlling weeds and competitive vegetation increases the chances of target plant survival and rapid growth. However, decrease of vegetative cover by weeding reduces the rate at which water is withdrawn from the root zone. For example, grasses have a very fibrous root system in the upper soil horizon that allows them to withdraw moisture very quickly and efficiently, lowering the available water in the upper soil horizons. On the other hand, perennial forbs (herbaceous, broad-leafed plants) are generally less competitive than grasses because their root systems are deeper and less concentrated in the surface where the seedlings are withdrawing moisture. Therefore, the establishment of a combination of different plant species may create advantages for site stability and plant succession.

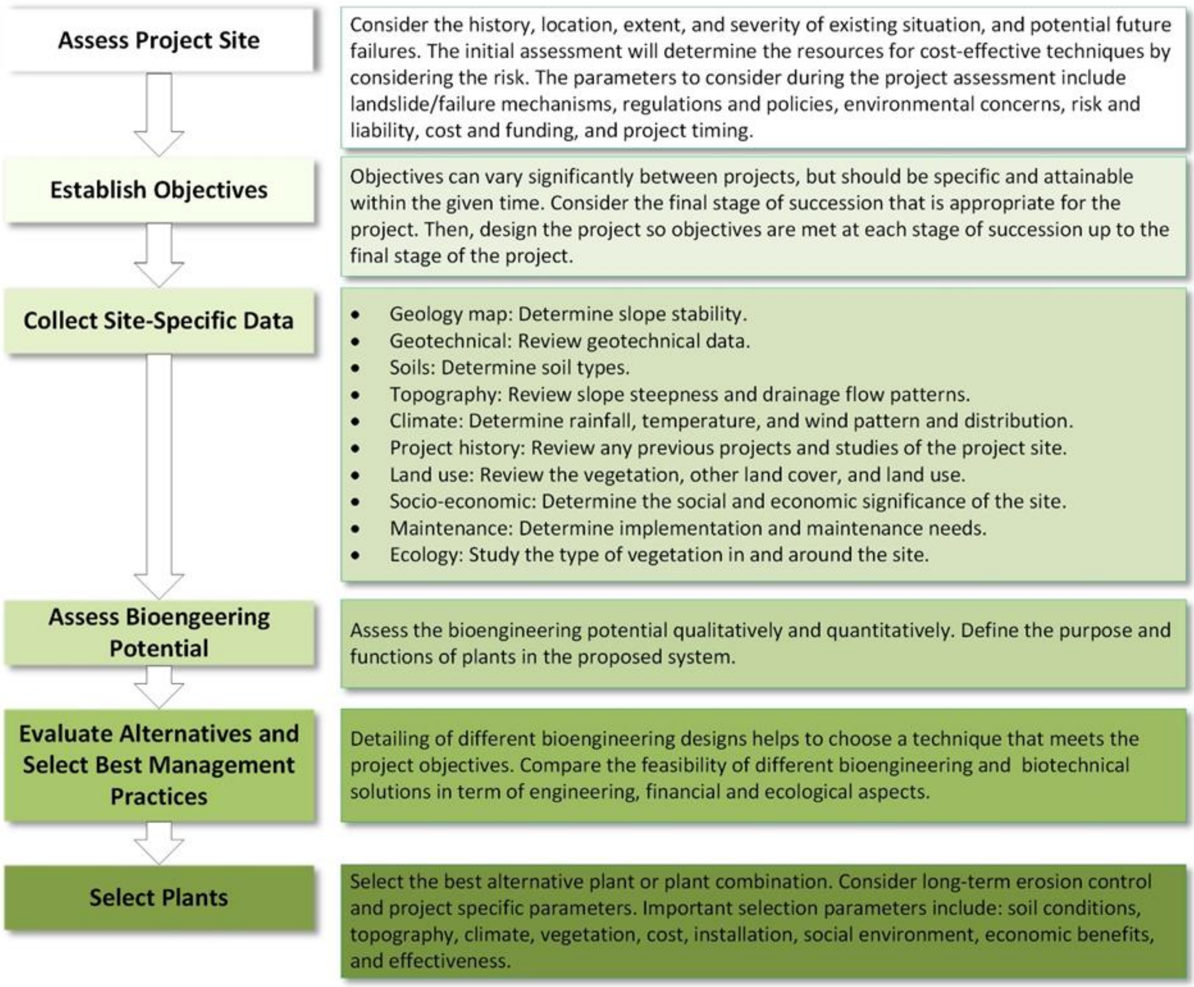


Figure 6-3 The six steps of the plant selection process

As discussed in previous chapters, the biological components of increased soil strength are the matrix of roots that reinforce the surface horizon, roots that anchor an unstable soil mantle to stable subsoils or rock, and stems that add support to the soil. However, desirable physical soil factors do not always support plant growth. Engineers and geologists regard high soil porosity as an undesirable characteristic, as high porosity soils have lower soil strength because soil particles are not packed closely together and interlock less. However, high porosity soils are of particular interest to the agronomist because of the role porosity plays in root growth. Therefore, balancing the needs of creating a healthy soil for optimum vegetation while still maintaining slope stability until established vegetation adds root strength to the soil is a challenge to engineers and revegetation specialists.

6.7 Types of plant

Soil bioengineering uses particular characteristics of plant components and integrates the specific characteristics of the soil and geomorphology of the site. The resulting soil-plant system and its components have benefits and limitations that need to be considered prior to selecting the appropriate plants for use. The following sections describe typical plant types and specific characteristics that need to be considered when selecting a plant species or several plant species in combination.

6.7.1 Herbaceous species

Herbaceous vegetation, especially grasses and forbs, offers long-term protection against surface erosion on slopes. Herbaceous vegetation has been used extensively as an erosion control measure as it exhibits excellent surface coverage, shallow soil reinforcement, rapid regeneration, and high evapotranspiration. These positive characteristics are due to several factors: they bind and restrain soil particles in place by their dense fibrous root structure, they reduce sediment transport by physical entrapment by aboveground stems and leaves, they intercept raindrops by thick foliage cover, they retard the velocity of runoff by increased drag from stems and leaves, and they enhance infiltration capacity by slowing overland flow velocity. Herbaceous species are almost always used in conjunction with soil bioengineering projects to add protection against surface erosion. Grass and forb species can become quickly established on drier sites, but soil strength is limited to the surface of the soil profile where the roots are most abundant. For this reason, grasses and forbs do not provide much stability. Consequently, herbaceous vegetation provides only a minor protection against shallow mass movement.

6.7.2 Woody tree species

More deeply rooted woody vegetation provides greater protection against shallow mass movement by mechanically reinforcing the soil with roots, depleting soil water through transpiration and interception, and buttressing and soil arching from embedded stems. Deeper-rooted woody perennials improve the mechanical reinforcement of soil at depth. While these species are slower growing, they usually have deeper root systems and persist longer once they are established. Ecologically appropriate plant materials are those that exhibit ecological fitness for their intended site, display compatibility with other members of the plant community, mediate succession, and demonstrate no invasive tendencies. If sites are to be restored to the natural landscape, individual species can be used to provide a significant contribution to mitigating hillslope instability during the early stages of stabilization. However, allowing succession to occur, and the replacement of pioneer plants by later successional communities, is highly desirable. Pioneer shrub and tree species are often short-lived and unable to reproduce in their own shade and may only enhance stability for a limited period. Nevertheless, trees may fall due to winds and localized instabilities. Therefore, if trees grow too tall for a fragile slope, they may need to be pruned or felled to ensure that the integrity of the slope (or engineering structure) is not compromised.

6.8 Ecological, management, and economic criteria

The root traits and plant-specific characteristics alone will not make the best selection. The practitioners will have to consider ecological, management, and economic criteria before making the final decision on plant selection. Table 6.1 details some criteria that may assist plant selection from the list of plants shown in Annex 1.

Table 6-1 Plant species selection based on objective criteria

Criteria	Description
Nativity	If the revegetation objective is to establish native plants, then species on the comprehensive species list (Annex 1) are first sorted by whether it is native or not.
Workhorse species	Workhorse species is a term used to describe locally adapted native plants that: (1) have broad ecological amplitude, (2) have high abundance, and (3) are relatively easy to propagate. The species listed in Annex 1 may need to be evaluated for their potential as a workhorse species based on the project objectives and needs.
Availability of starter plant materials	Seeds, plants, and cuttings often have to be collected from the surroundings and supplied to the nursery or seed producer for plant production. Species that are difficult to obtain or collect are not good candidates.
Nursery and seed production	Species that are difficult to propagate in the nursery, stooling beds, or seed production fields do not make good workhorse species. Techniques to propagate native species are rarely available, but this is slowly improving. Therefore, refer to documented plant production protocols available in the literature and consult experts.
Field establishment	Some species do not perform well because breaking seed dormancy and obtaining good germination may be difficult. Other species, planted as seedlings, experience unusually high transplant shock that significantly reduces plant survival.
Expense	The total cost to establish the plants on the project site is the easiest measure of whether a species is a good candidate for bioengineering.
Monoculture or mixture of species	A mix of species is often developed for a specific ecological function or management objective. One of the best ways to develop a compatible mixture of species is to sort the comprehensive species list by ecological setting and succession. This will assemble species into groups that naturally occur together. From these groups, mixtures are developed based on project objectives, such as root traits, weed control, visual enhancement, conservation management, and erosion control.
Specialist species	Projects that involve special microclimates or soils may require a unique mix of specialist species, while other projects may require a specific species to meet a project objective.
Value/ productivity	If the objective is to establish economically viable and productive plants, selection should be based on ecological and socio-economic feasibility assessments.
Maintenance	Some species require regular maintenance even after the initial phases of establishment. This may include logging, trimming, and replanting. The availability of a mechanism for maintenance should be considered.

6.9 A simplified plant species selection framework

One of the main objectives of this manual is to propose a simple, yet useful, plant selection criteria for application both in slope stability and landslide mitigation works. However, it is unlikely that a simple guideline can consider all factors controlling the plant-soil interactions; therefore, this manual proposes some key plant characteristics to use.

The effectiveness of plants for bioengineering depends on the plant architecture and mechanical properties, particularly its root system (Morgan, 2005). Some plants are more suitable for slope stabilization than others, but the same species may have low ecological and economic significance. Thus, the selection of suitable plant species to stabilize slopes and, more importantly, a complementary mixture of species requires a careful balance of considerations. For each field site and for each set of objectives, the factors to be considered may be different.

The following architectural and mechanical plant properties will influence the interaction between vegetation and soil hydro-mechanical forces:

i. The structural characteristics of the individual plants, such as the size and shape of its stems and roots, the spatial distribution of its plant stems and roots within a plant stand, and the spatial pattern of plants along or at a site;
ii. The hydrological significance of the plants;
iii. The behavior of the plant during soil shearing, expressed by the tensile strength of its roots and the flexibility of both individual plant stems and the whole plant stand (Styczen and Morgan, 1995).

Additionally, the practitioners may be interested in the ecological and socio-economic significance of the plant species. Therefore, the framework considers the ecological and socio-economic significance of vegetation.

A representation of the multi-criteria framework used to select suitable species is presented below. The following five main criteria were selected to provide the appropriate information for plant selection:

1. Plant type and structural characteristics
2. Hydrological significance
3. Root strength characteristics
4. Ecological significance
5. Economic value

6.9.1 Plant type and structural characteristics

Plant architectural traits allow for the description of stem and root system morphology and topology, each of which influence slope stability. There is a wide range of plant types from millimeters-high small creepers to giant trees that that stand up to 50 meters. The height and mass of the plant influences the stability of the plant itself and also influences the interaction with the soil system. Generally, smaller plants, such as grasses, sedges, and creepers, produce lower biomass, and thus impose lower forces on soil systems. Massive trees put a great weight on the soil system that may confer additional stress on the soil system if the root system does not adequately support the aboveground biomass.

A plant's root system architecture and its individual soil volume is known at the root system's overall envelope, which is calculated by its maximum radius (horizontal extension) multiplied by its maximum depth (vertical extension), and thus quantifies the root spread of an individual on a slope.

Trees have deeper-seated effects and can enhance soil strength to depths of three meters or more, depending upon the root morphology of the species. Yen (1972) characterized the patterns of root growth in trees into five groups (Table 6.2).

Table 6-2 Patterns of root growth in trees (after Yen, 1987)

a) H-type: maximum root development occurs at moderate depth, with more than 80% of the root matrix found in the top 60 cm; most of the roots extend horizontally and their lateral extent is wide.	
(b) R-type: maximum root development is deep, with only 20% of the root matrix found in the top 60 cm; most of the main roots extend obliquely or at right angles to the slope and their lateral extent is wide.	
(c) VH-type: maximum root development is moderate-to-deep but 80% of the root matrix occurs within the top 60 cm; there is a strong taproot but the lateral roots grow horizontally and profusely, and their lateral extent is wide.	
(d) V-type: maximum root development is moderate to deep; there is a strong taproot but the lateral roots are sparse and narrow in extent.	
(e) M-type: maximum root development is deep but 80% of the root matrix occurs within the top 30 cm; the main roots grow profusely and massively under the stump and have a narrow lateral extent.	

6.9.2 Hydrological significance

Evapotranspiration and interception are the key phenomena that contribute to lower the development of excessive soil moisture during heavy precipitation events. Evapotranspiration is the combined process of the removal of moisture from the earth's surface by evaporation and transpiration from the vegetation cover. Evapotranspiration from plant surfaces is compared to the equivalent evaporation from an open water body. The two rates are not the same because the energy balances of the surfaces are markedly different.

The interception of the canopy of a vegetation cover is the rainfall which directly strikes the vegetation cover during a rainfall and other precipitation events. If it is assumed that some of the intercepted rainfall is stored on the leaves and stems and is later returned to the atmosphere by evaporation. The remainder of the intercepted rainfall reaches the ground either as stem-flow or leaf drainage.

In addition, prevention of soil detachment by rain drop is an important aspect of the tree canopy. Vegetation affects these properties by altering the mass of rainfall reaching the ground, its drop-size distribution, and its local intensity.

A recent study by Fan et al., (2017) revealed strong sensitivities of rooting depth to local soil water profiles determined by precipitation infiltration depth from the top (reflecting climate and soil), and groundwater table depth from below (reflecting topography-driven land drainage). In well-drained uplands, rooting depth follows infiltration depth; in waterlogged lowlands, roots stay shallow, avoiding oxygen stress below the water table; in between, high productivity and drought can send roots many meters down to the groundwater capillary fringe. This framework explains the contrasting rooting depths observed under the same climate for the same species but at distinct topographic positions.

6.9.3 Root strength characteristics

Numerous studies show that root reinforcement can make significant contributions to soil strength, even at low root densities and low shear strengths. Generally, soil apparent cohesion increases rapidly with increasing root density at low root densities but increasing root density above 0.5 Mg/m3 on clay soils and above 0.7 Mg/m3 on sandy clay loam soils has little additional effect (Styczen and Morgan, 1995). This implies that vegetation can have its greatest effect close to the soil surface, where the root density is generally high and the soil is weakest. Since shear strength affects the resistance of the soil to detachment by rain drop impact, and the susceptibility of the soil to rill erosion, as well as the likelihood of mass soil failure, root systems can have a considerable influence on all these processes. The maximum effect on resistance to soil failure occurs when the tensile strength of the roots is fully mobilized and when, under strain, the behavior of the roots and the soil are compatible. This requires roots of high stiffness or tensile modulus to mobilize sufficient strength and leads to the 8-10% failure strains of most soils. The tensile effect is limited with shallow-rooted vegetation, where the roots fail by pullout, i.e., slipping due to loss of bonding between the root and the soil, before peak tensile strength is reached. Tree roots penetrate several meters into the soil and their tortuous paths around stones and other roots provide good anchorage. Root failure may still occur, however, by rupture, i.e., breaking of the roots when their tensile strength is exceeded. The strengthening effect of the roots will also be minimized in situations where the soil is held in compression instead of tension, e.g., at the bottom of hill slopes.

6.9.4 Ecological significance

Vegetation types and their ecology vary considerably across climatic zones, soil types, and land use patterns. The intention of this manual is to take a specific approach to select vegetation for the establishment and maintenance of hill lopes, with the aim of slope stabilization and landslide risk reduction. To do this in detail would require an immense amount of space, hence the emphasis is on principles which local specialists can apply using local knowledge.

Establishment involves the process of obtaining a vegetation cover using seeding and planting techniques, including a period of aftercare until the vegetation is fully established. In some situations, the aftercare period has to be quite long (2-5 years). Maintenance requires periodic input and management in order to maintain the required vegetation in the required form, and to prevent unwanted effects.

In order to be able to assess whether biological construction techniques are likely to be feasible in any particular area, it is important to have a broad understanding of the natural vegetation cover and the way in which it closely reflects the interaction of natural conditions prevailing at any given location. Whatever the climatic zone, a combination of factors affects the choice of approach to the establishment and management of vegetation. Phytosociological (ecological) and environmental factors and constraints have to be reconciled with biotechnical (functional) requirements. Before selecting vegetation, a basic choice has to be made between two approaches:

1. Modifying the site or environmental conditions to suit the desired vegetation. (This is most appropriate when the situation requires a specific type of vegetation or when resources are not limited.)
2. Selecting appropriate species to suit the prevailing site and environmental conditions.

The first principle is that of succession: a sequence of developing plant communities from the first colonizers of bare ground, through a series of stages, until a stable natural vegetation or climax is reached. The direction and rate of succession depends mainly on environmental factors, particularly climate, but is also greatly influenced by the availability of plant propagules. Natural succession, therefore, involves a large element of chance, though most vegetation is affected by human activity to some extent. Establishment of pioneer communities, which have the required biotechnical properties and will develop to a suitable climax or sub-climax by natural succession, is a desirable means of natural vegetation development. Less management is required, sufficient only to ensure succession in the desired direction. It may be appropriate to introduce further species at a later time in order to encourage the required succession. The concept is more applicable to the situation where a practitioner wishes to establish natural vegetation over a long period of time.

Secondly, the role and success of an individual species within a community will depend on its strategy for establishment and growth, based on basic strategies for dealing with varying intensities of environmental stress (brought about by the availability of light, water, nutrients, temperature, etc.) and disturbance (arising from the activities of humans, herbivores, pathogens, damage, erosion, and fire). This concept is more applicable to a situation where a practitioner wishes to establish selected plant species with the aim of extensive interferences such as cropping and plantation.

In addition, the introduction of plant species that are not commonly found in the site location or the introduction of non-native species may interfere with the site as well as its surrounding vegetation. For instance, a plant may have excellent characteristics in terms of bioengineering properties, yet may be an invasive plant for a particular region or country. The socio-ecological limitations may hinder the selection of such plant species.

6.9.5 Economic value

Areas that have already been disturbed by landslides or have been identified as risk areas are not always non-productive lands. One might need to continue the land for production, particularly for agriculture, if the land supports livelihoods through agricultural production. Therefore, the selection criteria should have an economic criterion that can recognize the value of the plant to be established. Plants and vegetation generate direct and indirect economic benefits. The harvest of fruits, fodder, timber, or many other vegetative produces directly earn an income. The soil stability improvement, erosion control, aesthetics, and environmental benefits are key indirect considerations.

6.10 Simplified scale for plant species characterization

In order to select a species, the specific characteristics (attributes) of each plant have to be evaluated. The plant characteristics are often qualitative, thus straightforward comparison is a challenge. Thus, a simplified scale was developed for each attribute that contribute to the stability of the system in different ways.

Development of comprehensive scaling system is a complicate process. A plant that has greater potential for erosion control and soil covering may have a shallow root system that poorly contribute to soil reinforcement or nailing. On the other hand, a larger and deep-rooted tree reinforce the soil, but its own weight may add extra weight on the slope that contribute negatively to the system.

Following section present a comprehensive scaling system to account the positive or negative attribute of a species for a given location. The selection of plant species for a site primarily depend on the place where the plant is to be established, Top of the slope, the potential shear zone or toe of the slope. Because a plant that is suitable for the top of the slope may not be suitable for toe of the slope. Thus, it is recommended to follow the sequence shown below:

1. Identify the place that a plant is to be introduce; 1) Top of slope, 2) Potential shear zone, and 3) Toe. Figure 6.4 shows a schematic of three different zones.
2. Identify the type of plant (herb, creepers, grasses, shrubs, trees).
3. Allocate the appropriate score for three attributes of the plant type (Height score, Plant weight & wind effect, and soil-plant interaction). For example, if the vegetation is a Shrub that grow to a height of 1-2m, medium weight and good ground cover, which is to be planted on middle section of the slope, the scores will be: height score =1; plant weight & wind effect = 2; Soil-plant interaction = 2. The cumulative score for the plant type and structural characteristics of said plant is 5.

Table 6-3 Score matrix for plant type and structural characteristics

Plant type and structural characteristics	Height	*Score*			Weight & wind effect	*Score*			Soil-plant interaction	*Score*			Cumulative score
		Top	*Middle*	*Toe*		*Top*	*Middle*	*Toe*		*Top*	*Middle*	*Toe*	
1. Herbs (Rooted, non-woody, self-supporting, non-grass like plants)	>2m	2	2	2	Low	2	1	1	Excellent ground cover	4	4	4	
	1-2m	3	1	1	Low	2	1	1	Good ground cover	3	3	3	
	0.5-1m	4	0	0	Very low	3	0	0	Normal ground cover	2	2	2	
	0.1 -0.5m	3	0	0	Very low	3	0	0	Low ground cover	1	1	1	
	< 0.1m	1	0	0	Very low	3	0	0	Poor ground cover	0	0	0	
2. Creepers (Rooted, non-woody, creep on ground/support, non-grass like plants)	< 0.1m	0	0	0	Very low	3	0	0	Excellent ground cover	4	4	4	
	< 0.1m	0	0	0	Very low	3	0	0	Good ground cover	3	3	3	
	< 0.1m	0	0	0	Very low	3	0	0	Normal ground cover	2	2	2	
	< 0.1m	0	0	0	Very low	3	0	0	Low ground cover	1	1	1	
	< 0.1m	0	0	0	Very low	3	0	0	Poor ground cover	0	0	0	
3. Grasses (Rooted, non-woody, herbaceous plant in Gramineae, Cyperaceous and Gentianaceae families)	>2m	2	2	2	Low	2	1	1	Excellent ground cover	4	4	4	
	1-2m	3	1	1	Low	2	1	1	Good ground cover	3	3	3	
	0.5-1m	4	0	0	Very low	3	0	0	Normal ground cover	2	2	2	
	0.1 -0.5m	3	0	0	Very low	3	0	0	Low ground cover	1	1	1	
	< 0.1m	1	0	0	Very low	3	0	0	Poor ground cover	0	0	0	
4. Shrubs (Rooted, non-	2-5m	2	2	2	Medium	0	2	2	Normal ground cover	1	1	1	

Plant type and structural characteristics	Height	*Score*			Weight & wind effect	*Score*			Soil-plant interaction	*Score*			Cumulative score
		Top	***Middle***	***Toe***		***Top***	***Middle***	***Toe***		***Top***	***Middle***	***Toe***	
woody, self-supporting plant up to 5m high, multi-stemmed and branching at ground or near ground level)	1-2m	3	1	1	Low	2	1	1	Normal ground cover	1	1	1	
	0.5-1m	4	0	0	Very low	3	0	0	Normal ground cover	1	1	1	
	0.1 -0.5m	3	0	0	Very low	3	0	0	Good ground cover	2	2	2	
	< 0.1m	1	0	0	Very low	3	0	0	Good ground cover	2	2	2	
5. Trees (Rooted, non-woody, self-supporting plants over 2m high with one or few definite trunks normally branching above ground level)	> 20m	0	4	4	Very high	0	3	4	Poor ground cover	0	0	0	
	10-20m	0	4	3	High	0	3	3	Poor ground cover	0	0	0	
	5-10m	0	4	2	Medium	0	2	2	Poor ground cover	0	0	0	
	2-5m	1	3	1	Medium	0	2	2	Poor ground cover	0	0	0	
	<2m	2	2	0	Low	2	1	1	Poor ground cover	0	0	0	
Attribute score (Height+ weight & wind effect + soil plant interaction)			1				2				2		

4. Then, the hydrological significance of the said plant should be identified and allocate an appropriate score. For example, if the said plant is having moderate evapotranspiration, the appropriate score is 2.

Table 6-4 Score matrix for hydrological significance

Hydrological significance	**Evapotranspiration**	***Score***		
		Top	***Middle***	***Toe***
	Insignificant	0	0	0
	Low	1	1	1
	Moderate	2	2	2
	High	3	3	3
	Very high	4	4	4
Attribute score			2	

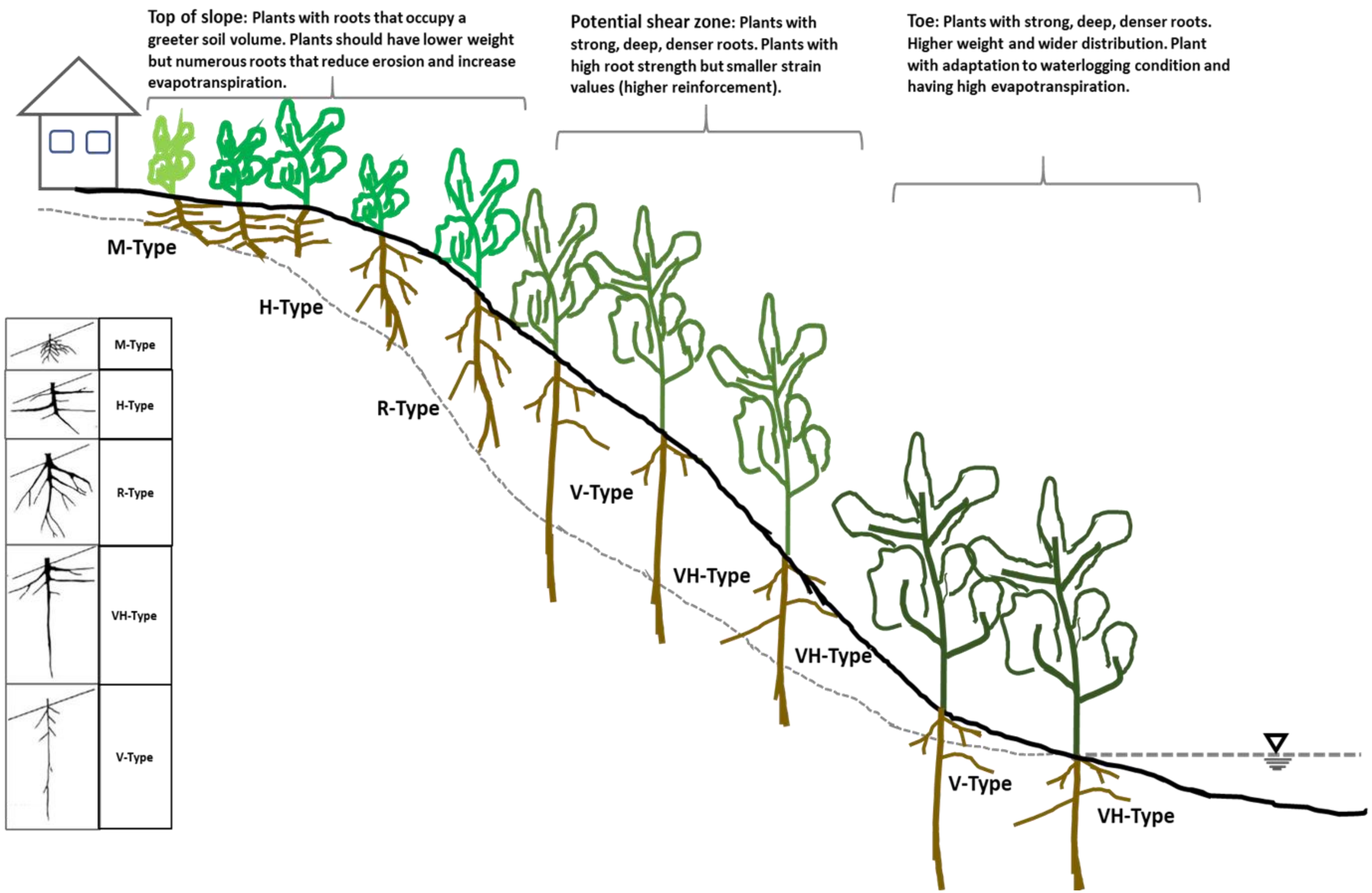


Figure 6-4 Three different zones of a slope that is to be stabilized using different plant species

5. The third plant characteristic is root strength characteristics. If the said plant can develop a VH type root system to 2-3m depth, the score for root depth is 3 and root type is 4. The cumulative score for root strength characteristics is 7.

Table 6-5 Score matrix for root strength characteristics

Root strength characteristics	**Root depth**	***Score***			**Root type**	***Score***		
		Top	***Middle***	***Toe***		***Top***	***Middle***	***Toe***
	>3m	4	4	4	VH type	2	4	4
	2-3m	3	3	3	V type	2	4	4
	1-2m	4	2	2	R type	2	3	2
	0.5-1m	4	1	1	H type	4	1	1
	< 0.5m	3	0	0	M type	4	0	0
Attribute score (Depth + type)			3				4	

6. The ecological significance of the selected plant is also an important factor to be considered. The ecological significance is made from three attributes: habited, succession and climate. For example, is the said species is a pioneer fast growth naturalized species best suited for wet climate, the score allocation is habited =2, succession = 4, and climate = 4.

Table 6-6 Score matrix for ecological significance

Ecological significance	**Habited**	***Score***			**Succession**	***Score***			**Climate**	***Score***		
		Top	***Middle***	***Toe***		***Top***	***Middle***	***Toe***		***Top***	***Middle***	***Toe***
	Native endemic	4	4	4	Pioneer fast growth	4	4	4	Wet climate	4	4	4
	Native	3	3	3	Fast growth	3	3	3	Wet & intermediate	3	3	3
	Naturalized	2	2	2	Normal growth	2	2	2	Intermediate	2	2	2
	Naturalized pioneer	1	1	1	Slow growth	1	1	1	Intermediate & dry	1	1	1
	Invasive	0	0	0	Very slow growth	0	0	0	Dry and arid	0	0	0
Attribute score (Habited + succession + climate)			2				4				4	

7. The last criterion is the economic value of said plant at the proposed location. If the said plant has indirect and low direct economic benefits, the score allocation for economic value is 2.

Table 6-7 Score matrix for economic significance

Economic significance	**Economic value**	**Score**		
		Top	***Middle***	***Toe***
	Very high indirect and direct benefits	4	4	4
	High indirect and direct benefits	3	3	3
	Indirect and low direct benefits	2	2	2
	Indirect only	1	1	1
	Unimportant	0	0	0
Attribute score			2	

8. As such, the said plant should be scaled for the five plant characteristics. The comprehensive attribute score should be calculated based on attribute prioritization procedure. The simplest scheme is to allocate equal weightage for each five characteristics and calculate the arithmetic summation of the attribute scores. For instance, the cumulative attribute of the said plant is shown in Table 6.8.

Table 6-8 Example of calculating final cumulative score by allocating equal weight for each characteristic

Characteristic	Attribute	Score	Attribute	Score	Attribute	Score	Cumulative	Weighing factor (w)	Final score
Plant type and structural characteristics	Height	1	Plant weight & wind effect	2	Soil plant interaction	2	5	0.2	1
Hydrological significance	Evapotranspiration	2					2	0.2	0.4
Root strength characteristics	Root depth	3	Root type	4			7	0.2	1.4
Ecological significance	Habited	2	Succession	4	Climate	4	10	0.2	2
Economic significance	Economic value	2					2	0.2	0.4
Final cumulative score									**5.2**

9. However, the contribution of each five characteristic cannot be considered equal in all instances. Therefore, the weighing factor (w) can be adjusted based on site-specific requirements. For example, if the designer expects to select a plant that should contribute to soil reinforcement and neglect the ecological and economic significance, the corresponding weighing factors can be adjusted accordingly. An example is shown in the Table 6.9 where more weights are placed on plant type and strength for the same plant.

Table 6-9 Example of calculating final cumulative score by allocating different weights for each characteristic

Characteristic	Attribute	Score	Attribute	Score	Attribute	Score	Cumulative	Weighing factor (w)	Final score
Plant type and structural characteristics	Height	1	Plant weight & wind effect	2	Soil plant interaction	2	5	0.35	1.75
Hydrological significance	Evapotranspiration	2					2	0.1	0.2
Root strength characteristics	Root depth	3	Root type	4			7	0.45	3.15
Ecological significance	Habited	2	Succession	4	Climate	4	10	0.05	0.5
Economic significance	Economic value	2					2	0.05	0.1
Final cumulative score									**5.7**

10. Likewise, the designer can evaluate the score of plant for different places of the slope based on different objectives linked to weighing factors.

This scaling process requires a detail description of each candidate plant species to be used. However, most of plant species have not been studied in detail, thus all the characteristics are not readily available. A sample list of plants that has been studied and characterized based on the proposed scheme is shown in Chapter 7.

CHAPTER 07

PLANT MANUAL

NBLRM

Chapter 7 PLANT MANUAL

7.1 Introduction

Ideally, a plant selection method should combine easily measurable plant traits with a sound geotechnical basis (Stokes *et al.*, 2009; Mickovski *et al.*, 2006), while the environmental variability at the plant, soil, and climate compartments is also considered. Geotechnical engineers, practitioners, landscape architects, land planners or restoration ecologists would benefit from effective plant selection criteria against landslides once an ecological evaluation of the candidate plants has been carried out (Evette *et al.*, 2012; Jones, 2013). Such a tool will permit to foresee long-term effects produced by different plant covers on slopes, the results of combining plant functional groups in restoration actions, or the responses under different soil and climate scenarios.

The objective of this plant manual is to assist professionals and practitioners concerned with planning and implementing soil bioengineering techniques by providing practical information on plant selection and use for a wide variety of situations.

7.2 Socio-economic, ecological and engineering significance of a plant manual

Sri Lanka is an island with a unique geomorphological setting that hills and mountains are concentrated within the central region, generally called central highlands. The highlands cover approximately 20% of land area and the elevation of the highlands ranges from about 300 to 2500 m. Due to its unique features, most of the major rivers have their main tributaries originating in the highlands and having radial flow pattern. The highlands were generally covered by evergreen tropical and mountain forests. There is no evidence of human habitation in the hill country above 1066 m up to the British period, ever since the disappearance of stone age peoples from these elevations (Deraniyagala, 1972). However, the hill country land use was changed from natural forest to plantation crops over a period of about a century (1830s to 1930s) under British colonial rule (Wickramagamage, 1998). This historical development has changed not only the environment setup but also the socioeconomic status of the country. Since the start of plantation cropping, the hill country was to undergo a rapid land use change: from lands predominantly under natural vegetation cover to lands predominantly under agricultural crops. The change of land use brought up issues such as accelerated soil erosion, slope failures and landslides (Wickramagamage, 1998). The issues were aggravated due to further transitions in recent history where plantation agricultural lands were rapidly converted to other urban uses such as home gardening, minor agriculture cropping, housing, roads and community infrastructures. Consequently, the environmental, economic and social issues caused by slope failures and landslides are increasingly recognized as a major natural hazard in recent Sri Lankan history.

Commercial tea plantations cover a vast land extend in hill country. Rubber plantations are often found in mid and low country regions of the island. Moreover, the recent changes in the socioeconomic setting of the country has transformed most of medium and small-scale plantation crop lands to either agricultural uses such as intensive vegetable cultivation, minor export crops and home gardens. The changes interact with biophysical environment in numerous diminutions; ecological, economic, social as well as agricultural. In a recent study by Perera et al., (2018) revealed that agriculture and the plantation-based socio-economic system are favorable for causing landslides, especially in the paleo-landslide environment. Moreover, they found that agriculture related activities bring a major share of rural livelihood in many landslides affected areas of Sri Lanka. Therefore, the landslide hazards mitigation strategies shall consider not only the physical and ecological features but also the socioeconomic setting of the vulnerable areas. Hence, the development of bioengineering solutions, particularly recommendation of plant species for slope stabilization shall aim at a win-win situation where the bioengineering solutions safeguard the rural livelihood while adequately contribute to landslide mitigation strategies.

7.3 Scientific approach adapted in formulating the Plant Manual

The plant manual is principally a review of existing knowledge in the form of literature, expert interviews, field visits and preliminary laboratory studies.

Information gained from the literature review was further developed by additional information from practitioners, scientists, engineers on the current practices, effective practices, and emerging solutions being used nationally or internationally. Information gained from the literature review and the additional sources was incorporated into this report as the body of the text, additional resources, references, current and effective management practices, useful points, photographs, and knowledge and research gaps.

7.4 Description of the Plant Manual

This section is organized into three parts. First a general description on native, introduced and commercially grown (economical) vegetation types in landslide prone Climatic/ Agro-ecological zones of Sri Lanka. In that, a summary of plant species that have been fully or partly studied for its bioengineering characteristics are presented as Annex 1. The plants its characteristics are described with brief detail of vegetation type, growing climate and ecological zones, soil types, establishment methods on ground, key soil bioengineering properties, and method of propagation. Whenever details are available, the general morphological features such as plant family, growth type, branching pattern and economically valuable parts are slow described. The list includes 120 selected species.

The second part presents an index of selected plants that are recommended to be used for bioengineering applications. This section gives an overview to the practitioners of the criteria-based assessment scheme.

The third section gives comprehensive details of indexed plants, thus allowing practitioners to identify specific features and characteristics related to bioengineering.

7.5 Recommended plant species

Grasses - *Cymbopogon citratus*

Cymbopogon citratus (Lemongrass)						
Characteristic	***Attribute***	***Description***	***Attribute***	***Description***	***Attribute***	***Description***
Plant type and structural characteristics	*Height*	*1 m*	*Plant weight & wind effect*	*Very low*	*Soil plant interaction*	*Excellent ground cover*
Hydrological significance	*Evapotranspiration*	*High*				
Root strength characteristics	*Root depth*	*0.5-1.0 m*	*Root type*	*M-type*		
Ecological significance	*Habited*	*Naturalized*	*Succession*	*Fast growth*	*Climate*	*Wet & intermediate*
Economic significance	*Benefits*	*High indirect/ direct*				

Cymbopogon citratus **Family** Poaceae **Common names** Sera, West Indian Lemongrass, Lemongrass	  
Character	Perennial grass
Description	Stiff stems are arising from a short rhizomatous rootstock. Root system is fibrous. Leaves are long and normally the length is about 1 m.
Major Growing Areas	Well suitable for tropics. It grows well between 100 and 1200 MSL under sunny conditions. It prefers annual daytime temperatures 23-30°c, mean annual rainfall range 1,500 - 3,000mm.
Soil Type	Requires a well-drained soil - commercial plantations often favor sandy soils. Prefers a pH 5 - 5.8. Hard clay soil is not suitable.
Products and Uses	The basal portions of the leafy shoots have a lemon-like aroma and are used as a flavouring in soups, sauces and curries. The essential oil obtained from the plant is an effective antifungal and antibacterial and also used in perfumery, scenting soaps, hair oils, cosmetics and as an insect repellent.
Contribution to Soil Conservation	A good soil conditioner in worn out land. The plants quickly produce a bulk of organic material, attracting worms and other beneficial creatures and quickly enriching the soil. The grass is useful for soil improvement and erosion control.

Grasses - *Chrysopogon zizanioides*

Chrysopogon zizanioides (Vetivergrass, Savandara)						
Characteristic	***Attribute***	***Description***	***Attribute***	***Description***	***Attribute***	***Description***
Plant type and structural characteristics	*Height*	*1-3 m*	*Plant weight & wind effect*	*Very low*	*Soil plant interaction*	*Good ground cover*
Hydrological significance	*Evapotranspiration*	*High*				
Root strength characteristics	*Root depth*	*Up to 4 m*	*Root type*	*M-type*		
Ecological significance	*Habited*	*Naturalized*	*Succession*	*Fast growth*	*Climate*	*Wet & intermediate*
Economic significance	*Benefits*	*High indirect/ direct*				

Chrysopogon zizanioides **Family** Poaceae **Common names** Vetivergrass, Savandara	 
Character	Perennial grass
Description	Forms dense and erect 1-3 m tall clumps with narrow linear, tightly folded leaves. Fibrous roots are long and white. It has an underground, horizontal stem known as rhizome.
Major Growing Areas	Well suitable for tropics. It grows well up to 2500 MSL under sunny conditions. It prefers annual daytime temperatures 22-35°c, mean annual rainfall range 500 - 2,500mm. This species can tolerate occasional flooding.
Soil Type	Suitable for light (sandy) and medium (loamy) soils. Prefer soil pH between 4.5 and 8. Moderately tolerate saline soils. It prefers moist or wet soil but tolerate seasonal drought.
Products and Uses	The essential oil obtained from the roots is used medicinally as a carminative, diaphoretic, diuretic, emmenagogue, refrigerant, stomachic, tonic, antispasmodic and sudorific. The plant is also used as an anthelmintic. Oil extracted from the roots is used perfume industry.
Contribution to Soil Conservation	Unlike most grasses, which tend to have a surface-rooting habit. The very dense root system has a strong tendency to grow downwards 4 meters or more, effectively anchoring strips of plants and the soil behind them. The grass is useful for soil improvement and erosion control.

Grasses - *Chrysopogon nardus*

Chrysopogon nardus (Ceylon Citronella, Heen pangiri, Nawa citronella)						
Characteristic	***Attribute***	***Description***	***Attribute***	***Description***	***Attribute***	***Description***
Plant type and structural characteristics	*Height*	*Up to 2.5 m*	*Plant weight & wind effect*	*Very low*	*Soil plant interaction*	*Good ground cover*
Hydrological significance	*Evapotranspiration*	*High*				
Root strength characteristics	*Root depth*	*Up to 2 m*	*Root type*	*M-type*		
Ecological significance	*Habited*	*Naturalized*	*Succession*	*Fast growth*	*Climate*	*Intermediate*
Economic significance	*Benefits*	*High indirect/ direct*				

Chrysopogon nardus **Family** Poaceae **Common names** Ceylon Citronella, Heen pangiri, Nawa citronella	
Character	Perennial grass
Description	It is an aromatic, evergreen, clump-forming grass. Grow up to 2.5 m height from a shout rootstock. Fibrous roots are long and widespread. It has an underground, horizontal stem known as rhizome.
Major Growing Areas	Well suitable for tropics and sub-tropics. It grows well up to 600 MSL under sunny conditions. It prefers annual daytime temperatures 20-30°c, mean annual rainfall range 1,300 - 2,000mm. This species can tolerate occasional drought.
Soil Type	Suitable for moisture-retentive loamy/ sandy-loamy soils. Prefer soil pH between 4.5 and 6.
Products and Uses	The leaves are used for flavoring curries, soups etc. The leaf oil contains geraniol, citral and citronellal. The plant is also used as an anthelmintic. Essential oil is obtained from whole plant distillation and is used for different products such as varnishes, insecticides, polishes, perfume etc.
Contribution to Soil Conservation	Erosion control by plant in live hedges in slope lands. The grass is also used for soil improvement in degraded lands.

Grasses - *Arundo donax*

Arundo donax (Bata, Arundo)						
Characteristic	***Attribute***	***Description***	***Attribute***	***Description***	***Attribute***	***Description***
Plant type and structural characteristics	*Height*	*Up to 5 m*	*Plant weight & wind effect*	*Low*	*Soil plant interaction*	*Good ground cover*
Hydrological significance	*Evapotranspiration*	*Very high*				
Root strength characteristics	*Root depth*	*Up to 2-5 m*	*Root type*	*M-type*		
Ecological significance	*Habited*	*Naturalized*	*Succession*	*Fast growth*	*Climate*	*Intermediate and wet*
Economic significance	*Benefits*	*High indirect/ direct*				

Arundo donax **Family** Poaceae **Common names** Bata	 
Character	Perennial grass
Description	Giant reed is a robust erect perennial grass species reaching up to 5 m height under optimal growth conditions, growing in many-stemmed clumps. Individual tough and hollow stems, 3-5 cm in thickness, have a cane-like appearance like bamboo with alternate leaves, 30-60 cm long and 2-6 cm broad, tapered tips and hairy tuft, at the base. Several stems grow from the rhizome buds during all the vegetative season, forming dense clumps. Arundo grow fast and produce huge biomass per unit land area.
Major Growing Areas	Well suitable for tropics and sub-tropics. It grows well up to 1000 MSL under sunny conditions. It prefers annual daytime temperatures 20-30°c, mean annual rainfall range 1,300 - 2,500mm.
Soil Type	Suitable for moisture-retentive clay and loamy soils. Prefer soil pH between 4 and 8.
Products and Uses	The leaves are used as animal fodder. Stems are used as poles and processed to cane like viewing materials.
Contribution to Soil Conservation	Erosion control by plant in live hedges in slope lands. Excellent wind breaker for cops. The grass is also used for soil improvement in degraded lands.

Grasses - *Bambusa vulgaris*

Bambusa vulgaris (Kaha-una)						
Characteristic	***Attribute***	***Description***	***Attribute***	***Description***	***Attribute***	***Description***
Plant type and structural characteristics	*Height*	*Up to 20 m*	*Plant weight & wind effect*	*Medium*	*Soil plant interaction*	*Normal ground cover*
Hydrological significance	*Evapotranspiration*	*High*				
Root strength characteristics	*Root depth*	*Up to 1-2 m*	*Root type*	*M-type*		
Ecological significance	*Habited*	*Naturalized*	*Succession*	*Fast growth*	*Climate*	*Intermediate and wet*
Economic significance	*Benefits*	*High indirect/ direct*				

Bambusa vulgaris **Family** Poaceae **Common names** Kaha-una	 
Character	Perennial grass
Description	The densely tufted culms grow 10–20 m high and 4–10 cm thick. Culms are basally straight and slightly thick. Nodes are slightly inflated. Several branches develop from mid-culm nodes and above. Culm leaves are deciduous with dense pubescence. Flowering is not common, and there are no seeds. The average apparent cohesion of the bamboo root system is estimated in the range of 18.4–26.3 kPa and its reinforcement effect on the slope stability is limited due to the very shallow rooting depth (0.8–2.0m) compared to stem (>10m). Plant structure is critical to the collapse failure of slope land with bamboo. The reinforcement effect of root systems on the slope stability is relatively small when compared with the influences of the wind loading and rainfall. The maximum stabilization capacity when compared with those of slope land with mild (<25◦) and steep slopes (>40◦).
Major Growing Areas	Well suitable for tropics and sub-tropics. It grows well up to 500 MSL under sunny conditions. It prefers annual daytime temperatures 20-35°c, mean annual rainfall range 500 - 2,500mm.
Soil Type	Suitable for wide range of clay, loamy and sandy soils. Prefer soil pH between 4 and 7.
Products and Uses	The leaves are used as animal fodder. Stems are used in construction industry many other wood processing industries.
Contribution to Soil Conservation	Erosion control by plant in live hedges in slope lands and shallow stream banks. Excellent wind breaker for crops.

Small tree (Shrub) - *Coffea arabica*

Coffea arabica (Coffee)						
Characteristic	***Attribute***	***Description***	***Attribute***	***Description***	***Attribute***	***Description***
Plant type and structural characteristics	*Height*	*Up to 3 m*	*Plant weight & wind effect*	*Low*	*Soil plant interaction*	*Normal ground cover*
Hydrological significance	*Evapotranspiration*	*High*				
Root strength characteristics	*Root depth*	*Up to 1-2 m*	*Root type*	*H-type*		
Ecological significance	*Habited*	*Naturalized*	*Succession*	*Fast growth*	*Climate*	*Intermediate and wet*
Economic significance	*Benefits*	*High indirect/ direct*				

Coffea arabica **Family** Rubiaceae **Common names** Coffee	 
Character	Perennial evergreen tree
Description	It is usually found as a compact shrub 1.5 - 3 meters tall with an open branching system. There is main vertical tap root, and lateral roots which grow parallel to the ground.
Major Growing Areas	Well suitable for tropics and sub-tropics. It grows well up to 750 MSL under sunny conditions. It prefers annual daytime temperatures 18-24°c, mean annual rainfall range 1,500 - 2,750mm.
Soil Type	Prefers a deep friable soil on undulating land. Plants are unsuited to stiff clay or sandy soils but are considered tolerant of acid soils. Prefers a pH in the range 5.5 – 7.
Products and Uses	The dried seeds are roasted, ground, and brewed to make one of the two most popular beverages in the world.
Contribution to Soil Conservation	Firmly hold on to soil, hold soil tightly, and a wind barrier. Erosion control can be achieved by cultivating coffee with low spacing.

Small tree - *Theobroma cacao*

Theobroma cacao (Cocoa)						
Characteristic	***Attribute***	***Description***	***Attribute***	***Description***	***Attribute***	***Description***
Plant type and structural characteristics	*Height*	*Up to 8 m*	*Plant weight & wind effect*	*Medium*	*Soil plant interaction*	*Normal ground cover*
Hydrological significance	*Evapotranspiration*	*High*				
Root strength characteristics	*Root depth*	*Up to 1-4 m*	*Root type*	*R-type*		
Ecological significance	*Habited*	*Naturalized*	*Succession*	*Fast growth*	*Climate*	*Intermediate and wet*
Economic significance	*Benefits*	*High indirect/ direct*				

Theobroma cacao **Family** Malvaceae **Common names** Cocoa	 
Character	Small evergreen tree
Description	Cacao plant grows about 8 meters tall, though exceptionally it can reach 20 meters. The cocoa tree has tap-roots that descends straight into the soil. The branch roots go down very deep but many small branch roots also grow near the surface.
Major Growing Areas	A tree of the lowland tropics. It grows well up to 600 MSL under sunny conditions. It prefers annual daytime temperatures 21-32°c, mean annual rainfall range 1,150 - 2,500mm.
Soil Type	The best soils are deep, well-drained clay loams rich in organic matter. Scattered stones and pebbles are tolerable up to 40%. Coarse gravelly soils, sandy soils, shallow soils, and soils which are underlain by slab rock or hard laterite are unsuitable. Soil pH 5-6.5 is recommended.
Products and Uses	The dried, fermented, and roasted seeds of this plant, called cacao beans, are the source of cocoa, chocolate and cocoa butter.
Contribution to Soil Conservation	Firmly hold on to soil, hold soil tightly, and a wind barrier. Act as soil anchors and evaporators.

Small tree (Shrub) - *Cinnamomum verum*

Cinnamomum verum (Ceylon cinnamon)						
Characteristic	***Attribute***	***Description***	***Attribute***	***Description***	***Attribute***	***Description***
Plant type and structural characteristics	*Height*	*Up to 15 m*	*Plant weight & wind effect*	*Medium*	*Soil plant interaction*	*Normal ground cover*
Hydrological significance	*Evapotranspiration*	*High*				
Root strength characteristics	*Root depth*	*Up to 2-3 m*	*Root type*	*R-type*		
Ecological significance	*Habited*	*Native*	*Succession*	*Fast growth*	*Climate*	*Intermediate and wet*
Economic significance	*Benefits*	*High indirect/ direct*				

Cinnamomum verum **Family** Lauraceae **Common names** Ceylon cinnamon	 
Character	Perennial evergreen tree
Description	It is a small tree native to Sri Lanka. Trees are 10–15m tall. Cinnamon roots can penetrate through the cracks of the parent material or rock to deeper layers.
Major Growing Areas	It grows well up to 2000 MSL under sunny conditions. It prefers annual daytime temperatures 25-30°c, mean annual rainfall range 2,000 - 2,500mm.
Soil Type	Prefers a fertile, sandy, moisture-retentive but freely draining soil. Rocky and stony ground is not suitable. Prefers a pH in the range 5 – 8.
Products and Uses	The stem bark is used as a flavoring. Essential oils, obtained from the leaves and the bark, are used as food flavorings in a range of foods.
Contribution to Soil Conservation	Firmly hold on to soil, hold soil tightly, and a wind barrier. Act as soil anchors and evaporators.

Small tree (Multipurpose) - *Gliricidia sepium*

***Gliricidia sepium* (Gilricidia)**						
Characteristic	***Attribute***	***Description***	***Attribute***	***Description***	***Attribute***	***Description***
Plant type and structural characteristics	*Height*	*Up to 15 m*	*Plant weight & wind effect*	*Medium*	*Soil plant interaction*	*Normal ground cover*
Hydrological significance	*Evapotranspiration*	*High*				
Root strength characteristics	*Root depth*	*Up to 2-5 m*	*Root type*	*R-type*		
Ecological significance	*Habited*	*Normalized*	*Succession*	*Very fast growth*	*Climate*	*Dry, intermediate and wet*
Economic significance	*Benefits*	*High indirect/ direct*				

Gliricidia sepium **Family** Fabaceae **Common names** Gliricidia, Watamaara	 
Character	Perennial evergreen shrub or small tree
Description	It is a medium-sized, open crown, fast growing tree that can grow 2 - 15 meters tall. The stem is twisted, or grows at an angle, up to 30cm in diameter. Simple and elongated roots penetrate down to 2-5 m depth but has number of lateral roots that often grow towards different soil horizons.
Major Growing Areas	It grows well up to 1600 MSL under sunny conditions. It prefers annual daytime temperatures 15-30°c, mean annual rainfall range 600 - 3,500mm. Adapted to wide range of climate conditions.
Soil Type	Tolerates a wide range of soil types, both alkaline and acidic, including low-fertility soils. It grows well on the calcareous soils of atolls. Prefers freely draining soils but can tolerate some waterlogging. Prefers a pH in the range 5.5 - 6.2. Plant establishes well on steep slopes with up to 40% gradient.
Products and Uses	It is widely cultivated as a shade tree for perennial crops. The wood is utilized for farm implements, tool handles, furniture, house construction and as mother posts in live-fence establishment. The wood is used as biomass-fuel or biomass for charcoal.
Contribution to Soil Conservation	Firmly hold on to soil, hold soil tightly, and a wind barrier. Act as soil anchors and evaporators.
Further reading	Petrone A, Preti F (2010) Soil bio-engineering for risk mitigation and environmental restoration in a humid tropical area. Hydrol Earth Syst Sci 14:239–250.

Small tree (Multipurpose) - *Leucaena leucocephala*

***Leucaena leucocephala* (Ipil Ipil)**						
Characteristic	***Attribute***	***Description***	***Attribute***	***Description***	***Attribute***	***Description***
Plant type and structural characteristics	*Height*	*Up to 20 m*	*Plant weight & wind effect*	*High*	*Soil plant interaction*	*Normal ground cover*
Hydrological significance	*Evapotranspiration*	*High*				
Root strength characteristics	*Root depth*	*Up to 2-3 m*	*Root type*	*V-H type*		
Ecological significance	*Habited*	*Invasive*	*Succession*	*Very fast growth*	*Climate*	*Dry, intermediate and wet*
Economic significance	*Benefits*	*High indirect/ direct*				

Leucaena leucocephala **Family** Fabaceae **Common names** Ipil Ipil	 
Character	A small fast-growing mimosoid tree
Description	*L. leucocephala* is considered one of the 100 worst invasive species. It grows quickly and forms dense thickets that crowd out all native vegetation. It is a medium-sized, fast growing tree that can grow 10 - 20 meters tall. Strong elongated roots penetrate down to 2-5 m depth but has number of lateral roots that often grow towards different soil horizons. Few lateral roots are oriented horizontally to the main taproot and most of the fine roots are surrounded by lateral roots. Tree achieves relatively high root reinforcement potentiality through the increment of root profiles, tensile strength, cellulosic composition and cohesion.
Major Growing Areas	It grows well up to 1500 MSL under sunny conditions. It prefers annual daytime temperatures 20-30°c, mean annual rainfall range 600 - 3,500mm. Adapted to wide range of climate conditions.
Soil Type	Tolerates a wide range of soil types, both alkaline and acidic, including low-fertility soils. It grows well on the calcareous soils of atolls. Prefers freely draining soils but can tolerate some waterlogging. Prefers a pH in the range 4.5 - 7.5. Plant establishes well on steep slopes with up to 40% gradient.
Products and Uses	*L. leucocephala* is used for a variety of purposes, such as firewood, fiber, and livestock fodder. Also used as share tree, wind barrier and hedge tree in plantations and farm fields.
Contribution to Soil Conservation	Firmly hold on to soil, hold soil tightly, and a wind barrier. Act as soil anchors and evaporators.
Further readings	Saifuddin M, Osman N, Rahman MM, Boyce AN (2015). Soil reinforcement capability of two legume species from plant morphological traits and mechanical properties. Curr. Sci. 108:1340-1347.

Small tree (Multipurpose) - *Jatropha curcas*

Jatropha curcas (Weta-endaru)						
Characteristic	***Attribute***	***Description***	***Attribute***	***Description***	***Attribute***	***Description***
Plant type and structural characteristics	*Height*	*Up to 6m*	*Plant weight & wind effect*	*Medium*	*Soil plant interaction*	*Normal ground cover*
Hydrological significance	*Evapotranspiration*	*High*				
Root strength characteristics	*Root depth*	*Up to 2-3 m*	*Root type*	*V-H type*		
Ecological significance	*Habited*	*Invasive*	*Succession*	*Very fast growth*	*Climate*	*Dry, intermediate and wet*
Economic significance	*Benefits*	*High indirect/ direct*				

Leucaena leucocephala **Family** Fabaceae **Common names** Ipil Ipil	  
Character	A perennial shrub or small tree
Description	*J. curcas* is a semi-evergreen shrub or small tree, reaching a height of 6 m or more. It is resistant to a high degree of aridity. The seeds contain 27–40% oil that can be processed to produce a high-quality biodiesel fuel. The lateral roots have the potential to decrease soil erodibility through additional soil cohesion, whereas the taproot and sinkers may increase resistance against shallow land sliding, enable exploitation of subsurface soil moisture and thus enhance vegetative cover, even in very dry environments.
Major Growing Areas	It grows well up to 2000 MSL under sunny conditions. It prefers annual daytime temperatures 20-35°c, mean annual rainfall range 600 - 3,500mm. Adapted to wide range of climate conditions.
Soil Type	Tolerates a wide range of soil types, both alkaline and acidic, including low-fertility soils. The plant can grow in wastelands and grows on almost any terrain, even on gravelly, sandy and saline soils.
Products and Uses	The seeds contain 27–40% oil and it has been recognized as an excellent biofuel crop.
Contribution to Soil Conservation	Firmly hold on to soil, hold soil tightly, and a wind barrier. Act as soil anchors and evaporators.
Further readings	Giadrossich F, D. Cohen, M. Schwarz, G. Seddaiu, N. Contran, M. Lubino, O.A. Valdés-Rodrŕguez, M. Niedda (2016) Modeling bio-engineering traits of Jatropha curcas L. Ecol. Eng., 89 (2016), pp. 40-48, 10.1016/j.ecoleng.2016.01.005.

Small tree (Medicinal) - *Vitex negundo*

Vitex negundo (Nika)						
Characteristic	***Attribute***	***Description***	***Attribute***	***Description***	***Attribute***	***Description***
Plant type and structural characteristics	*Height*	*Up to 8 m*	*Plant weight & wind effect*	*Low*	*Soil plant interaction*	*Normal ground cover*
Hydrological significance	*Evapotranspiration*	*High*				
Root strength characteristics	*Root depth*	*Up to 3-5 m*	*Root type*	*V-H type*		
Ecological significance	*Habited*	*Native*	*Succession*	*Normal growth*	*Climate*	*Dry, intermediate and wet*
Economic significance	*Benefits*	*Indirect/ low direct*				

Vitex negundo **Family** Lamiaceae **Common names** Nika	 
Character	A perennial shrub or small tree
Description	*Vitex negundo* is an erect shrub or small tree growing from 2 to 8 m. Tap root normally penetrate to 3m and even to 5m depth in extreme conditions.
Major Growing Areas	It is typically grown in tropical and semi-tropical regions.
Soil Type	Adapt to well drain loamy to clay soils. Grows on almost any terrain, even on gravelly and acidic soils. Prefers slightly acidic to neutral pH.
Products and Uses	Various parts of the tree such as leaves, leaf oil, roots, fruits, and seeds are used in Ayurveda. A source of rural fuelwood.
Contribution to Soil Conservation	Has a well grown taproot with numerous lateral roots and a mesh of fine roots. Roots penetrate to a comparatively deeper layers about 5m in dry soils, but contribution from lateral root system for soil stabilization is high. Presence of roots increases the effective cohesion of the soil, resulting in the increase in shear strength.
Further readings	Schroth, G. 1995 Tree root characteristics as criteria for species selection and system design in agroforestry. Agrofor. Syst. 30, 125–143.

Small tree (shrub) - *Melastoma malabathricum*

Melastoma malabathricum (Bowitiya, Katakaluwa)						
Characteristic	***Attribute***	***Description***	***Attribute***	***Description***	***Attribute***	***Description***
Plant type and structural characteristics	*Height*	*Up to 8 m*	*Plant weight & wind effect*	*Low*	*Soil plant interaction*	*Normal ground cover*
Hydrological significance	*Evapotranspiration*	*High*				
Root strength characteristics	*Root depth*	*Up to 3-5 m*	*Root type*	*V-H type*		
Ecological significance	*Habited*	*Native*	*Succession*	*Normal growth*	*Climate*	*Dry, intermediate and wet*
Economic significance	*Benefits*	*Indirect/ low direct*				

Melastoma malabathricum **Family** Melastomataceae **Common names** Bowitiya, Katakaluwa	
Character	A perennial shrub
Description	Plant is a perennial shrub up to 3 m in height. It is mainly occurring in the secondary vegetation as a pioneer species it occurs in disturb areas, roadsides, and dumpsites. As plant is a pioneer species no hard maintenance is required if transplanted when it reached 0.5 m height.
Major Growing Areas	It can be found at elevations up to 900 m in the wet zone of Sri Lanka. It requires warm and wet climate with an average temperature of 27 ^{0}C. It is grown in the areas which is having average annual rainfall around 2,000-2,500 mm.
Soil Type	Adapt to well drain loamy to clay soils. Grows on almost any terrain, even on gravelly and acidic soils. Prefers slightly acidic to neutral pH.
Products and Uses	Plant has a high potential to be used as an ornamental plant with a showy flower. It has an edible fruit. Whole plant has a high medicinal value as an astringent and is used as a dye.
Contribution to Soil Conservation	This plant had shown high performance on improving the slope environment and alleviating the erosion. *M. malabathricum* has a tensile strength of 29.72 MPa. The plant has a root system reaching about 1-2 m with M-type root system. The average pullout resistance of the plant is 2.02 kN.
Further readings	Aimee H. and Normaniza O. (2014). Physiological responses of Melastoma malabathricum at different slope orientations. J. Trop. Plant Physiol. 6 (2014): 10-22.

Small tree (shrub) - *Wendlandia bicuspidate*

Wendlandia bicuspidata (Wana edala, Rawan idala)						
Characteristic	***Attribute***	***Description***	***Attribute***	***Description***	***Attribute***	***Description***
Plant type and structural characteristics	*Height*	*Up to 4 m*	*Plant weight & wind effect*	*Low*	*Soil plant interaction*	*Normal ground cover*
Hydrological significance	*Evapotranspiration*	*Moderate*				
Root strength characteristics	*Root depth*	*Up to 1-2 m*	*Root type*	*V-H type*		
Ecological significance	*Habited*	*Native*	*Succession*	*Normal growth*	*Climate*	*Dry, intermediate and wet*
Economic significance	*Benefits*	*Indirect/ low direct*				

Wendlandia bicuspidata **Family** Rubiaceae **Common names** Wana edala, Rawan idala	
Character	A perennial shrub
Description	*W. bicuspidata* is an endemic shrub or small tree with bark light brown, fissured, thin stem. It is mainly occurring in the secondary vegetation as a pioneer species. As it is a pioneer species, high growth rate is observed. No special maintenance is required.
Major Growing Areas	The plant can be found at elevations up to 900 m in the wet zone of Sri Lanka. It requires warm and wet climate with an average temperature of 27 ^{0}C. It is grown in the areas which is having average annual rainfall around 2,000-2,500 mm.
Soil Type	Adapt to well drain loamy to clay soils. Grows on almost any terrain, even on gravelly and acidic soils. Prefers slightly acidic to neutral pH.
Products and Uses	Leaves, bark and stem is used in medicinal preparations in treating dysentery, fever, Diarrhea and ulcer. Stem used in light contractions.
Contribution to Soil Conservation	No direct information on W. bicupsidata as it is an endemic species. However, *Wendlandia spp*. with same external morphology has been used in reinforcement of slopes especially in Nepal. Further, *W. exserta* with similar external morphology has been used for bioengineering of slopes, this species further reported with deep root system with a spread of 1.9 m, thus, could be suggested for slope reinforcement as it created a network of roots holding soil particles.
Further readings	Devkota, B. D., Omura, H., Kubota, T. and Morita, K. (2006). State of Vegetation, Erosion Climatic Conditions and Re-vegetation Technology in Mid Hill Area of Nepal. 51.

Small tree (Medicianal) - *Murraya paniculate*

Murraya paniculata (Atteria)						
Characteristic	***Attribute***	***Description***	***Attribute***	***Description***	***Attribute***	***Description***
Plant type and structural characteristics	*Height*	*Up to 5 m*	*Plant weight & wind effect*	*Low*	*Soil plant interaction*	*Normal ground cover*
Hydrological significance	*Evapotranspiration*	*Moderate*				
Root strength characteristics	*Root depth*	*Up to 2-4 m*	*Root type*	*V-H type*		
Ecological significance	*Habited*	*Native*	*Succession*	*Normal growth*	*Climate*	*Dry, intermediate and wet*
Economic significance	*Benefits*	*Indirect/ low direct*				

Murraya paniculata **Family** Rutaceae **Common names** Atteria	 
Character	A Shrub or small tree
Description	A fine-textured, medium-sized shrub, with an upright and spreading, compact habit and dense crown of glossy green leaves. The shrub is well-suited to shearing into a formal hedge or screen. Plant three to four feet apart for a hedge.
Major Growing Areas	*Murraya paniculata* is a tropical, evergreen native plant. It has a moderate growth rate; a least maintenance is required.
Soil Type	They thrive in alkaline soils and do not tolerate salty conditions. Adapted to wide range of soil tolerance (alkaline, clayey, sandy, acidic and loamy soils).
Products and Uses	Traditionally, Murraya paniculata is used both in traditional medicine as an analgesic and for wood (for tool handles). An ornamental tree.
Contribution to Soil Conservation	Has a well grown taproot with numerous lateral roots and a mesh of fine roots. Roots penetrate to a comparatively deeper layers about 2-4m, especially in dry and arid climates. Contribution from lateral root system for soil stabilization is high.
Further readings	Rahardjo, H., Satyanaga, A., Leong, E. C., Santoso, V. A. & Ng, Y. S. (2014). Performance of an instrumented slope covered with shrubs and deep-rooted grass. Soils Found. 54, No. 3, 417–425.

Medium size tree - *Trema orientalis*

***Trema orientalis* (Gadumba)**						
Characteristic	***Attribute***	***Description***	***Attribute***	***Description***	***Attribute***	***Description***
Plant type and structural characteristics	*Height*	*Up to 12 m*	*Plant weight & wind effect*	*High*	*Soil plant interaction*	*Low ground cover*
Hydrological significance	*Evapotranspiration*	*High*				
Root strength characteristics	*Root depth*	*Up to 2 m*	*Root type*	*V-H type*		
Ecological significance	*Habited*	*Native*	*Succession*	*Fast growth*	*Climate*	*Intermediate and wet*
Economic significance	*Benefits*	*Indirect/ low direct*				

Trema orientalis **Family** Cannabaceae **Common names** Gadumba	 
Character	Native medium sized evergreen tree
Description	Medium-sized evergreen tree, to 12 m high.
Major Growing Areas	The plant can be found in wet and intermediate zone secondary forests. As it is a pioneer species with high growth rate, a last maintenance is required. Also very common in cleared areas and waste places in dry, wet and intermediate zones up to 1525 m of elevation.
Soil Type	Best grown in well-drained, sandy soil. However, succeeds on a wide range of soils from heavy clay to light sand, tolerating moderate alkalinity and salinity.
Products and Uses	The plant is vermifuge. Leaves and bark used in medicinal preparations used to treat coughs, sore throat, asthma, bronchitis, gonorrhoea, yellow fever, toothache. The tree can provide plenty of firewood and excellent charcoal which is even suitable for making gunpowder and fireworks.
Contribution to Soil Conservation	The tree has an extensive root system that enables to hold soil together and categorized as a tree with high anchoring root index with moderate capability in reinforcing slopes.
Further readings	Kurniatun H. et al. (2006). Root effects on slope stability in Sumberjaya, Lampung (Indonesia). International symposium towards sustainable livelihoods and ecosystems in mountainous regions, 7-9 March 2006, Chiang Mai, Thailand.

Medium size tree - *Trema orientalis*

Macaranga peltata (Kenda)						
Characteristic	***Attribute***	***Description***	***Attribute***	***Description***	***Attribute***	***Description***
Plant type and structural characteristics	*Height*	*Up to 15 m*	*Plant weight & wind effect*	*High*	*Soil plant interaction*	*Low ground cover*
Hydrological significance	*Evapotranspiration*	*High*				
Root strength characteristics	*Root depth*	*Up to 2 m*	*Root type*	*V-H type*		
Ecological significance	*Habited*	*Normalized*	*Succession*	*Fast growth*	*Climate*	*Intermediate and wet*
Economic significance	*Benefits*	*Indirect/ low direct*				

Macaranga peltata **Family** Euphorbiaceae **Common names** Kenda	 
Character	A perennial evergreen medium sized tree
Description	Early successional medium sized native tree growing up to 15 m in height.
Major Growing Areas	The plant can be found in wet and intermediate zone secondary forests, up to 750 MSL elevation. As it is a pioneer species with high growth rate, a least maintenance is required.
Soil Type	Adapt to well drain loamy to clay soils. Grows on almost any terrain, even on gravelly and acidic soils. Prefers slightly acidic to neutral pH.
Products and Uses	Leaves could be used as green manure where they are rich in Nitrogen and Potassium. Wood is light weight and suitable for match, paper and pulp industries.
Contribution to Soil Conservation	Twenty-two-year-old trees have a rooting depth of > 1.5 m with a root spread about 1 m. Consist of V-H type root system thus, could be used in soil reinforcement. Tree has high evapotranspiration rate.
Further readings	Kunhamu, T.K., Aneesh, S., Mohan Kumar, B. et al. Biomass production, carbon sequestration and nutrient characteristics of 22-year-old support trees in black pepper (Piper nigrum. L) production systems in Kerala, India. Agroforest Syst (2018) 92: 1171. https://doi.org/10.1007/s10457-016-0054-5

Large tree - *Michelia champaca*

***Michelia champaca* (Gini sapu)**						
Characteristic	***Attribute***	***Description***	***Attribute***	***Description***	***Attribute***	***Description***
Plant type and structural characteristics	*Height*	*Up to 50m*	*Plant weight & wind effect*	*Very high*	*Soil plant interaction*	*Low ground cover*
Hydrological significance	*Evapotranspiration*	*High*				
Root strength characteristics	*Root depth*	*Up to 3-5 m*	*Root type*	*V-H type*		
Ecological significance	*Habited*	*Normalized*	*Succession*	*Fast growth*	*Climate*	*Intermediate and wet*
Economic significance	*Benefits*	*High indirect/ direct*				

Michelia champaca **Family** Magnoliaceae **Common names** Gini sapu	 
Character	A perennial large tree
Description	It is an evergreen or semi-deciduous, large tree up to 50 m tall; bole straight, cylindrical, up to 1.9m in diameter, without buttresses. It has a well grown taproot with numerous lateral roots and a mesh of fine roots. Roots penetrate to a comparatively deeper layers about 5m, but contribution from lateral root system for soil stabilization is high. Presence of roots increases the effective cohesion of the soil, resulting in the increase in shear strength.
Major Growing Areas	It is found in Tropical and subtropical moist broadleaf forests ecoregions, at elevations of 200–1,600 m.
Soil Type	Adapt to well drain loamy to clay soils. Prefers slightly acidic to neutral pH, tolerating 4 – 8.
Products and Uses	It is known for its fragrant flowers, and its timber is used in woodworking. Branches are good source of fuelwood.
Contribution to Soil Conservation	Firmly hold on to soil, hold soil tightly, and a wind barrier. Presence of roots increases the effective cohesion of the soil, resulting in the increase in shear strength.
Further readings	Kong D, Li L, Ma C, Zeng H, Guo D. 2014. Leading dimensions of root trait variation in subtropical forests. New Phytologist 203: 863–872.

Large tree - *Pterocarpus indicus*

Pterocarpus indicus (Wal-ahala)						
Characteristic	***Attribute***	***Description***	***Attribute***	***Description***	***Attribute***	***Description***
Plant type and structural characteristics	*Height*	*Up to 40m*	*Plant weight & wind effect*	*Very high*	*Soil plant interaction*	*Low ground cover*
Hydrological significance	*Evapotranspiration*	*High*				
Root strength characteristics	*Root depth*	*Up to 3-5 m*	*Root type*	*V-H type*		
Ecological significance	*Habited*	*Native*	*Succession*	*Slow growth*	*Climate*	*Intermediate and wet*
Economic significance	*Benefits*	*Indirect only*				

Pterocarpus indicus **Family** Fabaceae **Common names** Wal-ahala	 
Character	Native evergreen large tree
Description	It is a large deciduous tree growing to 30–40 m tall, with a trunk up to 2 m diameter. The leaves are 12–22 cm long, pinnate, with 5–11 leaflets, the girth is 12–34 m wide. The flowers are produced in panicles 6–13 cm long containing a few to numerous flowers
Major Growing Areas	Native tree species, yet many populations of *Pterocarpus indicus* are seriously threatened. In agroforestry, it maintains ecosystem fertility and soil stability.
Soil Type	The tree can be found in wet and intermediate zone forests. Tree succeeds on a wide range of soils from heavy clay to light sand, tolerating moderate acidity.
Products and Uses	It is a premium timber species suitable for high grade furniture, lumber and plywood for light construction purposes.
Contribution to Soil Conservation	Root branching pattern of P. indicus exhibited strong tap root and its lateral roots. Tree roots grow horizontally and profusely. About 80% of its root matrix is found within the top 60 cm of soil depth. This type of root has three roles in slope stabilization: soil reinforcement, slope stability and wind resistance.
Further readings	Saifuddin M, Normaniza O (2016). Rooting characteristics of some tropical plants for slope protection. J. Trop. For. Sci. 28:469-478.

Medium sized tree (Introduced and naturalized) - *Hibiscus tiliaceus*

***Hibiscus tiliaceus* (Belipatta)**						
Characteristic	***Attribute***	***Description***	***Attribute***	***Description***	***Attribute***	***Description***
Plant type and structural characteristics	*Height*	*Up to 10m*	*Plant weight & wind effect*	*Moderate*	*Soil plant interaction*	*Low ground cover*
Hydrological significance	*Evapotranspiration*	*High*				
Root strength characteristics	*Root depth*	*Up to 1-3 m*	*Root type*	*V-H type*		
Ecological significance	*Habited*	*Introduced*	*Succession*	*Slow growth*	*Climate*	*Intermediate and wet*
Economic significance	*Benefits*	*Indirect only*				

Hibiscus tiliaceus **Family** Malvaceae **Common names** Belipatta	  
Character	Shrub or small tree
Description	*Hibiscus tiliaceus* reaches a height of 4–10 m, with a trunk up to 15 cm in diameter. The flowers of *H. tiliaceus* are bright yellow with a deep red center upon opening. The branches of the tree often curve over time.
Major Growing Areas	It is a tropical, evergreen native plant. It has a moderate growth rate; a least maintenance is required. *Hibiscus tiliaceus* can be found at elevations from sea level to 800 m in areas that receive 900–2,500 mm of annual rainfall.
Soil Type	It is well adapted to tolerate salt and waterlogging and can grow in quartz sand, coral sand, marl, limestone, and crushed basalt. It grows best in slightly acidic to alkaline soils (pH of 5–8.5).
Products and Uses	Wood is easy to plane and turns well, so it is regarded by many as a high-quality furniture wood. Its tough bark can be made into durable rope.
Contribution to Soil Conservation	The roots of the live pole can increase the apparent cohesion of the soil by about 300%. Roots have higher mechanical strength. Live cut stems and the branches provide immediate reinforcement; secondary stabilization occurs because of the growing roots along the length of the buried stems. The live poles can be used on the suspect slopes providing low-cost and environmentally suitable alternatives to the conventional methods of the slope stabilization.
Further readings	Prasad, A., Kazemian, S., Kalantari, B., Huat, B. B. K., Mafian, S., 2012. Stability of Tropical Residual Soil Slope Reinforced by Live Pole: Experimental and Numerical Investigations, Arabian Journal for Science and Engineering Volume 37, Number 3, 601-618.

Medium sized tree (Introduced and invasive) - *Dillenia suffruticosa*

Dillenia suffruticosa (Diyapara)						
Characteristic	***Attribute***	***Description***	***Attribute***	***Description***	***Attribute***	***Description***
Plant type and structural characteristics	*Height*	*Up to 6m*	*Plant weight & wind effect*	*Moderate*	*Soil plant interaction*	*Good ground cover*
Hydrological significance	*Evapotranspiration*	*High*				
Root strength characteristics	*Root depth*	*Up to 1-3 m*	*Root type*	*V-H type*		
Ecological significance	*Habited*	*Introduced, invasive*	*Succession*	*Very fast growth*	*Climate*	*Intermediate and wet*
Economic significance	*Benefits*	*Indirect only*				

Dillenia suffruticosa **Family** Dilleniaceae **Common names** Diyapara	 
Character	Shrub or small tree
Description	It is a large, evergreen shrub to 6m high. It flowers continuously with yellow flowers 10 to 12 cm wide. The plant is found in tropical South East Asia in secondary forest and swampy grounds that are undisturbed forest such as riversides up to 700 m altitude. They can also be found on alluvial places such as swamps, mangroves, riversides, but sometimes also present on hillsides and ridges, which have clayey to sandy soil texture.
Major Growing Areas	It is a tropical, evergreen non-native plant. It has a high growth rate; thus, easily becomes an invasive tree under suitable environment. Thus, it is considered as a highly invasive weed in Sri Lanka.
Soil Type	They can also be found on alluvial places such as swamps, mangroves, riversides, but sometimes also present on hillsides and ridges, which have clayey to sandy soil texture. Grow well in water logging conditions as well.
Products and Uses	*Dillenia suffruticosa* has some medicinal uses.
Contribution to Soil Conservation	The roots of the live pole can increase the apparent cohesion of the soil by about 600%. Roots have higher mechanical strength. Live cut stems and the branches provide immediate reinforcement; secondary stabilization occurs because of the growing roots along the length of the buried stems. The live poles can be used on the suspect slopes providing low-cost and environmentally suitable alternatives to the conventional methods of the slope stabilization.
Further readings	Prasad, A., Kazemian, S., Kalantari, B., Huat, B. B. K., Mafian, S., 2012. Stability of Tropical Residual Soil Slope Reinforced by Live Pole: Experimental and Numerical Investigations, Arabian Journal for Science and Engineering Volume 37, Number 3, 601-618.

CHAPTER 08

PLANTING TECHNIQUES

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Chapter 8 PLANTING TECHNIQUES

8.1 Plant materials and planting techniques

Once plant species have been selected and potential sources have been identified, the next step is to determine the most appropriate techniques for planting the selected species in the project site. In areas with relatively good soil stability that are bordered by healthy populations of plant species, the existing vegetation may provide the necessary plant materials for the new site. However, if vegetation in and around the site is not sufficient for propagation, additional plant materials will need to be obtained and established.

Typically, there is no such thing as an "ideal" all-purpose planting approach that will always work in any situation. After compiling a list of species to use for establishment, it is necessary to determine the optimal propagation methods for each species and to identify the most appropriate plant material sources for a particular site. This step is an integrated, sequential process for evaluating plant material requirements within the context of project objectives and site characteristics that may influence the suitability of planting materials, as well as the timing and optimal method of planting. Plant materials may include seeds, cuttings, and/or plants. The fitness of the plant material should be determined by its appropriateness to the site.

Determining which plant materials to select for establishment depends on the type of plant species. For example, many tree and shrubs species have been shown to establish better and faster from plants rather than from seeds or cuttings. Alternatively, grasses can be established from plants (turf), but growing grass plants and planting them is very expensive compared to using seeds. Some species, however, do not produce reliable crops of seeds and, therefore, other plant materials, such as cuttings, will have to be used.

8.1.1 Seeds

Seeds can be collected from stands of grasses, forbs, shrubs, and trees. If large amounts of grass or forb seeds are required for a project, seeds can be purchased from seed suppliers. Seeds of grass and forb species are best used for direct sowing, whereas seeds of shrubs and tree species are best used to grow nursery plants. One of the advantages of direct seeding is that it can be an inexpensive method of establishing plants for a large area.

8.1.2 Cuttings

Cuttings are taken from stems, roots, or other plant parts and directly planted on the project site or grown into rooted cuttings at a nursery for later planting. In the Sri Lankan context, information on vegetative propagation of wild plant species is scarce. However, substantial information is available on vegetative propagation of commercially grown plant species. Propagating plants from cuttings of most large native tree species is not possible under most conditions. If large quantities of cuttings are required, they can be propagated by growing in a nursery or other growing facility. However, in contrast to the deep taproot structure of naturally propagated large tree species, the root system developed from vegetative propagation (e.g., stem cuttings) often develop a root structure that spreads horizontally. If the purpose of tree species is to develop a deep and vertical root system, it is important to opt for seedlings.

8.1.3 Plants

Trees and shrubs are typically established using nursery stocks, rather than by direct seeding, for several reasons. First, obtaining seeds from most tree and shrub species is difficult. Second, shrub and tree seeds germinate and grow into seedlings at a slower rate than grass and forb species, giving them a disadvantage on sites where grasses and forbs are present. Therefore, starting shrubs and conifers from large plants instead of seeds gives them a competitive advantage over grasses and forbs because their roots are often longer and better developed, allowing access to deeper soil moisture. Grass and forb species are seldom established from nursery-grown plants because of the high cost of nursery management. Exceptions are when grass or forb seeds are rare or difficult to collect, if species are difficult to establish from seeds on disturbed sites, or when the project requires quick establishment.

8.2 Planting configurations

The pattern of vegetation which may be used in a given slope in order to achieve the best protection will depend on the purpose. The "Nepal Manual for vegetation structures for stabilizing highway slopes" recommends 04 basic configurations which is given below:

Root mats

The grass root "mat" is the commonest vegetation structure planted in Europe. Its main purpose is to reduce surface erosion, for which it is extremely effective. On steep slopes it has the disadvantage that under very wet conditions, the weight of the grass mat can exceed the shear strength of the soil just below the rooting zone, so that the mat slides off the slope. If it is to success on steep slopes, it must be planted in place by deeper-rooting plants spaced at intervals over the mat area.

Horizontal or contour lines

A great variety of techniques using vegetation and combination of live and dead materials have been developed in Europe. Their purpose is to break up long flow paths and to catch soil particles moving down the slope. Under conditions of moderate slopes and rainfall they are undoubtedly worthwhile. But on steep slopes in soils of low cohesion and under heavy rainfall they are far less effective. The water either runs straight through the planted grass lines, riling as it goes, or it ponds up behind the line until it bursts through as a mudflow. This destroys line and, in most cases, allows erosion to move rapidly up and down the slope. While these patterns have applications on steep slopes under the prevailing climate conditions in various countries, they are limited in usefulness.

Downslope or drainage course planting

The planting of vegetation in lines running down the slope is contrary to traditional techniques of soil conservation. It is techniques which has evolved in areas subject to short but intense periods of rain and where infiltration rates are high. The basic purpose is to is to impart strength is to top 50 com or so of the slope materials, while allowing excess water to run away rapidly before it has time to enter the soil mass. Damage to the slope is limited to riling and gullying, though there are ways to prevent this as well. But even a small amount so riling is infinitely preferable to the alternative of mass failure. Riling is usually slower to develop and easier to control. Plants grow on the ridges and keep the rills between relatively free of vegetation for rapid runoff. This technique has shown a considerable amount of success.

Diagonal lines

Making a compromise between contour and downslope planting is a challenging task. In certain situations, the advantage of the two configurations described above do not give the optimum benefits. Under those conditions, it is necessary to adopt a middle course. Vegetation concentrated in diagonal lines gives the advantage of partially breaking the flow of water while still allowing relatively rapid storm drainage.

Combinations of vegetation species

In time with the benefits of research, it may become possible to define the optimum configuration of planted or management vegetation for any particular site in Sri Lanka to suit its micro-climate and site conditions. Although the configurations mentioned above are more suitable for grass lines, they can be used effectively with mixture of different species. Natural vegetation supersessions include all levels and mixtures of vegetation types. Most natural forest have a high tree canopy, a middle storey and a ground layer which is also typical for the ancient Kandyan home garden system found in highlands of Sri Lanka. All of these contain a variety of species which interact to give a balanced system.

In using vegetation to stabilize slopes, plants are being manipulated to carry out an engineering role. Although it is possible to use certain species along for particular purposes, under certain conditions a combination of different plants may give the optimum results. The practical application should be to select a combine techniques of vegetative soil conservation techniques to give optimum results for any selected site. For each individual site it is necessary to establish the best configuration of techniques depending on the purpose, climate and site conditions in terms of soil fertility and other characteristics.

Some examples of combinations provided in the "Nepal Manual for vegetation structures for stabilizing highway slopes" are as follows:

- Contour grass lines can be seeded with shrubs to give a deeper low-weight rooting effect
- Bare slopes planted with trees can be seeded with grasses between the trees to improve surface cover
- Downslope grass lines can be strengthened with cuttings of trees placed among the grasses
- Contour cutting palisades can be interpolated with tree seedlings.

The best has to be determined though experiments in each site to give optimum treatment needed for the site in terms of erosion control and or arresting the conditions of shallow or deep-seated landslides.

8.3 Vegetative techniques

Howell (1999a) has suggested a set of main bio-engineering techniques in the Nepal road sector and their respective engineering functions which is given below:

Table 8-1 The main bio-engineering techniques used in the Nepal road sector and their engineering functions (Howell, 1999a)

System	Design and Function
Planted grass lines: contour / horizontal	Grass slips (rooted cutting), rooted stem cutting or clumps grown from seeds are planted in lines across the slope. They provide a surface cover, which reduces the speed of runoff and catches debris. Using this technique, a slope is allowed to develop a semi natural drainage system, gullying in a controlled way.
Planted grass lines: Downslope / Vertical	Grass slips (rooted cutting), rooted stem cutting or seedlings are planted in lines running down the slope. They armour the slope and help to drain surface water. They do not catch debris. Using this technique, a slope is allowed to develop a semi- natural drainage system. Gulling in a controlled way.
Planted grass line: Diagonal	Grass slips (rooted cutting), rooted stem cutting or seedlings are planted in lines running diagonally across the slope. They armour the slope and have limited functions of catching debris and draining surface water. This technique offers the best compromise of the grass line planting systems in many situations.
Planted grasses: Random planting	Grass slips (rooted cutting), rooted stem cutting or seedlings are planted at random on a slope, to an approximate specified density. They armour and reinforce the slope with their roots and by providing a surface cover. They also have a limited function of Catching debris. This technique is most commonly used in conjunction with standard mesh jute netting. Where complete surface protection is needed on very steep, harsh slope in most other cases, however, the advantages of one of the grass line planting systems. (Contour, downslope or diagonal) offer better protection to the slope.
Grass seeding	Grass is sown direct on to the site. It allows easy vegetation coverage of large areas. This technique is often used in conjunction with matching and jute netting to aid establishment.
Turfing	Turf, consisting of a Shallow rooting grass and the soil it is growing in, is placed on the slope. A technique commonly used on gentle embankment slopes. Its only function is armouring
Shrubs and tree planting	Shrubs or trees are planted at regular interval on the slope as they grow, they create a dense network of roots in the soil. The main engineering functions are to reinforce and later to anchor in the long-term large trees can also be used for slope support.
Shrubs and tree seeding	Shrubs (or tree) seeds applied directly to the site. This technique allows very steep, rocky and unstable slopes to be relegated where cutting and seedlings cannot be planted. There are two methods: direct sowing and broadcasting in the first, seeds are placed individually, whereas the second involves throwing the seeds all over the site. The main engineering functions are to reinforce and later to anchor.
Large bamboo	Large bamboos can reduce movement of materials and stabilize slope. They are usually raised by the traditional method or by rooted culm cutting from a nursery. Large clumps of the larger stature bamboos are one of the most substantial vegetation structures available to reinforce and support a slope. However, they do not have deeply penetrating roots and so do not serve an anchoring function; also, they can surcharge upper slope areas.
Brush layering	Woody (or hardwood) cutting are laid in lines across the slope, usually following the contour. These from a strong barrier, preventing the development of ills, and trap materials moving down the slope. In the long term, a small terrace will develop. The main engineering functions are to catch debris, and to armour and reinforce the slope, in certain locations brush layers can be angled to provide drainage.
Palisades	Woody (or hardwood) cutting are laid in lines across the slope, usually following the contour. These from a strong barrier and trap material moving down the slope in the long term, a small terrace will develop. The main engineering functions are to catch debris, and to armour and reinforce the slope, in certain locations, palisades can be angled to provide drainage.
Live check dams	Large woody or (hardwood) cutting are planted across a gully, usually following the contour. These from a strong barrier and trap material moving downwards. In the longer term, a small step will develop in the floor of the gully. The main engineering functions are to catch debris, and to armour and reinforce the gully floor.
Fascines	The word "fascine" means a bundle of sticks. In this technique, bundle of live branches is laid in shallow trenches. After burial in the trenches. They put out roots and shoots, forming a strong line of

System	Design and Function
	vegetation. It is sometimes called live contour Watling. The main engineering is to catch debris, and to armour and reinforce the slope in certain locations, fascines can be angled to provide drainage. Where time is at a premium, brush layers may be more appropriate as these are quicker to establish than fascines.
Vegetated stone pitching	Slopes are strengthened by a combination of dry-stone walling or cobbling, and vegetation planted in the gaps between the stones. There are two district uses: reinforced toe walls: and protected gully beds. This technique provides a very strong form of armouring. Because it specifically uses vegetation to strengthen a simple civil engineering technique, it represents a stronger form of normal stone pitching.
Jute netting (standard mesh)	A locally made geo-textiles of woven jute netting is placed on the slope. Standard mesh jute netting (mesh size about 40x 40 mm has 04 main functions. i.) Protection of the surface armouring against erosion and catching small debris. ii.) Allowing seeds to hold and germinate iii.) As it decays, it acts as a mulch for the vegetation to get established
Jute netting (wide mesh)	A locally made geotextiles of woven jute netting (mesh size about 150x450 mm) is placed on the slope. It is used to hold mulch on the slopes that have been seeded and serves no engineering functions itself. Any use of jute netting is a temporary measure designed to enhance the vegetation establishment. It does not protect a surface for more than one or two seasons of monsoons.

8.4 Comparative assessment of different vegetative techniques

The methods of vegetative techniques differ from site to site depending on the slope conditions, expected bio-engineering function, affordability etc. A Comparative assessment of different Vegetative techniques is provided in the Table 8.2 as indicated by Howell et al. (1991).

Table 8-2 Comparative assessment of different Vegetative techniques (Howell *et al.*, 1991)

Technique	Function	Sites	Advantages	Disadvantages	Timing	Care and Maintenance
Tree and shrub planting	Create a dense network of roots in the soil and canopy over the surface	Can be used on almost any slope up to 35. With care it can go up to 45	• Cuttings can be used not to have damages to slope • Moving debris have less chances for damages to cuttings	• Slower to establish than seedling • Roots need to develop in to undisturbed soil, which is difficult • Lower success rate than using seedlings from a nursery	During early monsoon period	• Weeding in the early years and thinning later • Disease and pest control
Planted grass lines	Protection of slope and providing a surface cover. Lines can be angled in order to reduce the run-off and give rapid drainage	On any slope. On cultivated slopes 35 horizontal lines can be used to minimize loss of soil and help	• Water moving down the slope is allowed and no possibility for scouring • Material moving down will be trapped behind grass lines • Moisture is conserved.	• When grass lines cannot evolve properly will be subjected to the forces of erosion. • Material collected behind grass lines can become too heavy for grass to hold. It can	During early monsoon period as soon as ground is wet enough to support sustained growth	Watering during the periods of not very effective monsoon periods. Replacing the dead grass which is labour intensive operation.

Technique	Function	Sites	Advantages	Disadvantages	Timing	Care and Maintenance
	possibility	conserve moisture		create small slump and gully features.		
Palisades of cuttings	When woody cuttings are planted in lines across the slope it can form a strong barrier and trap material moving down	Can be used on slopes up to 75. Slopes over 60 it is generally better	• Cuttings can be placed with minimum disturbance to slope • Method is much cheaper and quicker • Cuttings from shrubs produce a far stronger and more solid palisade	Slower to establish than rooted seedlings Plan has to put roots in to undisturbed slope with is difficult Debris accumulated behind the palisade can over wet in very heavy rain and slump	Just before the monsoon start after initial rains.	Some thinning after a few years. Necessary to chop trees periodically to prevent buildup of excessive weight of branches
Grass seeding	Grass is sown direct on to the surface. (often used in conjunction with physical soil conservation measures)	Any bare site with slopes up to 45. In case of steeper slopes up to 65 is used in conjunction with physical measures	• A cheap and rapid method of establishing a cover of grasses • Quick and non-intrusive when used in conjunction with other techniques • Highly effective when carried out at the right time.	• Grasses are slower to develop in to sizeable plants • Seeds can be washed completely off the slope during heavy rain • Newly germinated seedlings can be scorched and killed by hot sun if exposed	Ground preparations should be carried out in advance so that seedlings can be introduced during effective period of monsoon	Cover if any should be removed once the seedlings reach a height of 2-3 cm. Protection from animals and avoid grazing problems. Thinning the grass after 01 year will help speed up the development. Better to leave the more dominant plants and remove very small seedlings.
Tree and shrub seeding	This allows very steep, rocky and unstable slopes to be re-vegetated where cuttings and seedlings cannot be planted	Any steep, rocky and unstable sites (event near vertical slopes can be treated by direct seeding.	• Cheap and rapid as it requires minimum efforts. • Seeds are sown exactly where they are required to grow, on terrain too difficult for other planting techniques • Plants which cannot be raised well in nurseries can perform	• Sowing seeds individually is very labour intensive	Better if sowing to take place as soon as the monsoon rains are underway	Protection, replacement where failures are visible and thinning when necessary.

Technique	Function	Sites	Advantages	Disadvantages	Timing	Care and Maintenance
			better using this technique.			
Bamboo planting	The planting of large bamboo to reduce movement of material and stabilize slopes	Any fill site can be planted. Any cut slope with an angle of 45 except in very dry and stony sites. Best for stabilizing the lower part of a slope	• No nursery space is required • The rhizome will give a large new shoot relatively quickly • Proof against grazing animals	• Requires a lot of material and is damaging to the parent clump • Involves a large operation at a busy time of the year	The operation should be carried out during heavy monsoon rain periods	Replacement of failures Protection is essential for plants from node cuttings for the first two years After about 05 years culms will be available for cutting and process should be managed well.
Turfing	To prevent soil erosion. This technique also commonly used for cosmetic purposes and creating a better esthetic appearance	This technique is good for any gentle slopes (less than 35)	• It helps to provide an immediate surface cover • Little efforts for prior planning required.	• Only a shallow surface skin with no initial bonding to the material beneath. It can fail and slide off along the plane • Only shallow rooting grasses can be used • Safe sources are limited in the mountains	Early monsoon in order to give longer period for establishing after the placement on slope.	Replacement of failed areas. If dry period is selected for placement suitable supply of water should be arranged. Some protection is necessary for avoiding high grazing pressure.
Fascine constructions	A technique which involves bundling of live branches and laying them in shallow trenches. After burial in the trench to form a strong line of vegetation	Best used on consolidated debris or soft cut slopes. If the material is too hard growth will be slow. Maximum slope is less than 45	• Not affected by falling debris • Act as a scour check. If undermined they can bridge the gap and still thrive • Shoots tend to show more vigour than those from palisades or hardwood cuttings • Can be installed before the busy early monsoon planting period	• Require a large amount of cutting material • May encourage infiltration and saturation of the surface layer. In case of soft poorly drained material this can lead to shallow failures • Fascines run right across the slope and if a bad failure occur in one place that may affect the whole fascine	Because they are completely buried, fascines can be placed in mid or late monsoon period. In damp sites mid monsoon periods were not much heavy rains	Little later management required beyond protection against grazing. For failure areas most suitable if they are replaced through shorter fascines
Live fence constructio	Fences made out of live	Non-farmland on	Can be placed as pegs at intervals of	• Require a large amount of	Because of the large	There seems to be a large

Technique	Function	Sites	Advantages	Disadvantages	Timing	Care and Maintenance
n	cuttings are placed across the slope so that debris and water moving down the slope are trapped behind.	gentle slopes maximum up to 35. Very limited success elsewhere.	25 cm by hammering cuttings in to the ground. Pegs should protrude about 30 com	cutting stock • Although most of the cuttings should stay alive and grow roots there will be high failure rate • Many fences are thin and easily pushed over by accumulating debris • Infiltration is increased and moisture build up in the material accumulated behind	amount of exposed cuttings, installation should only take place once the monsoon rains have broken	failure rate and weak areas of the fence should be repaired and replaced.
Vegetated rip-rap and vegetated gabions	Slopes are strengthened by a combination of dry-stone walls and vegetation planted in the gaps between the stones.	Steep, low slope toe walls of up to 2 meters in height and gully areas with a maximum slope of 50	• A thin toe wall is strengthened by vegetation • Stones are not easily dislodged once the vegetation is established and as the life of the rip rap is considerably lengthened.	• Can only be used on short slopes and does not have the strength of gabion and masonry walls. • Cannot be used in steep gullies and in areas where supply of debris passing down the gully is high.	Rip-rap wall can be built at any time and dry season is preferable. Cuttings or seeds should be placed during early monsoon or before monsoon	Protection and restocking of failures Thinning may be necessary as shrubs may develop. They should not be permitted to become too tall.
Mulching	Chopped plant material or brushwood is laid across the slope to form a surface cover. This is good as a temporary measure to help other plants to establish	This is a technique used to help establishing a vegetation cover in suitable places	• Good as a temporary measure • Chopped plant material or brushwood can be used to pay across the slope to form a surface cover	Not much useful as a permanent measure	Simultaneously with other measures when and where suitable only	Should be removed after establishing the plant cover.

8.5 Slope stabilization techniques used at different scales of seriousness

Despite the versatility of the bioengineering measures and techniques, the complexity of most sites means that a range of techniques are usually required for slope stabilization. It is more or less similar to the approach adapted during selecting most appropriate geo-engineering measures that are meant for slope stabilization. As seen from the given explanations in above mentioned techniques are used to fulfill different but complementary functions. The engineers who are responsible for designing slope stabilization measures using bio-engineering or hybrid techniques need to assess every site individually and determine the optimum set of measures and stabilization procedures. It is seen that larger the scale of the problem, more techniques are required to fulfill the functions and therefore more functions need to be considered. Accordingly, solutions may become more complex and selection of techniques need to be based on such requirements. On the other hand, when the scale is smaller the problems also become simpler and more straightforward and inexpensive measures could be used in stabilizing slopes. As an example, the Table 8.3 provides a set of sample techniques required to fulfil the engineering functions of slope stabilization at different scales of seriousness as suggested by Howell (1999a).

Engineering Functions	Small Scale	Medium Scale	Large Scale	Major Scale
		Simple		
Catch	Contour grass lines	Bush layers or palisades	Large bamboo clumps	Gabion catch wall
Armour	Grass lines	Standard jute netting and random grass planting	Not applicable	Vegetated stone pitching
Reinforce	Grass lines	Brush layers, palisades or fascines	Planted shrubs or tress	Reinforced earth or cement slurry
Anchor	Not applicable	Planted shrubs or trees	Planted trees	Soil or rock anchors
Support	Not applicable	Not applicable	Large bamboo or trees	Retaining wall
Drain	Diagonal or downslope grass lines	Angled brush layers, palisades or fascines	Vegetated stone pitching	Masonry or gabion drain
		Composite		
Catch/armour	Contour grass line	Brush layer or palisades with grass line in between	Large bamboo clumps with grass line in between	Gabion catch wall with vegetated stone pitching
Catch/armour/ reinforce	Contour grass line	Brush layer or palisades with grass line in between	Large bamboo clumps with grass lines and planted shrubs or trees in between	Gabion catch wall with vegetated stone pitching and reinforced earth or cement slurry
Armour/support	Contour grass line	Brush layer or palisades with grass line in between	Planted shrubs or trees with grass lines in between	Vegetated stone pitching and reinforced earth or cement slurry
Reinforce/anchor	Not applicable	Brush layer, palisades or fascine with planted shrubs or trees in between	Planted shrubs and trees	Reinforced earth or cement slurry and soil or rock anchors
Anchor/support	Not applicable	Not applicable	Large bamboos and trees	Soil or rock anchors and retaining wall
		Composite		
Catch/armour/ drain	Diagonal grass line	Angled brush layer or palisades with grass lines in between	Large bamboo clumps with vegetated stone pitching	Gabion catch wall with vegetated stone pitching and possibly other

Engineering Functions	Small Scale	Medium Scale	Large Scale	Major Scale
				masonry drains
Armour/reinforce/ drain	Diagonal grass line	Angled brush layer or palisades with grass lines in between	Planted shrubs or trees with vegetated stone pitching	Vegetated stone pitching and reinforced earth or cement slurry and masonry or gabion drains

CHAPTER 09

MODELING THE ENHANCEMENT EFFECTS OF VEGETATION ON SLOPE STABILITY

NBLRM

Chapter 9 MODELING THE ENHANCEMENT EFFECTS OF VEGETATION ON SLOPE STABILITY

9.1 Introduction

Numerous research studies have demonstrated that vegetation could produce positive influences on stability of slopes (Ali *et al.*, 2012, Leung *et al.,* 2015). Pallewatta *et al.* (2019) used the term "Green Corridor" concept whereby ground conditions are improved for civil infrastructure with native vegetation. Vegetation has been used in slope stabilization for centuries to prevent erosion and provide stability, albeit carried out without proper engineering quantification or design. Bioengineering aspects of native vegetation in relation to geotechnical engineering have been included to some extent over the previous decades to increase soil stiffness, stabilize slopes, and control erosion. The lack of proper details regarding the quantification and design methodologies has been the main factor that has hindered the more widely application of this method in practice.

Conducting a detailed geotechnical assessment to acquire the necessary parameters for the detailed modelling according to different scenarios will be a comprehensive coverage on this subject. This chapter discusses the information on conducting a geotechnical assessment, acquiring necessary parameters, and modelling for different scenarios.

9.2 Geo-technical assessment

Conducting a geo-technical assessment is necessary to acquire the required information to model the situation and assess the level of stability of the slope.

Slope stability will depend on the following (modeling requires following information):

a) Materials involved including:
   - Material properties (cohesion and the internal friction)
   - Fracture density and quality
   - Degree of weathering of the material
b) Geometry of material
c) Slope angle
d) Weight and load distribution
e) Water content and the phreatic surface
f) Type of vegetation and its density
g) External impulsive forces (such as vibrations due to earthquakes, change of phreatic surface due to rainfall, etc.)

Assessment of factor of safety

The factor of safety of a slope describes the stability of the slope and is a ratio of the resisting forces to driving forces. A factor of safety greater than one indicates a stable slope, however greater than 1.2

indicates a safer slope. There are multiple methods for calculating the factor of safety of a slope. The calculation of safety of a sliding block on a plane (a layered slide with preferential failure along pre-existing weaknesses) is shown in Figure 9.1. This calculation considers slope angle, friction, cohesion, and ground water table. Increase in ground water table and slope angle will decrease the factor of safety. Also, increase in friction and cohesion will increase the shear strength and therefore increases the factor of safety. This calculation for sliding plane to obtain the factor of safety cannot be applied to homogenous soils where there is no preferential weak layer to initiate a failure. The failure surface in homogenous soils is sub-spherical, resulting in a rotational slide.

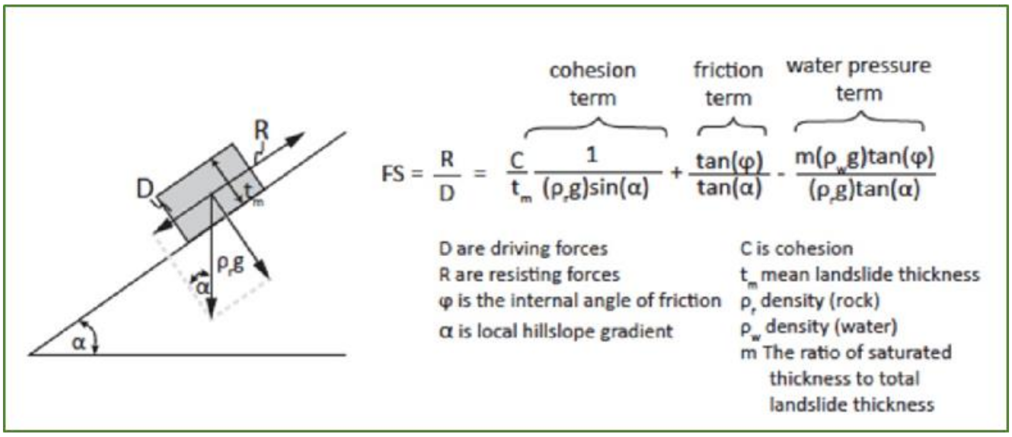

Figure 9-1 Factor of safety calculation for a sliding block

Material properties which control the strength of a rock or soil are key governing factors on the type of failure. The intrinsic strength of a rock or soil comes from cohesive strength and the internal friction. In fine-grained soils, cohesion is a result of electrostatic bonds between clay and silt particles and is in the order of a few kPa. Sands and gravels are effectively cohesion-less. Rock has much greater cohesion due to interlocking particles and cementation. Cohesion values for rock may be 1000 times larger than those of soils. The internal friction of a soil or rock is due to the frictional forces between grains, and is often represented as the internal angle of friction, Φ. The internal angle of friction depends on grain size and grain properties, and can range from 0 to 45. Sandy soils and gravels generally have a friction angle between 30 and 40 degrees when there is no influence from clayey fraction, while a considerable clayey fraction in soils tend to have a friction angle from a very low value up to about 35 degrees. These values are generalizations and do not apply to all soils in these categories.

The cohesion and internal angle of friction can be determined for small representative samples in the lab using a tri-axial compression test or direct shear or a uniaxial compression test (among others). Small-scale tests can also be used to measure the strength of individual discontinuities. However, these small-scale tests do not consider the large-scale heterogeneities encountered in the field, such as variable weathering, fractures, jointing, and bedding. Large-scale heterogeneities often control the initiation and location of failure. Therefore, multiple failure criterions to evaluate the stability of a slope accounting for large-scale discontinuities have been developed. All these parameters require a careful study of a field site and they are difficult to apply broadly in all cases due to site specific restraints.

Changes in the center of gravity of a potential failure can trigger a failure or serve to stabilize a slope. Adding more weights to the top of a potential failure will decrease the stability while adding weight to the base of the same potential failure can increase the stability. The role that weight distribution plays is also dependent on geometry of the slope. Vegetation generally serves to stabilize a slope; the roots of plants serve as anchors, and vegetation reduces the water content of a slope. However, vegetation also adds weight to a potential slide, and can decrease the stability. All of these factors must be evaluated for each potential and already occurred slides when analyzing them.

9.3 Parameters needed for modeling

The effect of vegetation on slope stability relies on (a) the mechanical strengthening provided by the tree roots due to the anchoring effect of main roots, (b) the improvement in cohesion due to hair roots and (c) an increase in the matric suction of soil induced by the root water uptake.

9.3.1 Root reinforcement effect

Tree roots can increase the shear strength of soil by mechanical means. Over the past few decades the increase in the shear strength of soil with tree roots has been discussed and examined in numerous different ways by various research groups. Docker and Hubble (2001) suggested that tree roots can provide mechanical strength to soil in two main ways;

1. Increase the shear strength due to the anchoring effect of larger, stiffer roots
2. An increase in shear strength due to the apparent cohesion provided by smaller roots

Wu et al. (1979), Waldron & Dakessian (1981) and Docker & Hubble (2009) studied the effect of mechanical strengthening generated through root reinforcement as an increase in the shear strength (ΔS) in saturated conditions. Waldron & Dakessian (1981) and Wu *et al.* (1979) developed a simple root model to mathematically explain the behavior of roots under a shearing action, however, according to Docker and Hubble (2001), the results from using this model are only 50% of the actual experimental results because of oversimplification of the root system behavior.

Development of a simple root model (mathematical model)

Waldron (1977) and Wu et al. (1979) independently developed a simple model to evaluate the contribution of the tree roots to the shear strength of soil (i.e. to determine $\Delta\tau$). This model simulates an idealized situation where the vertical roots extend across a potential sliding surface in a slope. It consists of a flexible, elastic root extending vertically across a horizontal shear zone of thickness z, as shown in Figure 9.2.

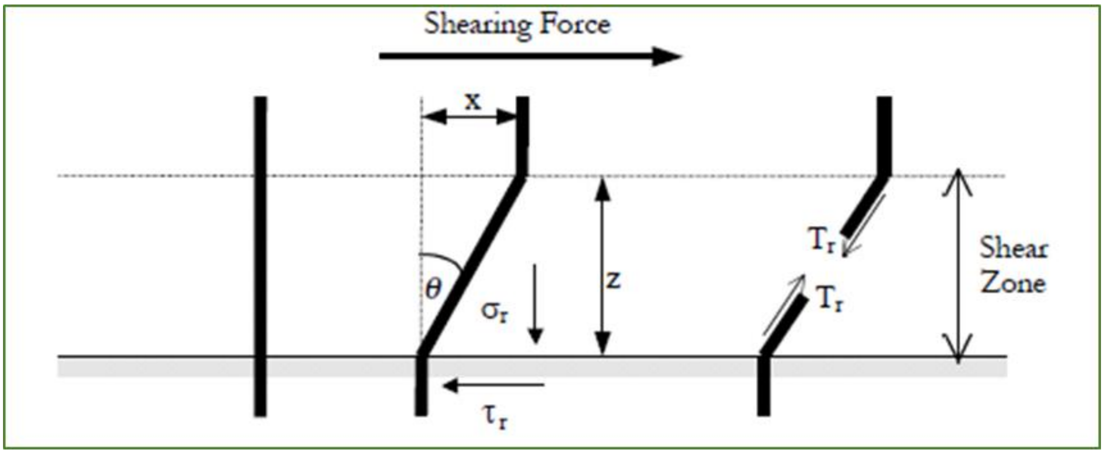

Figure 9-2 Schematic Diagram to show root deformation under shearing (after Waldron 1981)

As Figure 9.2 shows, soil is sheared as the tensile force T_r develops in the roots. This force can be resolved into a tangential component (τ_r) which resists shear, and into a normal component (σ_r) which increases the confining stress on the shear plane. The average tensile strength of roots per unit area of soil is t_r while Θ is the angle of shear distortion of the root.

$$\tau_r = t_r \sin\Theta \; and \; \sigma_r = t_r \cos\Theta \qquad (1)$$

According to Waldron (1981), ΔS which is the soil reinforcement calculated from root properties can be added directly to the Coulomb equation, as shown in Equation 2, because there is no change in the friction angle.

$$\tau = c + \Delta S + \sigma_N tan\varphi \qquad (2)$$

In Equation 2, τ is the shear strength of soil, c is the cohesion of soil, σ_N is the applied normal stress, and φ is the friction angle of soil.

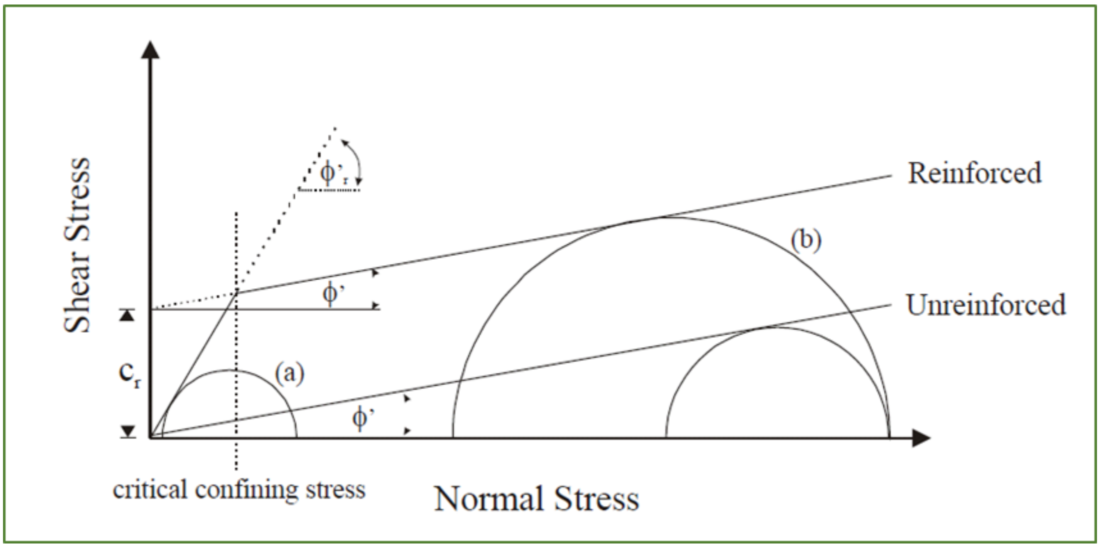

Figure 9-3 Mohr-Coulomb envelopes for reinforced and unreinforced soils with circles describing failure by (a) slippage and, (b) reinforcement rupture

Figure 9.3 represents the behavior of Mohr-coulomb envelopes in reinforced and unreinforced soils. The critical confining stress varies for different soil-fiber systems and is a function of properties such as the tensile strength and modulus of the fibers, the length/diameter ratio of fibers, and the frictional characteristics of the fibers and soil. The contribution of the root to shear strength (△S) is then given by Equation 3.

$$\Delta S = \sigma_r tan\varphi + \tau_r = t_r(\cos\Theta \tan\varphi + \sin\Theta) \qquad (3)$$

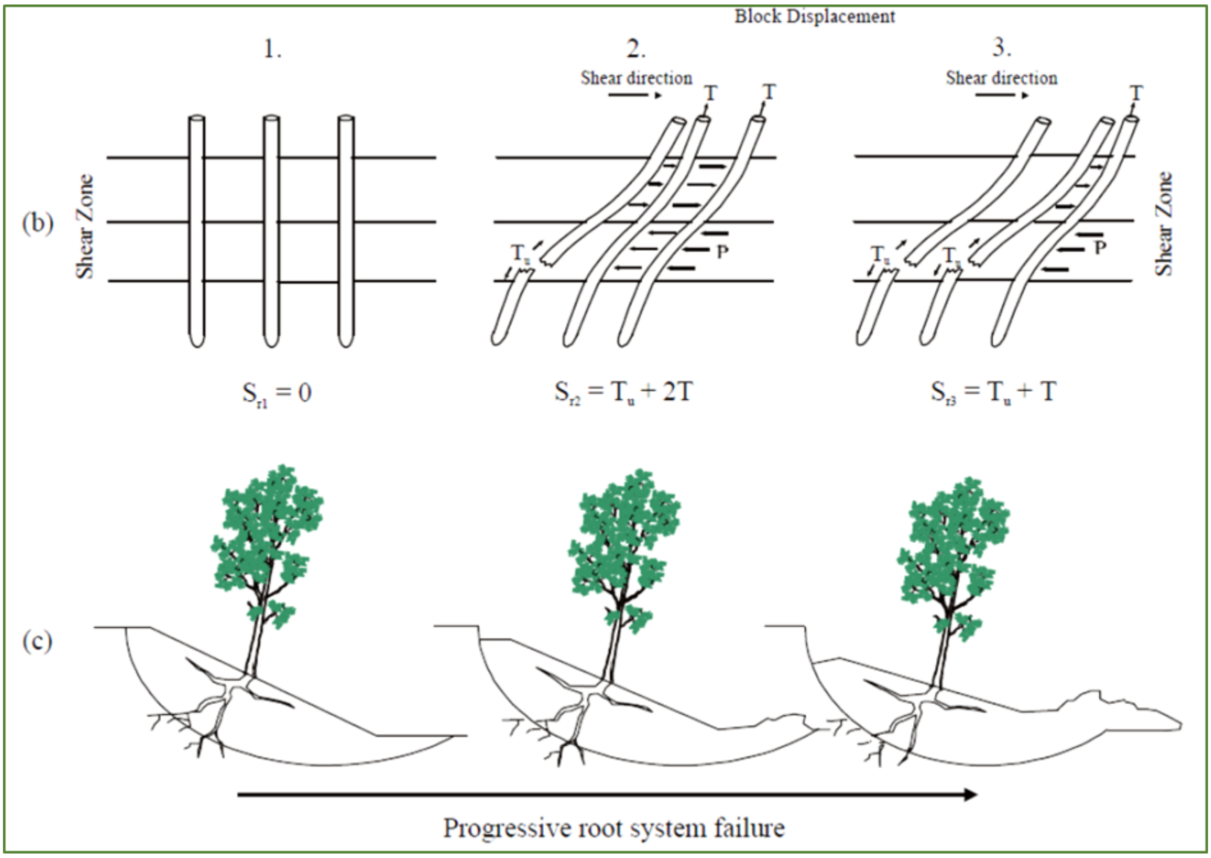

Figure 9-4 Schematic diagram to show the progressive root failure of roots (after Docker and Hubble 2001)

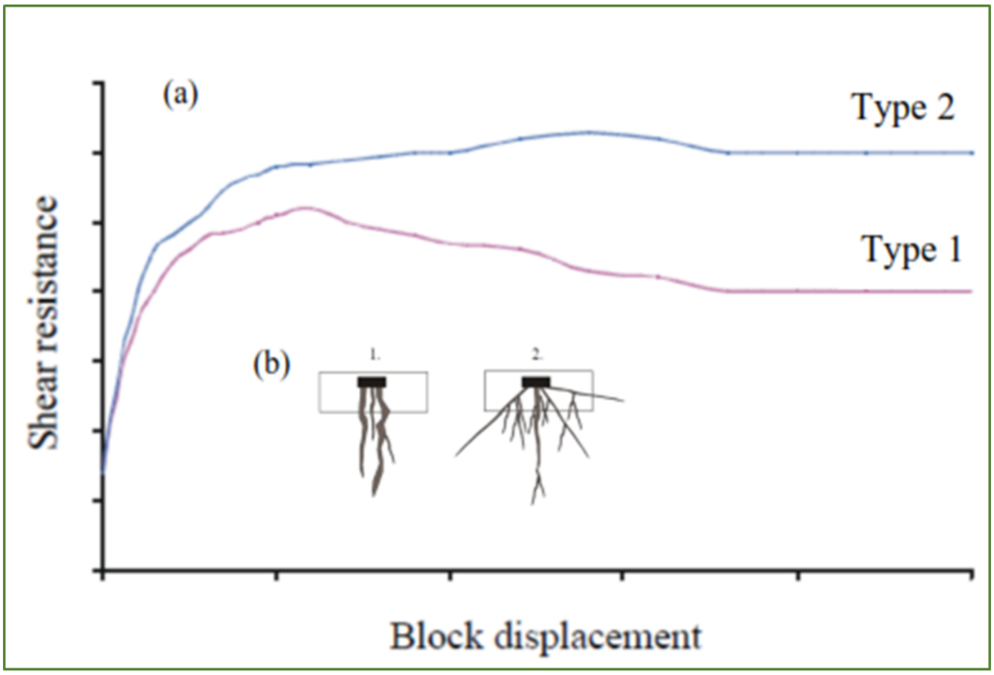

Figure 9-5 Shear resistance over block displacement for two types of spatial distribution of roots (modified after Docker and Hubble 2009)

In Figure 9.5, Type 1 exhibits a reduction in shear resistance after reaching a peak in the same manner as a soil only test, but with higher peak resistance values and at greater displacements. Type 2 exhibits little or no reduction of shear resistance throughout the test, where the final shear resistance generally becomes peak resistance. These facts indicate that the spatial distribution of roots would contribute to soil reinforcing more than all the other factors (Pallewattha, 2017).

9.3.2 Hydrological effect

The root water uptake of trees increases the matric suction of adjacent soils due to a reduction in the moisture content, which therefore makes the tree-soil matrix unsaturated for almost one whole year. Trees like Pinus radiata can absorb a water content equal to its own weight per day from the soil underneath and most mature trees can generate suction in the soil- root system of up to 30MPa. The main factor that affects the root water uptake is the rate of transpiration of the tree, and this depends mainly on the environmental parameters and the physiology of the tree(s). The humidity, temperature, wind speed, and the soil moisture condition (soil water potential) and tree physiology are the main environmental factors which affect the transpiration of trees.

Indraratna *et al.* (2006) developed a relationship for root water uptake based on the potential transpiration of a tree and the reduction factors due to soil suction, as shown in Equation 4.

$$S(x, y, z, t) = f(\psi)G(\beta)F(T_P) \qquad (4)$$

Where $f(\psi)$ is computed using Feddes et al. (as cited in Indraratna et al. 2006), $F(T_P)$ is the factor related to the potential transpiration by referring to the relationship developed by Nimah and Hanks (as cited in Indraratna et al. 2006), as represented in Equation 5.

$$F(T_p) = \frac{T_P(1+k_4 z_{max}+k_4 z)}{\int_v^t G(\beta)(1+k_4 z_{max}+k_4 z)dv} \qquad (5)$$

Where $G(\beta)$ is root density effect and k_4 is an experimental coefficient.

Considering all the relationships shown above, it is logical to conclude that the root water uptake is directly proportional to the shape of the root system, soil suction, and the potential occurrence of transpiration which is related to the leaf system of trees. Figure 9.6 provides a general understanding of the dependency of the stability of slopes on thermo-hydro-mechanical process which is taking place in the soil, which are connected to both climatic and vegetation conditions at the ground surface.

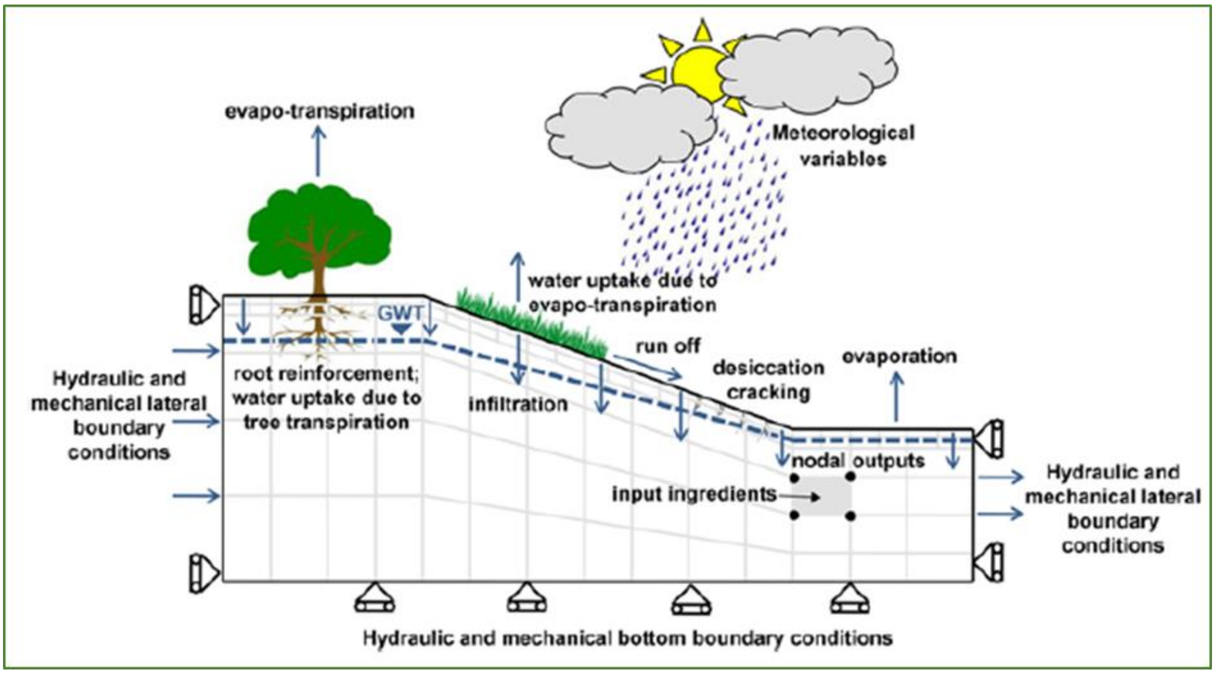

Figure 9-6 Schematic slope model and potential slope-vegetation-atmosphere interaction phenomena. (Elia *et al.*, 2017)

9.4 Case study

In the World Bank funded Nature Based Landslide Risk Management project implemented in Sri Lanka by NBRO, a computer model was generated to evaluate the positive impacts of vegetation and hybrid solution on slope stability. Data from pilot site at Badulusirigama in Badulla district is presented to demonstrate the type of analysis carried out. General information about these pilot sites are provided under Chapter Four.

9.4.1 Numerical analysis of the slope

The conditions of the slope were simulated in Geo Studio modules considering both Finite Element and Limit Equilibrium approaches. The analysis was conducted under three cases:

1. Slope without any mitigation measures,
2. Modified slope with subsurface drains and
3. Modified slope with application of a hybrid system (Sub-surface drains + vegetation).

Information on the sub surface profile were extracted from the investigations done by JICA team of investigation in September, 2015 and the test results available at NBRO. Idealized subsurface profile is shown in Fig. 9.7 and the different strength properties assigned for each subsurface layer is summarized in Table 9.1.

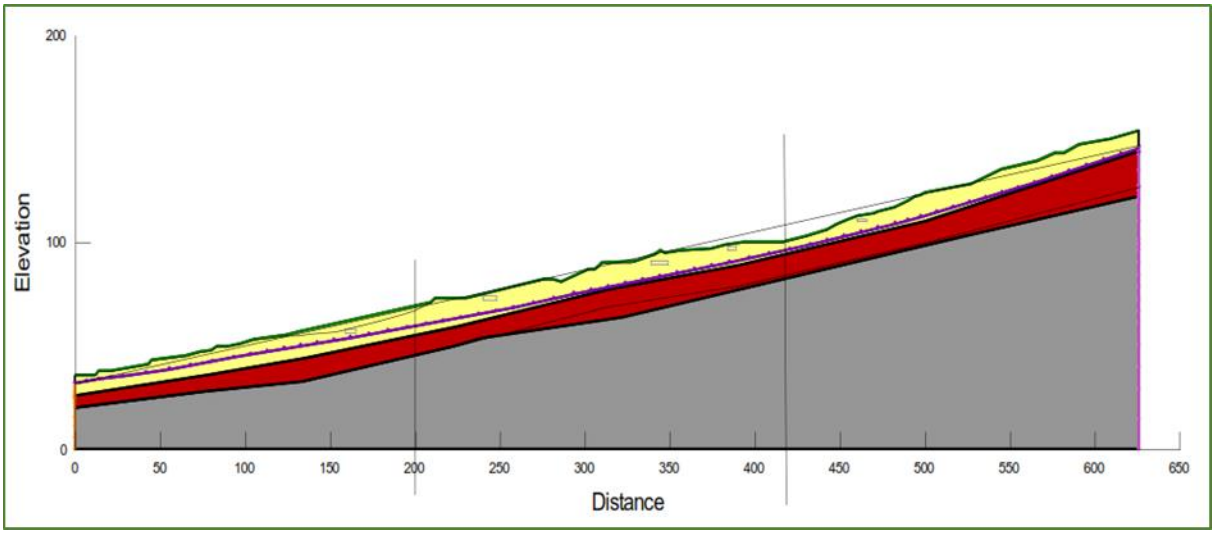

Figure 9-7 Idealized subsurface profile

Table 9-1 Geotechnical parameters assigned for each subsurface layer

Layer	Colour code	Cohesion (kPa)*	Internal friction angle (deg)*	Angle of shearing resistance with respect to suction (deg)**	Unit weight (kN/m^2)
Colluvium		7	12	10	15
Completely weathered rock (soil)		7	14	-	16
Mod. Weathered Rock		20	40	-	19

**Japanese International Cooperation Agency (JICA), (2015)*
***Kankanamge et.al (2018*

The subsurface profile shown in Figure 9.7 was divided into three zones after studying the results of the geophysical investigations carried out by JICA team of experts. Figure 9.8 shows the division of those three zones. In the stability analysis, each zone was modelled separately. The slip surfaces for respective zones were assumed to be at a depth of around 3m to 5 m.

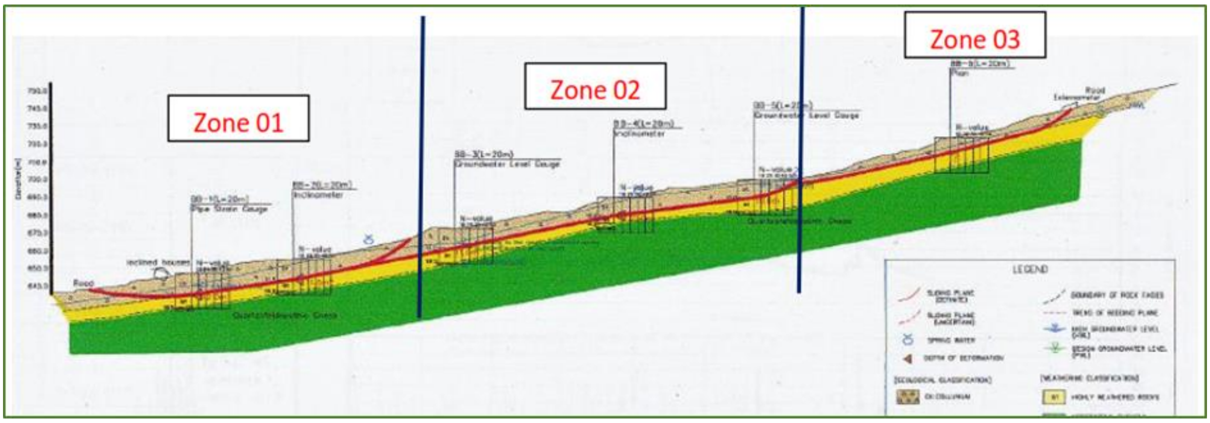

Figure 9-8 Division of three zones for stability analysis

9.4.2 Results and discussion

Case 1: Slope without any mitigation measures

Table 9-2 Factor of safety (FoS) for different zones when there are no mitigation measures

Zone	FoS under existing conditions
01	1.001
02	0.959
03	0.913

From the stability analyses conducted, it is evident that the Zone 03 has the lowest safety margin indicated by a factor of safety value of less than one. The safety criteria of the other two zones are also not satisfactory as the FoS value is slightly greater than one which is not acceptable (Table 9.2). Therefore, appropriate mitigation measures are needed to apply in order to improve the safety margins of the entire slope.

Case 2: Modified slope with subsurface drains

Under this case, the slope was analyzed by introducing subsurface drains drilled at different levels and having length of approximately between 30- 40 m. The angle of inclination of these drains are maintained between 6 degrees and 9 degrees with respect to the horizontal. The new safety margins of the slope and the percentage increase of the FoS are summarized in the Table 9.3.

Table 9-3 Factor of safety improvement after drainage improvement

Zone`	FoS before drainage improvement	FoS after drainage improvement	Percentage increase of FoS
01	1.001	1.180	17.9
02	0.959	1.137	19.6
03	0.913	1.140	24.9

Table 9.3 indicates that stability has increased upon the introduction of subsurface drainages. The highest increase of factor of safety is observed in zone 3.

Case 3: Modified slope with hybrid solutions (Subsurface drainage + vegetation)

The effect of vegetation was incorporated to slope stability by incorporating an additional soil cohesion due to presence of roots which is defined as root cohesion.

Calculation of root cohesion and its variation due to different spacing patterns

Step 1:

The formula given in Equation 6 was used to calculate the tensile strength (T_r):

$$T_r = \frac{F_{max}}{\pi\left(\frac{D^2}{4}\right)} \qquad (6)$$

where F_{max} is the maximum force (N) needed to break the root and D is the mean root diameter (mm) before the break.

Step 2:

Root cohesion (C_r) which is needed for design and analysis of the stability of slopes was obtained from the formula given in Equation 7. It was obtained from the study carried out by Schwarz et al. (2010);

$$Cr = 0.48 * Tr * (RAR) \qquad (7)$$

$$RAR = \frac{A_R}{A} = \frac{\sum n_i a_i}{A} \qquad (8)$$

where

n_i= the number of roots in size class i

a_i= the mean cross-sectional area of roots in size class i

A = total area of soil

This increment in cohesion value is used in stability assessments to evaluate the vegetation effect and was applied in function of the plants' root zone.

Step 3:

In this step, an average value of root cohesion for the entire slope, $\bar{c}_r$ was calculated considering the spacing between each plant row as suggested by Mahannopkul & Jotisankasa (2019). They have applied Equation 9 for testing *chrysopogon zizanioides (vetiver)* plants:

$$\bar{c}_r = \frac{c_r l_r}{l_r + l_s} \qquad (9)$$

l_r – width of the plant row

l_s – spacing between each plant row (width of the non-reinforced zone)

For this analysis, *Eugenia caryophyllus* species which is commonly known as Clove was used. Its properties were given in the Table 9.4.

Table 9-4 Properties of the Clove root

Width of plant row (l_r) (m)	Average root cohesion (MPa) for different spacing between each plant row (l_s) (m)			
	2.0	1.5	1.0	0.5
0.5	0.010	0.012	0.016	0.020

The shear strength parameters of Colluvium soil layer were adjusted accordingly due to presence of *Eugenia caryophyllus* roots. The amended values are given in Table 9.5.

Table 9-5: Revised geotechnical parameters upon application of vegetation (Eugenia caryophyllus)

Layer	Colour code	Cohesion (kPa)	Internal friction angle (deg)	Angle of shearing resistance with respect to suction (deg)*	Unit weight (kN/m^2)
Colluvium with vegetation		22	12	10	15
Colluvium		7	12	10	15
Completely weathered rock (soil)		7	14	-	16
Mod. Weathered Rock		20	40	-	19

The soil layer "Colluvium with vegetation" was assigned by considering the average root depth zone of *Eugenia caryophyllus* which is around 2m to 3m. The variation of factor of safety upon introduction of subsurface drainages and vegetation (hybrid solution) is given in Table 9.6.

Table 9-6: Variation of factor of safety (FoS) after applying sub-surface drainages with vegetation

Zone	FoS before introducing vegetation for shallow slip surfaces	FoS after introducing vegetation for shallow slip surfaces
01	1.18	1.38
02	1.13	1.41
03	1.14	1.23

This analysis shows that the factor of safety values could be increased even further by introducing vegetation coupled with subsurface drainages (or engineering measures for mitigation).

9.4.3 Conclusions & Remarks

- Application of subsurface drainage alone improves the FoS to a value near 1.2;
- Application of the hybrid system improves the safety margin of the slope to a value greater than 1.20;
- When designing a hybrid system, it is important to have a quantitative idea about the amount of additional strength which can be provided by roots to the soil. In this regard, already proposed models in quantifying the additional strength can be used;

- In order to provide a cost-effective solution, the contributions of both engineering and nature-based systems must be assessed;
- The applicability of such mitigation technique could be analyzed by Finite Element and Limit Equilibrium methods;
- The proposed model could be applied to similar conditions to assess the stability of hybrid systems for slope mitigation.
- In this analysis the root reinforcement effect is modeled as an increase in the cohesion. The real contribution could be even more if the exact evapotranspiration effects of plant species were modeled.

CHAPTER 10

ESTABLISHMENT OF PLANT NURSERIES

NBLRM

Chapter 10 ESTABLISHMENT OF PLANT NURSERIES

10.1 Factors to consider during establishment

It is necessary to establish Plant Nurseries to serve as the sources for plant material that will be used in execution of bio-engineering designs aimed at improving the stability of slopes and erosion control. Currently such nurseries are being operated by government institutions and private parties in different scales. But it may not be possible to obtain required plants from such nurseries as per the requirement of the designs prepared for various sites. This chapter will attempt to provide some idea on establishment, operations and maintenance of plant nurseries, for those stakeholders involved in application of NbS and Hybrid solutions for landslide risk mitigation. Some of the information described herein were extracted from the work of Howell (1999a) and Howell (1999b).

It is desirable to establish plant nurseries for all the sites where the NbS is planned for landslide risk mitigation. The idea is to create an opportunity for uninterrupted supply of necessary quantity of healthy plants to the intended sites during execution of NbS and during maintenance period. If there are few sites within a close distance it is also appropriate to establish one nursery at a common location not very far from the sites. It is also need to consider climate variations covering each eco-system as it is necessary see the possibility of adaptation to the climate when some new plants are introduced. Usually it is better to select always the plants that are usually available within a given area rather than selecting some new or not habitual or invasive plants for bio-engineering work in a given area. As well there is a need to consider other factors such as reduction of costs related to transport, maintenance etc. and availability of trained staff to work in plant nurseries. However, it is necessary to establish a threshold limit of plants as usually maintaining many small-scale nurseries may not be economical and cost effective. The other factors that are useful to consider in establishing plant nurseries are:

1. Spreading the risk due to external factors such as decease control, poor management, maintenance etc.
2. The possibility of shortage of water from the general supply or lack of water supply due to drying out of sources
3. Reduction of cost of transportation, material, land rent and leasing fees etc.
4. Optimization of labour, supply of fertilizer, weedicides etc.
5. Potential for obtaining the support of community members.

If the community members can be persuaded to maintain such nurseries through provision of knowhow and technical guidance it will an ideal situation and that can be an additional source of livelihood for such community members. Moreover, such community-based approaches may be a more cost-effective operation provided they get adequate training for production of healthy plants required for the bio-engineering work.

Further information of the following factors too would be useful:

Ownership of the land – If the nurseries are established under a project it will be useful to have control of the land, where plant nursery will be set up. The project management team should make necessary arrangements to either set up the nursery within the land acquired for the project purpose or to obtain long term lease of the land for anticipated lifespan of the project before setting up the nursery.

Water supply: All nurseries will have an adequate and permanent source of water throughout the period of its operations. There can be possibilities to get water from a close by source and that will be ideal. However, if water can be supplied through a pipe line from a source located elsewhere it is ok provided that it is cost effective and safe (usually long pipe lines have a liability for damage and might be expensive to operate within a longer period.

Slope gradient and suitability of the land: Ideal situation is to have a flat area or area with a gentle gradient with possibility of making terraces for developing plant beds. The land should not be an area with good drainage facility without connected problems such as water accumulation and stagnation, the area should have enough space but should be compact convenient for management. The other important factor is the access as there is a need to transport material, fertilizer etc. as well as to transport plants to site if that cannot be done through manual operations.

10.2 Construction process

During construction there are number of facts that need to be considered. The usual understanding is that all plants that are required for the NbS project will be propagated in the nursery and supplied to the site. Usually there are several types of propagation and it is assumed that vast majority of tree and shrub seedlings will be propagated in containers like clay or poly pots, polythene bags etc. Most other plants need to be propagated using beds.

10.2.1 Nursery beds

Several types of beds can be used in propagating plants under nursery conditions. All beds can be of about 100-120 cm wide with path between beds of 50-60 cm wide. Length can be as convenient as possible but mainly depend on the size of the plot selected for nursery establishment.

Soil beds

Soil beds are mostly used for propagation of grass varieties and some selected types of trees. When preparing beds soil need to dug up from the path and fill the beds to form a bed around 15 cm higher than the ground. If dog up soil is not sufficient to make the beds additional soil should be transported. It is good to transport better quality top soil or add composting material to improve the quality so that the beds become fertile enough for propagating plants. When necessary the periphery of beds can be improved by stone cover to reduce damages to edges during watering and heavy rain. All paths in between beds should be done in such a way that surplus water from all beds will get drained properly out of the nursery area.

Standout beds

Usually the standout beds are rectangular shaped frame which can be used to stack seedlings in clay or polythene containers or polythene bags without them falling over. The sides can be strengthened using stone, bricks or wood. The floor of the bed should be higher than the ground and with a good drainage facility so that it will not have any impact due to retention of water inside the bed.

Seed beds

It should be prepared in such a way that it gives a good medium in which seeds can be germinated. Subsequently young plants will be able to remove carefully and transfer in to clay or polythene containers or polythene bags. Seed beds should be prepared using well drained soil with compost fertilizer for improving the quality. The width of beds can be around 1m but length need to be selected to suit the area. After marking the shape of the beds on the ground the sides can be strengthen using bricks, stone or wood. The top soil layer should be carefully done with mixture of top soil, compost material and sieved sand to form a layer of about 10 cm thickness.

10.2.2 Bed shades and fencing

The early shoots of seedlings and cuttings can get damaged when they are exposed to direct sun and rain and therefore it is necessary to provide shade for the young plants. Greenhouse shade cloth is available in the market and is manufactured using knitted polyethylene fabric that does not rot, mildew or become brittle. Currently such shade material is available in multiple shade densities and can be used for such nursery applications. Such shade fabric helps protects plants from direct sunlight and offers superior ventilation, improves light diffusion, reflects summer heat and keeps nursery area cooler. The shade material are available in 30% to 80% densities to meet specific requirements and appropriate material is selected depending of the exposure level to sunlight and intense rain.

The Fencing is required to keep animals away from the Nursery area. Usually chicken, birds, stray dogs can enter the nursery area and scratch the surface of beds or damage plants. So, it is useful to erect a fence around the plant nursery area using wire mesh or barbed wire and protection cover with stronger shade material.

10.2.3 Water supply

It is essential to have a direct water supply to the plant nursery. Within the premises of the Nursery a suitable arrangement should be made to provide water to plant beds. Usually very good sprinklers are available in the market in various sizes and lengths and appropriate type should be selected in such a way that it can be regulated properly avoid supply of excess water to plants. It is also good to have additional storage tanks so that some additional quantity of water can be stored for any eventualities. Usually there can be break down of supply due to malfunctioning of pumps, electricity failures, damage to supply lines etc. In such cases emergency supply can be through storage tanks provided within the nursery premises.

10.3 Compost production

It is better to include compost production as a part of nursery activities as usually the waste material, plant particles etc. added with top soil and cow dung can become a good compost fertilizer. It is cheaper to make them as a part of nursery activity and will become a reliable source of material to improve the quality of soil used in beds, or containers to raise plants. Some additional compost material also could be used during planting of trees in the ground. Once compost material is produced such material need to be stored in a safe environment using polythene bags or containers so that it can be used later.

10.4 Nursery management

The management function of the Plant Nursery should be a part of the bio-engineering project and executed through appointment of appropriate qualified staff to undertake all nursery management functions. There can be support staff unskilled works to help them in undertaking daily functions. Propagation and multiplication, weed removal, removal of decease affected plants, pest & weed control, and removal of weaker plants etc. should be done under the supervision of qualified and experienced staff. For example, grasses can be multiplied rapidly in the nursery. Initially they can be planted in beds using the optimum means for each particular species. When they are grown up, and bed is completely filled they should be lifted, split up and replanted in other beds and this propagation practice should continue until we have enough material for planning at the site. Even the plants raised in pots or containers should be carefully transferred to site and removed from containers when replanting at the site. All such operations should be handled by skilled workers, supervised by experienced Nursery management staff. Some photos of a Vetiver Plant Nursery maintained in Thailand in given in Figure 10.1 below.

Figure 10-1 “Vetiver” Plant Nursery

CHAPTER 11

MAKING THE RISK ENVIRONMENT AN OPPORTUNITY FOR COMMUNITY DRIVEN RESILIENCE BUILDING

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Chapter 11 MAKING THE RISK ENVIRONMENT AN OPORTUNITY FOR COMMUNITY DRIVEN RESILIENCE BUILDING

11.1 Introduction

Although the larger interest of the disaster risk management community is to build hazard resilient and well-prepared communities, it is seen that selling the idea of mitigation and preparedness to local communities, is difficult. The survey conducted to make an updated assessment about the nature of engagement of at-risk communities in building disaster resilience show that their interest in risk reduction is high, but their own commitment or volunteer contributions to risk reduction measures are not at a desired level. It is no different in the case of landslide risk management efforts among the communities living in landslide prone areas. The result is the considerable increase in devastating landslide events in landslide prone areas in recent years.

Many of the slope failures currently found in human settlement areas located in landslide prone districts of Sri Lanka, are bank failures or cutting failures. In many cases such failures are not natural and can be considered mostly as human induced failures. Current popular practices in house and infrastructure construction in landslide prone areas generate more risks The circular of the Secretary of the Ministry of Disaster Management dated 2011.02.10 issued consequent to a cabinet decision on 2011.01.05, provides strict directives to restrict development and execute development control in highly vulnerable areas to landslides. As per the same it is mandatory for all local government institutions to request the proponents to obtain Land Suitability Certificate with recommendations of NBRO, prior to granting permission for any type of construction/development projects, within all landslide prone districts. The circular is applicable to all construction projects, including housing, community infrastructure etc. within the areas subjected to the landslide hazard. This directive is taken by GOSL, with a view to reduce the impeding danger, reduce the trigger of new landslides and thereby reducing the potential for landslide induced devastations in future, so that the loss of life and property damage in these areas could be minimized. In certain urban areas, following the Government Directives, NBRO used to issue technical guidance but follow up actions by authorities are not at a desirable level. The authorities do not interfere much to control them, or monitor the subsequent implementation of technical advises provided by NBRO during the project approval process.

The reasons for the poor engagement of communities in mitigating risk are their affordability in implementing mitigation options, poor technical understanding, poor awareness on the advantages and benefits, institutional weaknesses in motivating them, implementation gaps and poor compliance with existing regulations etc. Government efforts to undertake risk reduction measures in isolation is not sustainable in the long run and also not cost effective.

World Bank (2017) highlights the multiple benefits of NbS, in addition to its applicability in improving the stability of slopes, landslide protection, erosion control etc. They highlight the potential of NbS in helping the reduction of vulnerability to climate change while also creating multiple benefits to the environment and local communities. These include sustaining livelihoods, and sequestering carbon, restoration, conservation, and management of ecosystems, which are considered as additional crucial elements or benefits of implementation of nature-based solution. Therefore, in addition to engineering, and ecological benefits, this chapter describes the potential economic benefits that can be gained in proposing NbS for mitigating the landslide risk at community level.

11.2 User friendly technologies that can be adapted at community level

Topography, local geology, location of the landslide on the slope, steepness of slope, thickness of debris or soil, soil texture, biotic influence, and drainage system are mainly considered in designing landslide risk mitigation measures. Environmental criteria such as sensitiveness of the slope to erosion/mass movement, potential for downstream damages (to population, agricultural fields, human settlements, roads and other community infrastructure) and socio-economic criteria such as demand of local people, possibility of people's participation, budget limitation, and extent of impact on people's livelihood should be further considered for landslide risk mitigation.

There are number of user-friendly applications and low-cost NbS that can be regarded as community level landslide risk management practices, implemented in countries such as India, Nepal, Thailand and Vietnam etc. They basically meet with requirements mentioned above. However, obviously such practices need to be converted in to home grown practices appropriate for a respective country, by finding suitable local alternative materials, vegetation and even techniques familiar to respective communities. Such concepts combine the techniques for use of living vegetation either alone or in conjunction with small-scale civil engineering structures and non-living plant materials, to reduce the instability problems and erosion control on slopes.

11.2.1 Planted grass lines

Planted grass lines can be made as contour/horizontal, down slope/ vertical or diagonally placed lines. Grass slips (rooted cuttings), rooted stem cuttings or seedlings can be planted in lines according to the requirements and slope characteristics. Such planted grass layers along contour lines or horizontally, armor and reinforce the upper and lower soil layers as the roots anchor and reinforce the soil in addition to catching the debris. It can help in slowing down the runoff and can filter sediments. However, if the planted grass lines are placed as vertical lines or diagonal lines, the capacity to armor the slope around the plants and function as a barrier for catching debris and draining surface water is limited (Howell, 1999). Usually most suitable types of plants among grass species are vetiver, pangiri, lemongrass etc. Further research will be needed to collect characteristics of different plant types and weigh them against the plant selection criteria proposed under Chapter 6, in order to qualify them as a suitable plant species that can be used in this method. Figure 11.1 show the application of the suggested methodology in the North–South expressway in Vietnam.

Figure 11-1 Vetiver grass planting in North- South expressway – Vietnam

11.2.2 Vegetated crib walls

Stabilizing natural as well as man-made slopes generally using conventional retaining structures (masonry, concrete or gabion walls) is very common and popular in South Asia. However, the construction and maintenance costs of such walls are getting increased every year and cannot be afforded by the general public if they are to use such technology for stabilizing slopes. A soil bioengineering approach to stabilize slopes using bamboos and plants are gaining popularity in many countries due to several reasons. The construction of bamboo crib walls to retain the slopes and stabilize them as an alternative to conventional retaining structures is a simple and cost-effective technique (Acharya, 2020). Instead of bamboo they also can use any other durable type of timber suitable for the purpose. The performance of such crib walls is satisfactory technically and community members can easily use the technology for use in domestic purposes in particular for unsupported cuttings and excavations during house and road construction.

The design and construction procedure are simple, and other advantage is that the community members can use any other suitable or locally available material. The strength and durability of bamboo crib walls can be enhanced through reinforcement with vegetation. Various type of preservatives can be used to prolong the durability of bamboo or any other durable types of timer material used in construction. For instance, Boron salts provide effective protection against attack by insects. The treatment consists of soaking freshly obtained unseasoned timber in solutions of boron salts. On the other hand, the introduction of plants inside the bamboo crib wall will not only increase the life of such walls, but also increases the stability of whole slope in the long-run. Construction costs are comparatively much lower than the conventional masonry, concrete or gabion walls. Experimental results and qualitative assessment of bamboo crib walls show that the technique of making vegetated crib wall using bamboo (Figure 11.2) could be a sustainable alternative to conventional retaining walls and has potential to add socio-economic value to the communities.

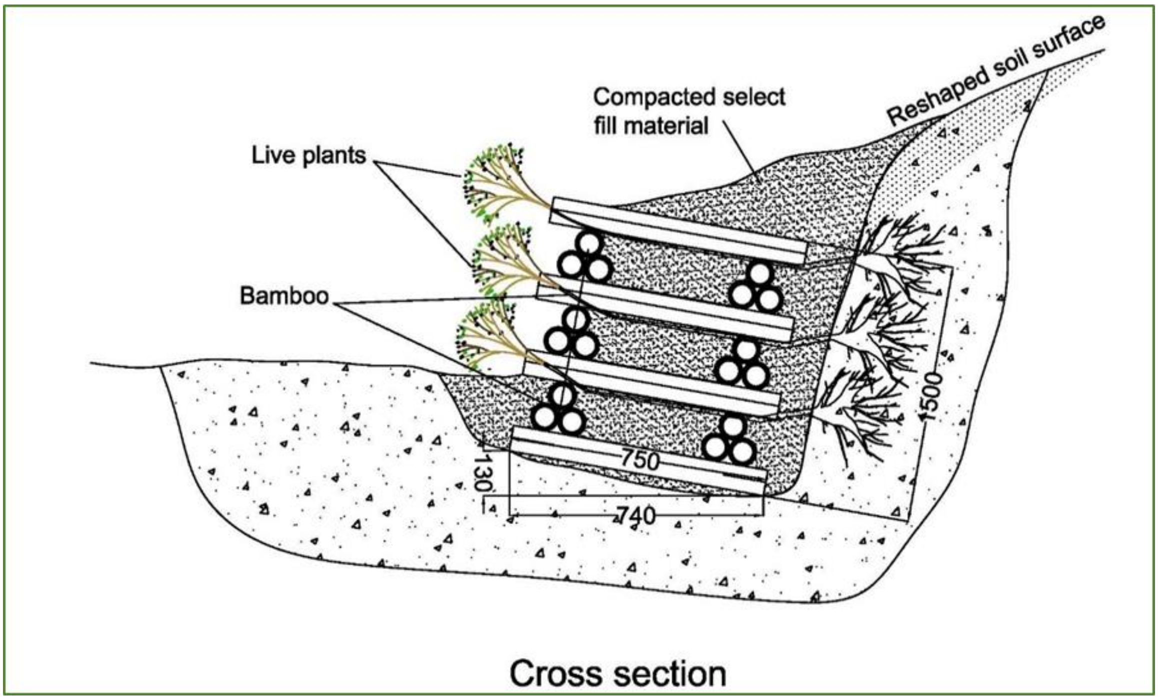

Figure 11-2 A Vegetated Crib Wall made up of bamboo

11.2.3 Tiered wall with bench plantings

The tiered wall system can be built using "TOR" blocks made out of compacted soil-cement mixture and arranged in such a way that it creates a leveled surface outside (Figure 11.3). "TOR" block is an innovative product made by Dr. Suttisak Soralump and his research team at Geotechnical Engineering Research and Development Center (GERD), Kasetsart University, Bangkok, Thailand. Blocks are placed against the slope that is to be stabilized and blocks are arranged with a sand layer as the fill material in between blocks and slope (Figure 11.4). It provides a media for free release of water from the slope. Drainage is provided by creating weep holes at the toe blocks as seen in the Figure 11.5 which were photos taken at Chiang Rai Province, Thailand. The spacing in between the blocks will serve as drainage paths. It is a very cost-effective mitigation practice and easily be carried out using unskilled labour. When failed slopes are mitigated by using "TOR" blocks there is a possibility of planting various vegetation species in the upper slope and in between block walls (Figure 11.3).

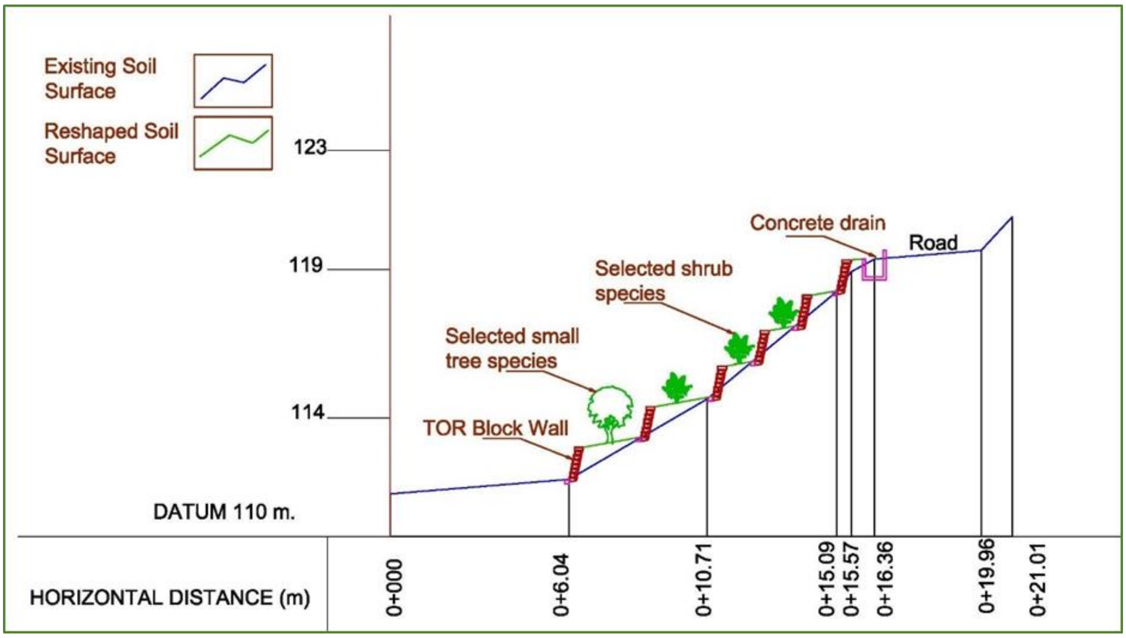

Figure 11-3 A tiered wall made out of soil-cement blocks with bench plantings

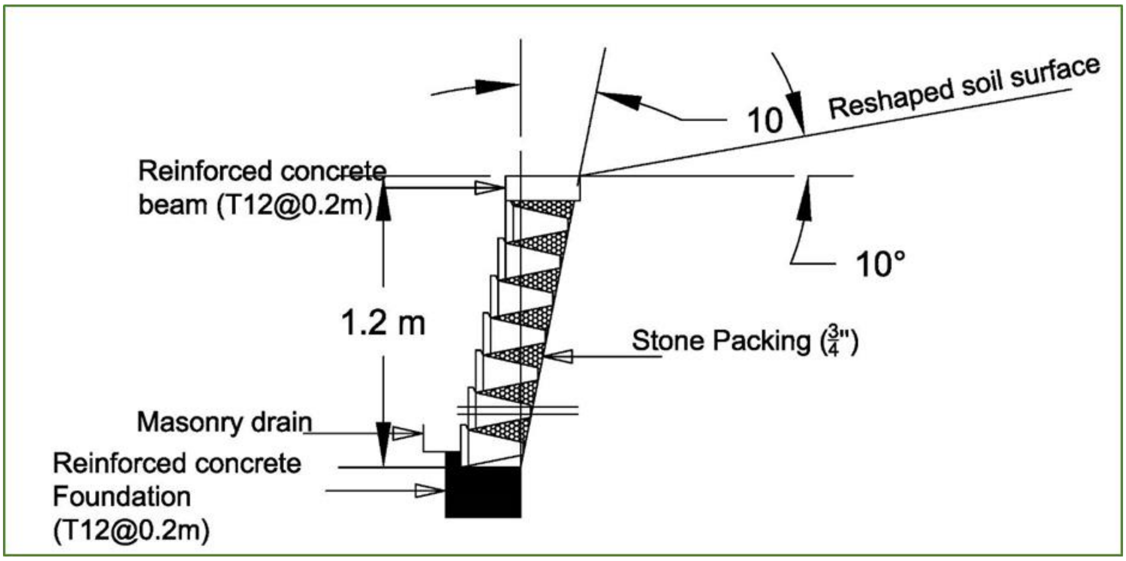

Figure 11-4 Design details of a TOR block wall (Adapted from Soralump *et al.*, 2020)

Figure 11-5 Appearance of a TOR Block Wall system with space for bench planting. Chiang Rai, Province, Thailand

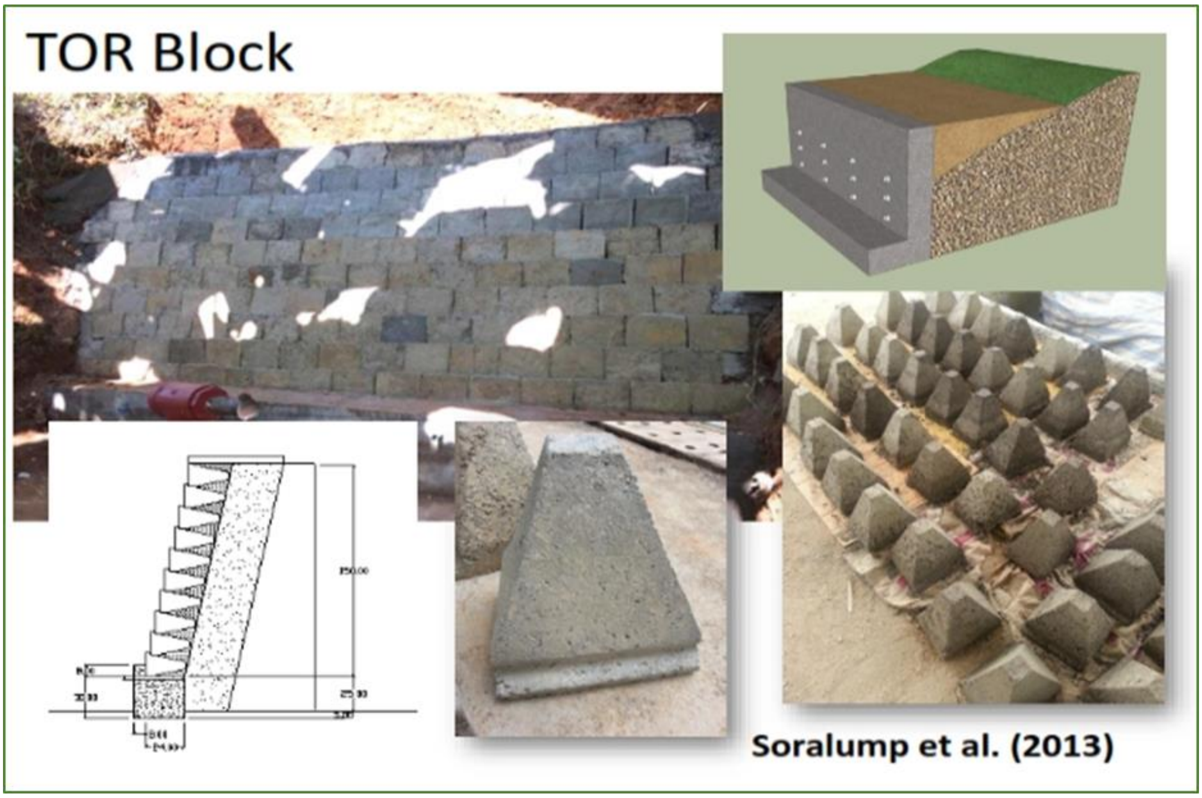

Figure 11-6 Soil cement block (TOR block) (Received from Dr. Suttisak Soralump, February 8, 2019)

11.2.4 Live slope grating

Vegetated slope gratings made of a wooden frame, and anchored using planted live cuttings, is a commonly used method for stabilization of slopes. Even this method is good for already failed slopes as after providing a backfill, the newly constructed area can be supported using this method. The frame can be constructed using bamboo or any other suitable type of timber or any other substitutes such as concrete, discarded metal elements etc. The cross poles should be anchored using live cuttings driven in to the soil layer to a sufficient depth so that it will develop a good root system quickly and support the sub-surface layers. When selecting live cuttings much attention should be given to the fact that it is capable of developing a root system quickly as possible and has a reasonable resistance to dry weather. In addition, the space inside the frame can be covered with suitable vegetation such as vetiver grass, lemon grass, etc. so that the area will have a good vegetation cover. If a type of vegetation which is capable of providing some economic benefits, it will have an additional advantage. Medicinal herbs, plant varieties which are edible or capable of providing fruits, etc. can be easily grown inside the grids. Materials used for crossed poles should retain the strength for some times until the area is stabilized by planted live cuttings, after developing its root system to armor the soil layer around. The toe area can be supported with a stone packed wall or live vegetated crib wall. This method can be used for even steeper slopes with around 45▪ or less or even highly weathered surfaces after providing a sufficient backfill. The suitable size of the square grid should not be larger than 2 m by 2 m and it is better the grid size can be smaller than that. This kind of vegetated gratings are effective when revegetation is done as soon as possible to make it a permanent solution (Vegetated slope gratings (Hybrid), n. d.).

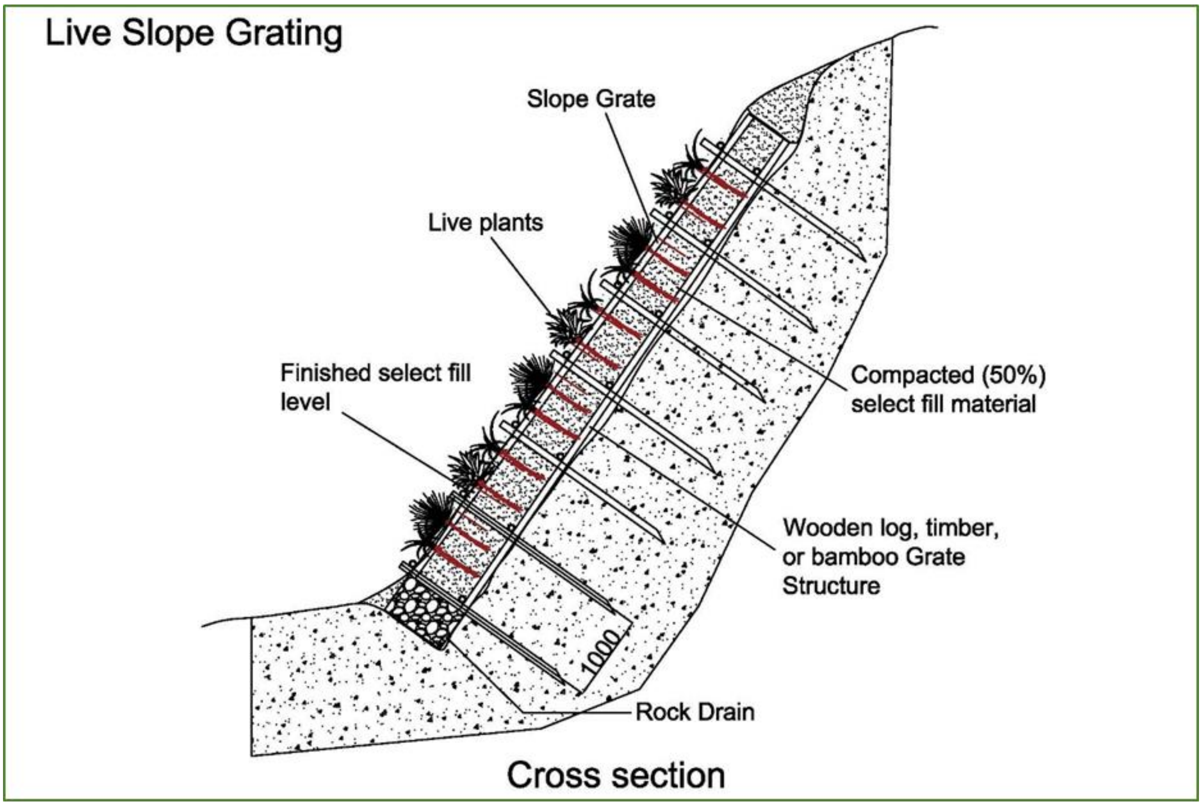

Figure 11-7 Cross section of a typical live slope grating

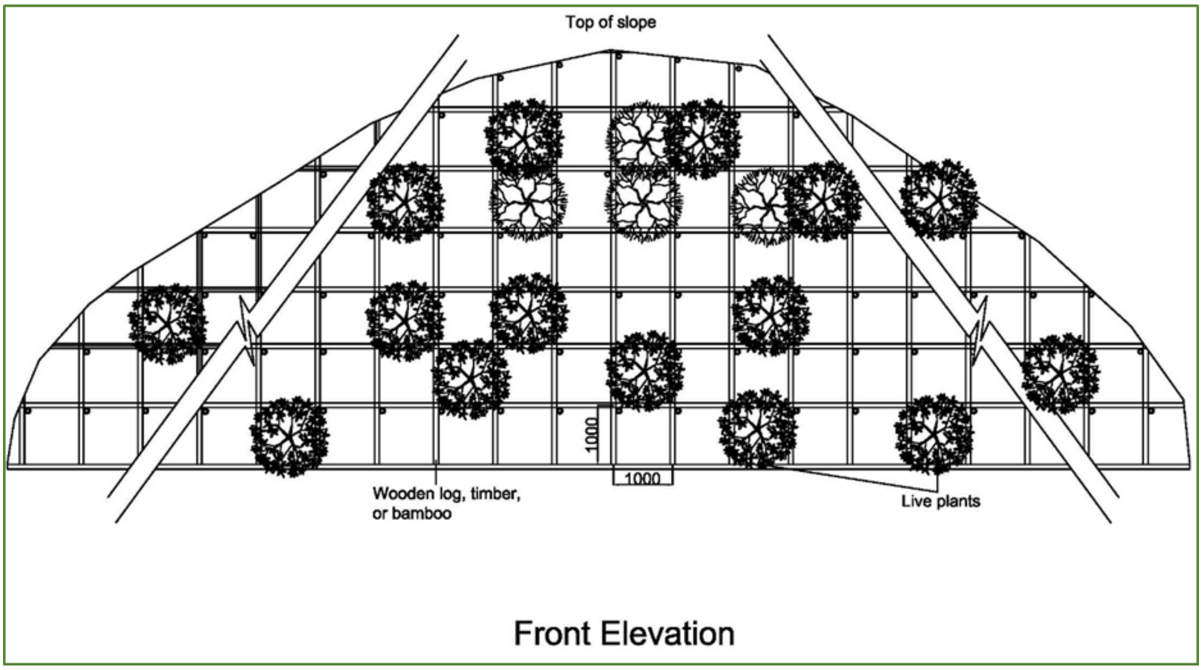

Figure 11-8 Front Elevation of a typical live slope grating

11.2.5 Hollow vegetated block cover

The hollow vegetated cover blocks is a good measure for erosion control as well as for preventing formation of gully or shallow erosion path which can ultimately create a larger destabilizations on slopes. The concrete blocks made with openings in the middle can be used for covering the slope area. If concrete blocks with regular edges can be developed in such a manner that construction can be done using interlocking, such pavements can be done using unskilled labour. The hollow area can be planted with grass or any other suitable type of plants with good root system and then in time to come, slope will become safer. The plants can be selected in such a manner that it gives some economic benefits to communities.

Figure 11-9 An example of Hollow Block vegetated cover in a slope in Vientiane, Lao

11.3 Selection of plants with multiple benefits

The above given set of measures in the section 11.2 will meet the growing needs in finding cost effective, sustainable and environmental friendly landslide risk management techniques. Further such measures can provide multiple benefits in terms of ecological environment, economic benefits as well as better returns for the investment. The criteria applicable to plant selection provided in Chapter 6 discusses the basic characteristics needed for utilization in nature-based landslide risk management solutions. Basically, selected candidate plant species must have positive contributions towards factors such as root strength, hydrological significance, ecological significance and economic importance in order to become optimum candidate species for NbS in landslide risk mitigation. If suggested NbS possess a potential to address socio-economic vulnerabilities and multiple benefits for the local communities, it will be easily acceptable to local communities as a good measure for landslide risk.

A description of bioengineering properties of the selected plant species as well as their economic potential is provided in this section, so that such plants can become candidates for usage in above mentioned criteria. Incorporation of such plants with potential multiple benefits, in nature-based landslide risk management solutions can lead to creation of viable business models where potential investors can take part in mitigating landslide vulnerable areas, in partnership with local communities. Hence, the innovative approach suggested herein, will contribute in formulating a sustainable landslide risk management strategy, as well as in building the resilience of vulnerable communities.

Having understood the significance of such plants in nature-based landslide risk mitigation, the most appropriate, species are suggested under different categories of plant communities namely grass, shrub, creeper and tree (Fig. 11.10 to 11.13) and Table 11.1 presents the characteristics of some of the selected grass species related to its application in nature-based landslide risk management together with ecological and economic importance.

Figure 11-10 Selected grasses

(1. Cymbopogon citratus; 2. Cymbopogon nardus; 3. Cymbopogon species; 4. Vetiveria zizanoides; 5. Pandanus amaryllifolius; 6. Acorus calamus)

Table 11-1 Characteristics of selected grass species

Candidate plant	Photo	Hydrological significance	Root system & root strength characteristics	Ecological significance	Economic value
Vetiveria zizanioides (Vetiver grass - Savandara)		Moderate evapotranspiration rate. Dense root system extracts more water from the soil and release through evapotranspiration.	Spongy, fibrous & finely structured root system providing large surface area. Penetrate vertically deep into soil. Rooting depth can reach 4-5m. (Extremely drought tolerant)	Native species Not invasive or a threat to other plants. Provide habitats to many beneficial micro and macro flora.	Lucrative cash crop. Highly used in flavor and fragrance industry. Essential oil has high therapeutic value.
Cymbopogon nardus (Citronella – Heen Pangiri mana)		Low to moderate evapotranspiration rate. Dense root system extracts more water from the soil and release through evapotranspiration.	Dense fibrous root system about 1-1.5m length. Clump forming nature provides rapid green coverage. Can be cultivated even unfertile soil and low water conditions.	Native Species. Provide an excellent mulch to the soil.	Food and beverage industry. Spice & essential oil industries. Cosmetic and perfumery industries.
Cymbopogon citratus (Lemongrass - Sera)		**Low to moderate evapotranspiration rate.** Dense root system extract more water from the soil and release through evapotranspiration.	Dense fibrous root system. Cover the soil surface within 4-5 months. Rooting depth can reach 0.5 – 1.5m.	Exotic species. Excellent mulching properties.	Food and beverage industry. Spice & essential oil industries. Cosmetic and perfumery industries.

Figure 11-11 Selected shrubs

(S1 - Cassia auriculata (L.) Roxb.; S2 - Woodfordia fruticosa (L.) Kurz; S3 - Atalantia ceylanica (Arn.) Oliv.; S4 - Adhatoda vasica Nees)

Table 11.2 presents the details of Adhatoda vasica Nees.

Table 11-2 Characteristics of selected shrub species

Candidate plant	**Photo**	**Hydrological significance**	**Root system & root strength characteristics**	**Ecological significance**	**Economic value**
Adatoda vesica Nees (Malabar nut – Pavatta)		Large leaf surface facilitates evapotranspiration. Compact root system extracts more moisture from the soil and release to environment through evapotranspiration process.	Strong root system extends both vertically and laterally. Help to bind soil aggregate.	Highly attractive plant. Provide shelter for many micro and macro fauna.	Heavily used in traditional and ayurveda systems of medicine. High demand for raw materials and phytochemicals extracted from the plant

Figure 11-12 Selected live creepers

(H1 - Desmodium triflorum (L.) DC., H2 - Alysicarpus vaginalis (L.) DC.)

Characteristics of Desmodium triflorum and Alysicarpus vaginalis are presented in table 11.3.

Table 11-3 Characteristics of selected creeper species

Candidate plant	**Photo**	**Hydrological significance**	**Root system & root strength characteristics**	**Ecological significance**	**Economic value**
Desmodium triflorum (Creeping tick trefoil – Udupiyaliya) Annual to perennial herb		Dense roots extract moisture from the soil and release through evapotranspiration. Dense vegetation cover the surface completely to prevent surface run off and water infiltration to the soil.	Produces stems 8-50cm long roots. Stems are strongly branched and frequently root at the nodes. Grown as a green manure & cover crop to prevent soil erosion. Thrive well in deep shade to full sun condition.	Provide habitats to many macro and micro fauna. Provide foods for wild animals. Significantly reduce soil erosion. Help to fertile soil by fixation of environmental nitrogen and provide good fertile soil to other plant species.	Used in traditional medicine for the treatment for fever, cough, dysentery, wound healing and many skin diseases.
Alysicarpus vaginalis (Aswenna) Herbaceous annual)		Dense vegetation root system prevent water infiltration to the soil.	Each stem node produces root which extend up to 10 to 50 cm both laterally and vertically. Fast growth of the plant covers whole surface of soil in a short period of time. Grown as a green manure & cover crop to prevent soil erosion. Thrive well in unfertile soil, shade to full sunlight conditions.	Provide habitats to many macro and micro fauna. Provide foods for wild animals. Help to fertile soil by fixation of environmental nitrogen and provide good fertile soil to other plant species.	Ayurveda Treatment http://www.instituteofayurveda.org/plants/plants_detail.php?i=567&s=Local_name

Figure 11-13 Selected trees

T1 - Vitex negando L.; T2 - Pongamia pinnata (L.) Pierre; T3 - Terminalia arjuna (Roxb. ex DC.) Wight & Arn.; T4 - Phyllanthus emblica L.; T5 - Cinnamomum zeylanicum Blume.; T6 - Terminalia bellirica (Gaertn.) Roxb

Table 11.4 presents the characteristics of some of the tree species listed in Figure 11.13.

Table 11-4 Characteristics of selected tree species

Candidate plant	**Photo**	**Hydrological significance**	**Root system & root strength characteristics**	**Ecological significance**	**Economic value**
Vitex negando (Chaste tree – Nika)		Low to moderate evapotranspiration rate.	Taproot system up to 2m. H type roots.	Native species. Good honey and pollen source for honey bees. Can grow even degraded soils.	Widely used materials in traditional and Ayurveda medicine. Essential oil industry Perfumery and cosmetic industries.
Pongamia pinnata (Indian beech - Karada)		Transpiration rate is medium to high. Foliage intercepts rain water and prevents water	Strong root system comprising both lateral and vertical roots, distributed as reticulate structure. It can directly help to bind surface and	Root nodule fix the environmental nitrogen and fertile the soil. Tolerate wide range of climatic	Good source of edible biodiesel. Popular ingredient in therapeutic cosmetics. High demanded ingredient in

Candidate plant	Photo	Hydrological significance	Root system & root strength characteristics	Ecological significance	Economic value
		infiltration to the soil. Long root system absorb large amount of water and release to atmosphere through transpiration.	subsurface soil layers.	changes and thrive well under extreme weather and soil conditions.	traditional and Ayurveda medicine.
Terminalia arjuna (Kumbuk/ Arjun tree)		Dense vegetation intercepts rain and reduces water infiltration to the soil. Medium to high evapotranspirati on rate. Well adopted to water logging conditions.	Has buttressed and interlocking root systems which stabilize the tree. Act as a barrier against erosion and stabilizes riparian zone.	Native plant. Help purification and cooling of water. Well suited for water logging conditions. Facilitate habitat to other flora and fauna.	Heavily used in traditional and ayurveda medicine. Source of timber, and charcoal Very good tannin source.
Cinnamomum zeylanicum (Cinnamon - Kurudu)		Moderate evapotranspirati on rate. Foliage intercepts and prevent water infiltration to the soil.	Root system consists of deep tap roots and lateral roots. About 90% of lateral roots are confined to 50cm depth and make a strong reticulate structure, to bind the soil while tap root extend up to 1-2 m.	Native species provide services for many fauna species for feeding, nesting and resting purposes.	Highly valued in; Spice and essential oil industries. Nutraceutical and pharmaceutical industries. Cosmetic and perfumery industries.
Terminalia bellirica (Bulu)		Moderate evapotranspirati on rate. Deep and wide root system extract moisture from soil and release to the environment through evapotranspirati on process.	Strong, laterally and vertically developed root system effectively bind surface and subsurface soil layers.	Good honey and pollen source for honey bees. Very good food source for wild animals.	Highly valued ingredient in Ayurveda and traditional medicine. Suitable for tannin production. Seed oil is used for high end cosmetic production.

Plants given in Figure 11.10 to 11.13 play an important role as a source of raw materials for both traditional and modern systems of medicines, home remedies, nutraceuticals, and pharmaceutical industries. Different parts of proposed medicinal plants including barks (Cinnamomum zeylanicum, and Terminalia arjuna), fruits (Madhuca longifolia, Phyllanthus emblica, and Terminalia bellirica) and flowers of Cassia auriculata and Madhuca longifolia are considered as highly demanded raw materials by the industries.

Figure 11-14 Some selected semi processed medicinal materials as raw materials for Ayurveda hospitals and other industries

(R1 - Cinnamomum zeylanicum bark; R2 - Terminalia arjuna bark; R3 - Madhuca longifolia seeds; R4 - Phyllanthus emblica fruits; R5 - Cassia auriculata flowers; R6 - Terminalia bellirica fruits)

In addition to the application as raw materials, the plants given above, play an important role as initial materials for the extraction of a concentrated forms of natural products containing active constituents such as essential oils, alkaloids, tannins, and other phytochemicals that possess prominent therapeutic properties. Therefore, once rural communities get familiarize in producing such plant-based raw material production, it is important to train them for value-added product development using such plants. As shown in Figure 11.15, production of value-added herbal teas, extraction of essential oils, and production of herbal powder etc. can be introduced during the initial stage. This approach will help increase the market value for medicinal materials than selling them in the form of raw material.

Figure 11-15 Some selected value-added products from medicinal plants

(P1 - Madhuca longifolia oil; P2 - Cymbopogon nardus oil; P3 - Cinnamomum zeylanicum oil; P4 - Cinnamomum zeylanicum tea; P5 - Cassia auriculata tea; P6 - Terminalia arjuna bark powder)

Once the affected communities get sufficient experience in primary level value-added product development, it is necessary to select the people who are successful of secondary level value-added product development process using existing raw materials. Then these selected groups of communities should be adequately trained to strengthen the entrepreneurial skills by providing advisory services on business management, accounting, drafting business plans, developing visions for the future, and establishing contacts with relevant financial entities.

Figure 11-16 Some selected value-added secondary products from medicinal plants

(A - Cymbopogon nardus based cleaner; B - Cinnamomum zeylanicum tablets; C - Cinnamomum zeylanicum joss ticks; D - Cinnamomum zeylanicum based soaps; E - Cinnamomum zeylanicum creams;
F - Thripala tablets)

As shown in Figure 11.16, secondary level value added products include production of nutraceuticals, functional foods, cosmetics, perfume and toiletries, ready to serve beverages, and some other therapeutically active functional foods.

Further, Ghosh & Bhattacharya (2018) mentioned that vetiver grass which was used in landslides and erosion control measures could be used in the making of handicrafts as one of the options for livelihood regeneration in India.

Figure 11-17 Utilization of vetiver grass in the making of handicrafts for livelihood regeneration in India (Ghosh & Bhattacharya 2018)

As described in this section, incorporation of plants that can offer multiple benefits, as candidate plants that can be used in nature-based landslide risk mitigation efforts, will make them environmentally friendly, cost effective and sustainable solutions. Further, utilization of plants, which has multiple benefits permit the creation of different business models which will immensely help the vulnerable local communities to uplift their socioeconomic conditions and build their resilience to the landslide hazard.

CHAPTER 12

LANDSLIDE RISK MANAGEMENT PLANNING WITH NbS

NBLRM

Chapter 12 LANDSLIDE RISK MANAGEMENT PLANNING WITH NbS

12.1. Preparation of risk mitigation plan

Preparation of a mitigation plan needs to consider overall technical guidance provided in previous chapters. However, there is a need to adapt to a general sequential order but may change depending on the contextual setting and site specifics.

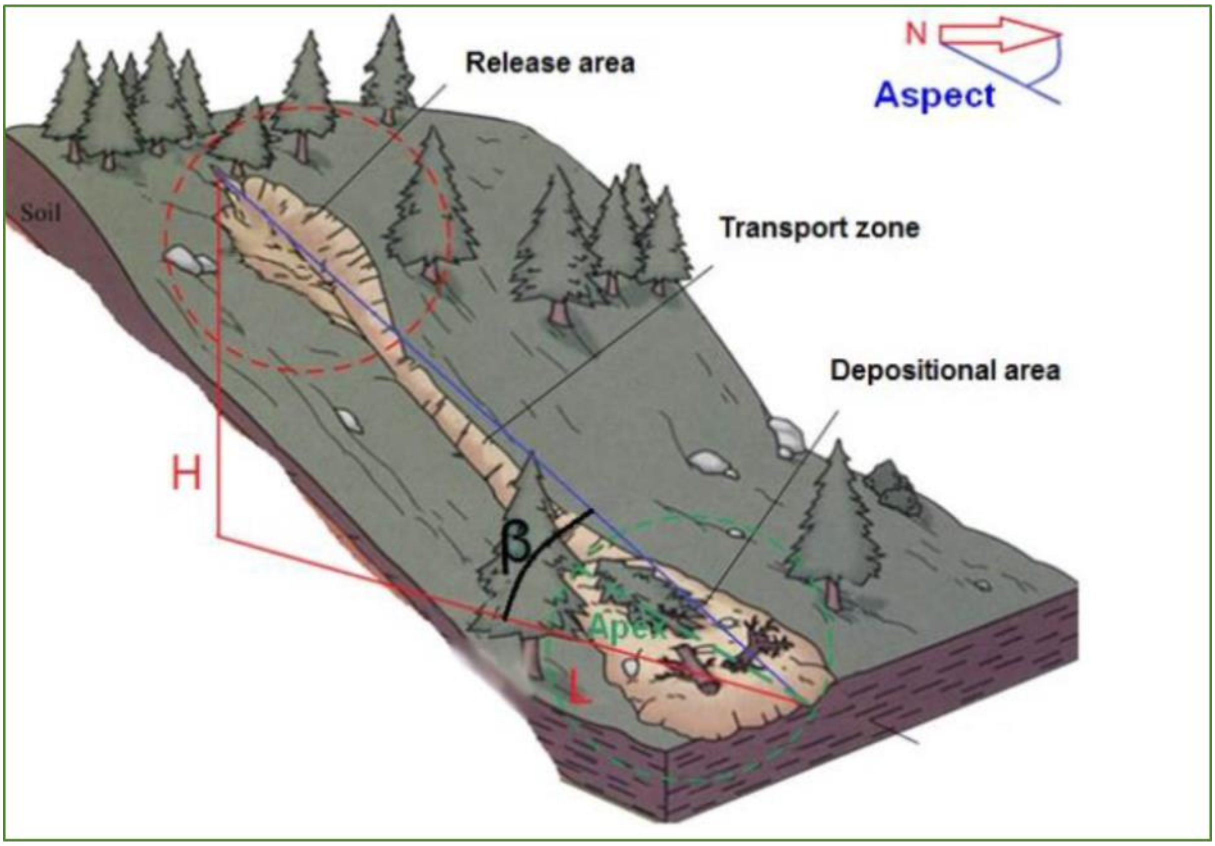

Figure 12-1 Sketch of a landslide indicating its three main zones. (Anfinnsen, 2017)

A landslide is divided in to three zones an initiation zone or release area, transport zone and depositional area. The release area is usually defined as the area where the initial slope failure or movement originated. The transport zone is the area immediately below the release area extending up to the point where the deposition starts. The deposition zone can extend further along the slope depending on the quantity of the released material which has been transported down along the slope. However, all three zones are arbitrary and can extend in length and width depending on the further activation of the areas subjected to failure mechanism. As shown in Figure 121, the horizontal distance from the upper most boundary of the release zone up to the front end of the depositional area is the runout length (L) and the elevation difference of each ends is the height of the failure zone(H). General zoning of a landslide affected slope area is provided in Figure 12.1.

Increased volume normally increases the velocity and runout area length and as the material get eroded and transported the volume within the deposition area started swelling. High pore pressure increases the velocity and roughness in the terrain increases the friction and helps to reduce the velocity. As the first step, all such terrain material needs to be studied and characteristics for each zone have to be documented in the process of mitigation planning using NbS.

The pilot demonstration site of Badulusirigama site (located near Uva-Wellassa University, which is described in the previous Chapters) is a good example to provide an explanation on the demarcation of three zones and ways of application of soil bio-engineering measures to mitigate the landslide risk. It is a site where already directional drilling has been used to draw down the water table but there are areas with marginal safety factor as described in chapter 9. The Layout plan of Badulusirigama pilot site and the proposed zonation map (Figure 12.2), the elevation profile (Figure 12.3) and the average gradient of each zone (Table 12.1) is given below.

Figure 12-2 Layout plan of Badulusirigama pilot site and the proposed zonation map

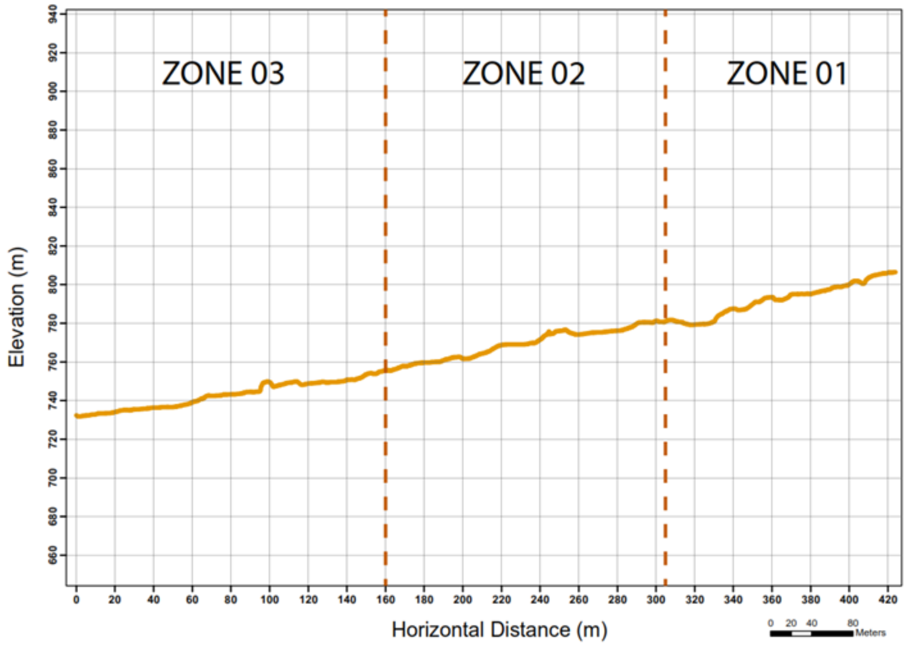

Figure 12-3 Elevation Profile

Table 12-1 Average gradient of each zone

Zone No	Average gradient in degrees
Zone 1	15.5°
Zone 2	10.3°
Zone 3	7.13°

Subsequently field studies were carried out and a SWOT analysis (Table 12.2) identified following characteristics for the three zones.

Table 12-2 SWOT analysis

Strengths (S)	Weaknesses (W)	Opportunity (O)	Threats(T)
• Availability of spring water released from pipes connected to drill holes • Multiple access roads • Natural succession of plans has stared already • Scenic view of the site	• A landslide prone area, which has a potential for reactivation • There is a risk to the community living at the toe of the landslide area • Existence of structural mitigation measures, which should not be disturbed • Need of surface soil improvement • Limitation of tested plants that can be used. • Lack of bio diversity • Limitations for land modifications.	• Currently an abandoned land • Closeness to a village and agreement of the community for participatory work. • Agreement of the university to extend assistance in post monitoring work • Agreement of the university for conducting studies and research on various aspects of landslide risk mitigation and monitoring	• Unauthorized activates and misuses observed within the area. • Invasive species • High-tension electrical line going across the site • Water logged area near the village • Limited experience of the community for cultivation and management of planted areas (harvesting method, life cycle etc.)

During the design stage the project team had consultations with the Uva Wellassa University (the owner of the land) which is located next to the landslide area and the community living in the area immediately downstream of the landslide. Primarily, landslide mitigation work has been initiated to minimize the risk to the community living below the landslide area. This project has taken initiatives to incorporate aspirations of the university as well as the community at risk in designing the landscape plan and mitigation measures through soil bioengineering measures in order to incorporate into the mitigation work already undertaken to draw-down the water table in the area through directional drilling.

It was decided to divide landslide area into three zones considering its morphology and the landslide actions. They are upper section (zone 1), middle section (zone 2) and lower section (zone 3). The proposed plan is developed accordingly, focusing on the individual characteristics of these zones. Each zone was assigned a separate theme as shown in the Figure 12.4. Final layout of the proposed mitigation plan is shown in Figure 12.5. Table 12.3 indicates special characteristics/restrictions assigned to different thematic zones.

Figure 12-4 Allocation of themes for different zones

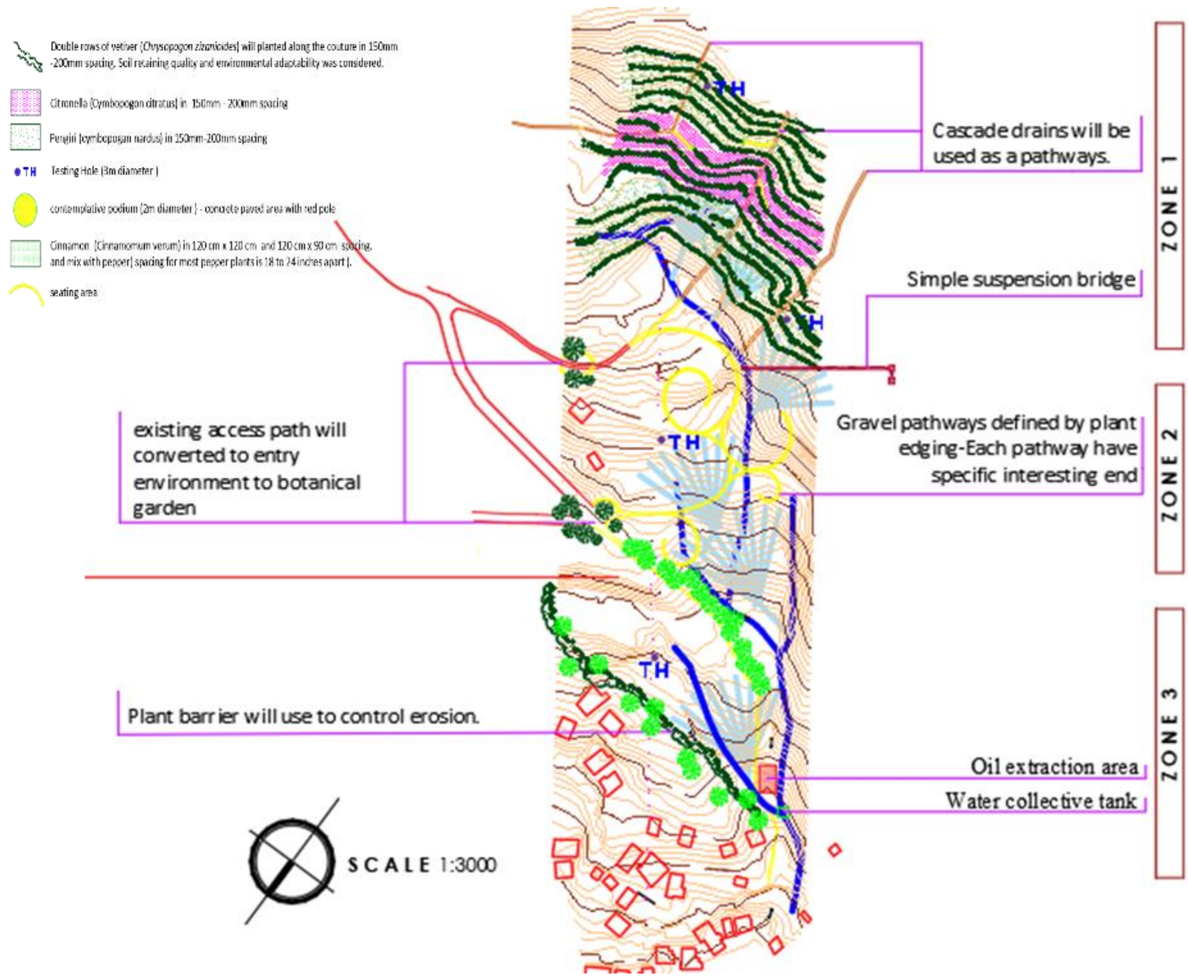

Figure 12-5 Layout of the proposed mitigation plan

Table 12-3 Special characteristics/restrictions assigned to different thematic zones

Zone 1 - Grassland	**Zone 2 - Botanical garden**	**Zone 3 - Community integration areas**
• No vehicular access • Soil improvements must be done after testing the nutrition level of soil formations • Minimum ground modifications will be carried out. • Rhythmic motion of the plants will create the comparative feeling on user	• Slight ground shaping will be conducted to arrange plant beds. To manage high level of diversity edible plants and flowering plants will be used to attract fauna. • Seating will provide for small group gathering. • Not suitable for night time functions, however lighting will be allowed to ensure security. • Soil depth must be calculated before introducing plants to prevent damage to sub-surface drains	• Mainly used for cultivation of species such as cloves, cinnamon etc. to give benefits to villagers. • Access will be provided for villages to attend to maintenance work.

12.2. Main tasks in implementing NbS for landslide risk management

For comprehensive landslide risk mitigation planning and execution, like implementing any other landslide risk mitigation project, when NbS is applied as a standalone practice or hybrid (in combination with other engineering measures) measure, a sequential order needs to be followed. After susceptibility mapping or special investigations, when a site is found to be risk prone then a suitable mitigation measures must be undertaken. The site suitability and selection criteria for NbS is provided in Chapter 3. Once the decision is made for undertaking NbS it is essential to follow the sequence of actions provided in Figure 12.6 for developing a landscape design for a given site for mitigating the landslide risk.

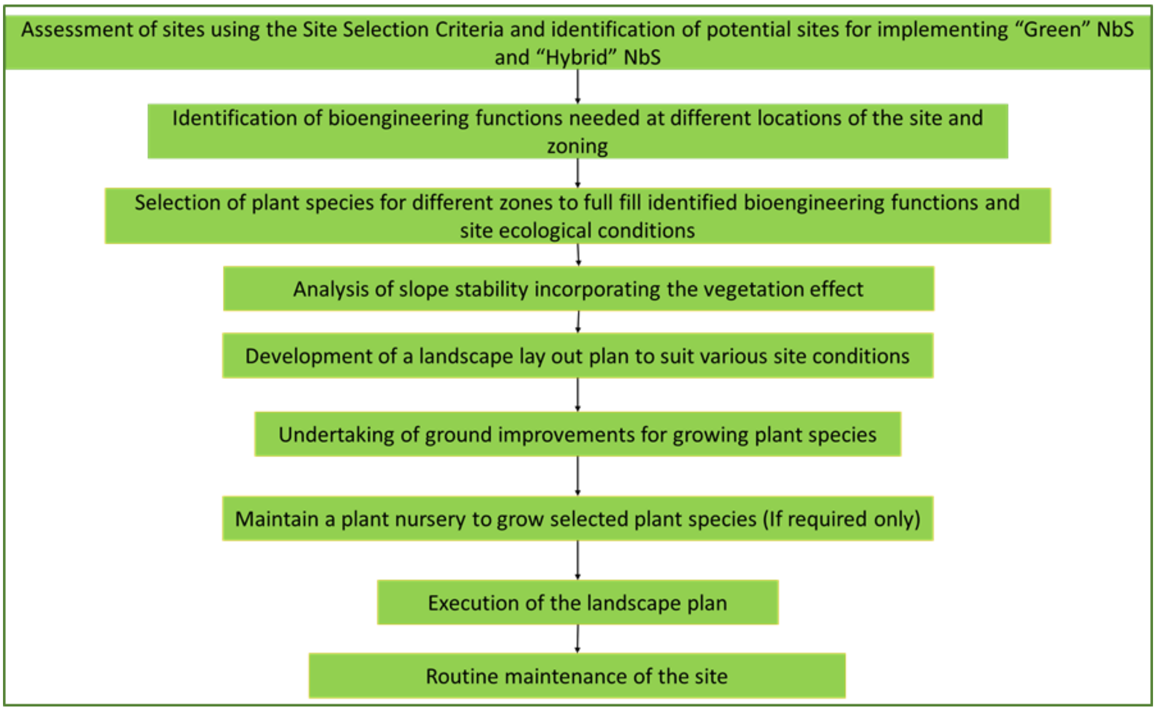

Figure 12-6 Sequential order of activities that need to follow in executing a NbS project for landslide risk mitigation

In contrast to other landslide related engineering mitigation interventions, the NbS approach has an additional requirement for post implementation care and maintenance work. Those who are responsible for supervising and implementation of NbS execution plans should ensure that the above sequential order is followed and the requirements that will be mentioned under each step are fully understood and design requirements are fulfilled while executing NbS. However, during the course of execution of the plan for NbS, there might be some final adjustments to be made to suit actual site conditions depending on the conditions prevailing at the site such as slope gradient, cover of vegetation in existence, degree of the susceptibility to landslides, extent of the combination of geo-engineering and bio-engineering work. Designers may need to review the site conditions during the time of the execution of the plan and suggest suitable changes or amendments to the design during routine inspections or depending on the complaints made by the staff at site, who will be executing the work.

12.3. Different work packages

Depending on the full set of activities involved in executing NbS project and bio-engineering and other engineering work proposed, the full assignment can be divided in to several work packages. However, depending on the site conditions, the volume of work under each package as well as the list of activities may change and the list (Table 12.4) will only serve as a sample set of activities that need to be planned under the assignment.

Table 12-4 Proposed work packages under NbS project for landslide risk mitigation

#	Major tasks	Sub-tasks
1	Site preparations	• Slope clearance and trimming operations • Retention of selected tree species, trimming if necessary, providing cover and support • Disposal of spoil material and leveling. • Final ground preparations for executing the selected bio-engineering and civil engineering measures
2	Civil engineering work	• Survey & leveling work to establish the lay out for civil engineering work • Ground preparations for identified engineering structures • Construction of horizontal/contour drains • Construction of cascade drains • Construction of masonry walls • Construction of Gabion walls • Construction of Irrigation & water supply lines • Construction of foot paths, passages, walkways etc.
3	Bio-engineering work	• Slope preparations (beds, contour lines, diagonal lines, etc.) for executing the selected bio-engineering measures • Use of fertilizer, composting material etc. • Execution of selected bio-engineering measures (Sowing of grass species in site, grass planting and seeding, site planting of tree species, placement of hardwood cuttings, erosion protection mats etc.) as per the design of the mitigation plan • Mulching and supply of cover for plants when and where necessary
4	Plant nursery development and maintenance	• Nursery establishment • Construction of Nursery beds • Nursery production of selected grass types • Nursery production of trees and shrubs in poly-bags and poly-pots • Nursery production of hardwood plants • Compost and mulch production • Extraction of plants from Nursery and transportation
5	Post execution inspection and maintenance	• Routine maintenance of plants and all bio-engineering works • Weeding and removal of unnecessary or excess plants and disposal • Mulching as required to protect plants • Replacement of failed, weak, decease affected and damaged plants • Fertilizing and grassing • Replanting and enrichment work • Thinning, pruning and disposal of material
6	Remunerations for supervisory staff	• Civil engineers • Geotechnical engineer/ engineering geologists • Agricultural engineers • Agronomists

#	Major tasks	Sub-tasks
		• Botanists • Landscape architects • Technical officer • Work supervisor

The idea of dividing the full assignment in to work packages is to have an easy way out for implementation of the work. When the site is not very large, full set of work packages will be able to accomplish using direct labour. Otherwise full set can be converted in to one contract and handed over to a suitable competent contractor. Otherwise only part of the work such as plant nursery maintenance can be carried out using direct labor or with contributions from community members.

12.4. Items for budget and work plan preparation

Following sections list out some of the possible items that could be included in budget and work plan preparation in undertaking implementation of NbS. The items list could be customized depending on the nature of the project.

12.4.1. Sample budget

	Task	Sub-tasks	Unit	Rate	Quantity	Cost (SLR)
1	Site preparations	• Slope clearance and trimming operations	Ha			
		• Retention of selected tree species, trimming if necessary, providing cover and support	No			
		• Disposal of spoil material and leveling.	M3			
		• Final ground preparations for executing the selected bio-engineering and civil engineering measures	Ha			
		• Slope clearance and trimming operations	Ha			
		• Retention of selected tree species, trimming if necessary, providing cover and support	No			
2	Civil engineering work	• Survey & leveling work to establish the lay out for civil engineering work	Ha			
		• Ground preparations for identified engineering structures	Ha			
		• Construction of horizontal/contour drains	M			
		• Construction of cascade drains	M			
		• Construction of masonry walls	M3			
		• Construction of Gabion walls	M3			
		• Construction of Irrigation & water supply lines	M			
		• Construction of foot paths, passages, walkways etc.	M2			
3	Bio-engineering work	• Slope preparations (beds, contour lines, diagonal lines, etc.) for executing the selected bio-engineering measures	Ha			
		• Use of fertilizer, composting material etc.	Kgs			
		• Execution of selected bio-engineering measures (Sowing of grass species in site, grass planting and seeding, site planting of tree species, placement of hardwood	Labour days			

	Task	Sub-tasks	Unit	Rate	Quantity	Cost (SLR)
		cuttings, erosion protection mats etc.) as per the design of the mitigation plan				
		• Mulching and supply of cover for plants when and where necessary				
4	Plant nursery development and maintenance	• Nursery establishment	Labour days			
		• Construction of Nursery beds				
		• Nursery production of selected grass types				
		• Nursery production of trees and shrubs in poly-bags and poly-pots				
		• Nursery production of hardwood plants				
		• Compost and mulch production				
		• Extraction of plants from Nursery and transportation				
5	Post execution inspection and maintenance	• Routine maintenance of plants and all bio-engineering works	Labour days			
		• Weeding and removal of unnecessary or excess plants and disposal				
		• Mulching as required to protect plants				
		• Replacement of failed, weak, decease affected and damaged plants				
		• Fertilizing and grassing				
		• Replanting and enrichment work				
		• Thinning, pruning and disposal of material				
6	Remunerations for supervisory staff	• Civil engineers	m/m			
		• Geotechnical engineer/ engineering geologists	m/m			
		• Agricultural engineers	m/m			
		• Agronomists	m/m			
		• Botanists	m/m			
		• Landscape architects	m/m			
		• Technical officer	m/m			
		• Work supervisor	m/m			
7	• Cost of material					
9	• Higher of equipment & machinery					
9	• Transportation					
10	• Electricity					
11	• Water supply					
12	• Communication					
13	• Miscellaneous					
	Total					

12.4.2. Sample work plan

No	Task Name	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M19	M20	M21	M22	M23	M24
1	**Site preparations**																								
1.1	Slope clearance and trimming operations																								
1.2	Retention of selected tree species, trimming if necessary, providing cover and support																								
1.3	Disposal of spoil material and leveling																								
1.4	Final ground preparations for executing the selected bio-engineering and civil engineering measures																								
2	**Civil engineering work**																								
2.1	Survey & leveling work to establish the lay out for civil engineering work																								
2.2	Ground preparations for identified engineering structures																								
2.3	Construction of horizontal/contour drains																								
2.4	Construction of cascade drains																								
2.5	Construction of masonry walls																								
2.6	Construction of Gabion walls																								
2.7	Construction of Irrigation & water supply lines																								
2.8	Construction of foot paths, passages, walkways etc.																								
3	**Bio-engineering work**																								
3.1	Slope preparations (beds, contour lines, diagonal lines, etc.) for executing the selected bio-engineering measures																								
3.2	Use of fertilizer, composting material etc																								
3.3	Execution of selected bio-engineering measures (Sowing of grass species in site, grass planting and seeding, site planting of tree species, placement of hardwood cuttings, erosion protection mats etc.) as per the design of the mitigation plan																								
3.4	Mulching and supply of cover for plants when and where necessary																								
4	**Plant nursery development and maintenance**																								
4.1	Nursery establishment																								
4.2	Construction of Nursery beds																								
4.3	Nursery production of selected grass types																								
4.4	Nursery production of trees and shrubs in poly-bags and poly-pots																								
4.5	Nursery production of hardwood plants																								
4.6	Compost and mulch production																								
4.7	Extraction of plants from Nursery and transportation																								

No	Task Name	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M19	M20	M21	M22	M23	M24
5	**Post execution inspection and maintenance**																								
5.1	Routine maintenance of plants and all bio-engineering works																								
5.2	Weeding and removal of unnecessary or excess plants and disposal																								
5.3	Mulching as required to protect plants																								
5.4	Replacement of failed, weak, decease affected and damaged plants																								
5.5	Fertilizing and grassing																								
5.6	Replanting and enrichment work																								
5.7	Thinning, pruning and disposal of material																								

CHAPTER 13

CASE STUDIES FROM NEIGHBORING REGIONS

NBLRM

Chapter 13 CASE STUDIES FROM NEIGHBORING REGIONS

13.1 South Asia

Balasuriya *et al.* (2018) explored the suitable bioengineering plants and their use for slope stabilization in Sri Lanka. The study was carried out in Badulla District due to the presence of severe erosion and abundances of more frequent landslides. The authors identified a set of plants through literature review and field observations as suitable bioengineering plants for Sri Lankan slopes. Few of the plants listed in the study are: Imperata cylindrica, Mimosa pudica, Wedelia trilobata, Bouteloua dactyloides, Arachis pintoi, Gleichenia linearis, Desmodium Sp, Microstegium vimineum, Digitaria sanguinalis, Lunularia etc.

Dharmasena and Kulathilaka (2015) studied the effect of reinforcement by modelling the roots of the vegetation in the slope surface as soil nails. The roots were modeled as nails of drill hole diameter 50 mm and tensile strength 200kN. The results of the analysis indicated that in early days of rainfall the critical failure surfaces are quite deep. A typical critical failure surface extends much deeper than the roots and roots cannot generate a reinforcing effect. At later stages, the critical failure surface is shallower and with a lower FOS and the roots of same length are more effective. This is indicated by the maintained higher factor of safety on day 5 when nailing effect of vegetation is also accounted. If the roots are to apply a significant reinforcing effect such as with soil nailing, deeper roots should be present at closer spacing

Nawagamuwa *et al.* (2014) carried out a study on Sri Lankan tea plants to find out the effect of Tea roots on slope stability as most of the critical slopes are occupied by tea plants. They carried out some root tensile strengths through the tensile testing machine normally used for yarn testing and some through the traditional tensometer. The authors used the relationship developed by Lateh *et al.* (2011) (TFr = 0.023d2 + 0.051d +0.069) which is a function of root diameter to calculate root tensile capacities. Slopes of the tea estates were modeled considering the no. of tea plants available in a particular slope. They had found that the factor of safety tends to increase with the no. of tea plants under completely dry, saturated and unsaturated conditions. However, authors concluded that the impact of tensile capacity of roots had not been so high under dry and saturated cases for cohesion less soils compared to the same situation under unsaturated condition which had high factor of safety values due to the plant properties.

Cebeda (2017), assessed the role of vegetation as part of Ecosystem-based Risk Reduction Measures used for shallow-landslides in Rasuwa district, Nepal. The study analyzed the mechanical effects of 17 plant species on slope stability. It also looked into the additional benefits the plants can provide to local community population. Root cohesion and surcharge effects were analyzed with the Infinite Slope Model and the Factor of Safety (FOS) was calculated for a hypothetical slope configuration.

Furthermore, in Nepal, Dhital *et al.* (2013) addressed the role of community participation and responsibility for successful application of vegetation-based techniques in management, maintenance and utility aspects for the future. They also listed out the main soil bioengineering techniques used in Nepal, namely, brush layering, palisades, live check dams, fascines, and vegetative stone pitching.

Gupta (2016) from India undertook a study to compare the relative effectiveness of two different types of vegetations (trees and shrubs) in slope stabilization with different slopes under the influence of heavy wind and no wind conditions. His findings suggested that in case of no wind conditions trees with deeper roots in both low and steep graded slope provides highest stability whereas in case of heavy winds, stability of slope decreases drastically, especially in case of vegetation with deep rooted trees in steeper slopes. However, he indicated that shrubs being negligibly affected by wind gave a better stability to the slopes.

Singh (2010) showed that bioengineering is highly cost effective and has very high cost-benefit ratio. He indicated that bioengineering techniques when used in combination with civil and social engineering measures reduce the overall cost of landslide mitigation considerably, which is the key factor for developing nations. Furthermore, bioengineering techniques are much more sustainable, eco-friendly and affordable than other available options.

13.2 East Asia and Pacific

Leung et. al. (2015) investigated the characteristics of root systems of four Hong Kong native shrubs (Rhodomyrtus tomentosa and Melastoma sanguineum) and trees (Schefflera heptaphylla and Reevesia thyrsoidea) to evaluate their enhancing effects on slope stability. The studied species had heights that ranged between 1 and 1.5 m. They statically compared the distribution of roots and root area ratio (RAR) with depth, relationship between root tensile strength (Tr) and root diameter (d), and also the variation of root cohesion (Cr) with depth of four species. The study revealed that roots of the trees were found to extend deeper into the ground (up to 0.8m) whereas roots of shrubs extended up to around 0.4 m only. RAR lies between 0.03 and 0.14% for the top 0.1m soil and decreased with depth. They also indicated that there exists a power decay relationship between the root tensile strength and root diameter for all the studied species considering root diameter range between 1mm and 10mm. Roots of the tree species have higher resistance to tension than those of the shrub species. The root cohesion lied below 1.5 kPa even at shallow depth and became very small at depths below 0.5 m for both studied shrubs and trees. The authors concluded that the studies young vegetation can bring an unsafe slope to marginally safe (factor of safety slightly larger than unity).

Yang *et al.* (2016) investigated five most popular tree species used for slope stabilization in the rocky mountainous areas of northern China. The tree species are: Betula platyphylla, Quercus mongolica, Pinus tabulaeformis, and Larix gmelinii.

The results showed that:

1. Root moisture content had a significant influence on tensile properties;
2. Slightly loss of root moisture content could enhance tensile strength, but too much loss of water resulted in weaker capacity for root elongation, and consequently reduced tensile strength;
3. Root diameter had a strong positive correlation with tensile resistance; and
4. The roots of Betula platyphylla had the best tensile properties when both diameter and moisture content being controlled.

Osman and Barakbah (2011) studied the enrichment of biodiversity of the slope at an early phase of succession, initiated by selected pioneers, and how this enrichment related to enhancement of the slope stability. The case study was carried out in Malaysia. The authors, designed four experimental plots, with differing plant pioneers and number of species (diversity), in order to assess the effects of plant succession on slope stability. This study revealed a positive influence of the plant diversity and density and the natural succession process on slope stability.

Van *et al.* (2005) stated that the use of Vetiver grass for natural disaster mitigation in Vietnam has become very popular. Vetiver is planted in a very wide range of soil types and climatic conditions, from very cold winter in the North, very hot summer-cold winter, pure sand in Central Vietnam to acid sulfate soil, saline soil in the Mekong Delta. They discussed the benefits of Vetiver grass protecting cut slopes and also the prerequisites the sloping land must poses before planting vetiver grass species.

Jotisankasa *et al.* (2015) evaluated quantitatively the effectiveness of Vetiver grass in mitigating erosion and shallow slope instability. They conducted laboratory root tensile strength tests as well as direct shear testing and permeability tests of root-reinforced soil samples. Based on the study they concluded that vetiver plants appeared to have mainly beneficial effects for slope of 26° gradient (1V:2H). However, when applying vetiver plants on very steep slope (>60°, 2V:1H), practitioner should exercise certain cautions, especially for the case of easily degradable rock such as claystone, since there could be theoretical adverse effect of increased infiltration through root zone, amount to 10% reduction in factor of safety.

Ekanayake *et al.* (1997) carried out a study to find the effectiveness of New Zealand indigenous species kanuka (Kunzea ericoides var. ericoides) and exotic species Pinus Radiata in enhancing the slope stability. They conducted in-situ direct shear tests on soil with and without roots. Their study concluded that safety factors for stands of Pinus Radiata in the first 8 years after establishment would be lower than for equivalent-aged stands of fully-stocked regenerating kanuka under similar conditions. However, after 16 years the safety factor for a stand of kanuka would be lower than that for P. radiata at final stocking densities typical of framing and biomass regimes.

13.3 Lessons learnt

A summary of lessons learnt is given in Table 13.1

Table 13-1 Summary of lessons learnt

Country	**Authors**	**Lessons learnt**
Sri Lanka	Balasuriya et. al. (2018)	Suitable plant species for bioengineering applications in Sri Lanka
Sri Lanka	Dharmasena and Kulathilaka (2015)	Mathematical modelling of the root reinforcement effect
Sri Lanka	Nawagamuwa et. al. (2014)	Mathematical modelling of the tensile effect of Tea roots on slope stability
Nepal	Cebeda (2017)	Mechanical effects of plant species
Nepal	Dhital et al. (2013)	Involvement of local community population for successful application of vegetation-based techniques. Main soil bioengineering techniques used in Nepal.
India	Gupta (2016)	Influence of the wind effect on trees and shrubs and how it affects the slope stability

Country	Authors	Lessons learnt
India	Singh (2010)	Bioengineering techniques when used in combination with civil and social engineering measures reduce the overall cost of landslide mitigation considerably, which is the key factor for developing nations.
Hong Kong	Leung et al (2015)	Mathematical equations to quantify root tensile strength and root cohesion.
China	Yang et al (2016)	Effect of root moisture content on root tensile strength and how it affects the slope stability.
Malaysia	Osman and Barakbah (2011)	The importance of using different plant pioneers and other species (diversity) to improve the enhancement effects of vegetation on slope stability.
Vietnam	Van et al. (2005)	Benefits of Vetiver grass protecting cut slopes. Prerequisites the sloping land must poses before planting vetiver grass species.
Thailand	Jotisankasa et al. (2015)	Quantitative evaluation of Vetiver grass in mitigating erosion and shallow slope instability.
New Zealand	Ekanayaka et al. (1997)	**The field set-up used to perform *in situ* direct shear tests on soil with and without roots.**

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ANNEXURE 1

Summary of bioengineering characteristics of plants in wet and intermediate zones of Sri Lanka

#	Scientific Name	Family	Local Name	Type	Soil Type	Stabilization Method	Root System	Propagation	Available Site	Agro Ecological Region
1	Gleichenia linearis	Gleicheniaceae	Kekilla	Fern	Clay loam, sandy loam and sandy clay loam	Ground covers and soil stabilizers	Numerous roots arise along rhizome	Rhizome pieces	Degraded open areas of rain forests, along paths in secondary forests, waste lands, vicinity of streams	Wet zone
2	Asplenium sessilifolium	Aspleniaceae	Spleenworts	Fern	Clay loam, sandy loam and sandy clay loam	Ground covers and soil stabilizers	Short rhizome with fibrous roots	Rhizome pieces, spores	Rocky wooded slopes, rocky banks along roads	
3	Pteridium aquilinum	Dennstaedtiaceae	Werella	Fern	Clay loam, sandy loam and sandy clay loam	Ground covers and soil stabilizers	Wide-creeping underground rootstock	Spores, division	Woodland and grassland/rock garden	Wet zone
4	Lunularia cruciate	Lunulariaceae	Meewana	Fern	Clay loam, sandy loam and sandy clay loam	Ground covers and soil stabilizers	Arbuscular mycorrhizal roots	Clonal fragments that splash from the mother plant to form a new plant		
5	Thysanolaena maxima	Poaceae	Kusa-thana	Grass	Well drained but humus rich soils are ideal, though it will withstand many soil types	Preventing surface soil erosion on steep hillsides		Divisions of clump, seeds	Steep hills, sandy banks of rivers and damp steep	
6	Sporobolus heterolepis	Poaceae	Prairie dropseed	Grass	Clay loam, sandy loam and sandy clay loam	Ground covers and soil stabilizers	Extensive root system that runs deep into the ground	Seeds		
7	Poa labillardierei	Poaceae	Tussock-grass	Grass	Clay loam, sandy loam and sandy clay loam	Ground covers and soil stabilizers	Shallow and spreading fibrous root	Seeds		
8	Miscanthus sinensis	Poaceae	Chinese silver grass	Grass	Clay loam, sandy loam and sandy clay loam	Ground covers and soil stabilizers	Fibrous	Seeds, rhizomes	Garden grass	
9	Desmodium heterophyllum	Fabaceae	Maha-Undupiyaliya	Grass	Clay loam, sandy loam and sandy clay loam	Ground covers and soil stabilizers	Fibrous	Seeds, cuttings of half-ripe wood with a heel	Riversides, roadsides, field margins, grasslands	
10	Desmodium Sp.	Fabaceae	Undupiyaliya	Grass	Clay loam, sandy loam and sandy clay loam	Ground covers and soil stabilizers	Fibrous, prostrate branches rooting at node	Seed	Roadsides, grasslands, home gardens	
11	Imperata cylindrica	Poaceae	Illuk	Grass	Clay loam, sandy loam and sandy clay loam	Ground covers and soil stabilizers	Roots are up to 1.2 m deep	Seed, rhizomes	Weed grows in coastal areas, sand dunes, open places, roadsides, waste lands, agricultural fields, ditch banks	Dry, intermediate zones
12	Digitaria	Poaceae	Guru-	Grass	Clay loam,	Ground covers	Fibrous;	Seeds	Weedy meadows,	Wet zone

#	Scientific Name	Family	Local Name	Type	Soil Type	Stabilization Method	Root System	Propagation	Available Site	Agro Ecological Region
	sanguinalis		thana		sandy loam and sandy clay loam	and soil stabilizers	sometimes the nodes of the lower culms will form new fibrous roots		edges of degraded wetlands, areas along roads and railroads, lawns and gardens, vacant lots, fields, grassy paths, and miscellaneous waste areas	
13	Juncus prismatocarpus	Juncaceae	Pan	Grass	Sandy loam and	Anchors	Roots and rhizome	Seeds	Widespread in wet situations	
14	Juncus usitatus	Juncaceae	Pan	Grass	Sandy loam and	Anchors	Fibrous	Branching rhizomes, seeds	low-lying moisture retentive sites, banks and riparian zones in parks and reserves or areas adjoining urban, recreational and industrial sites	
15	Glochidion moonii	Phyllanthaceae	Be Hunukirlla	Endemic shrub		Anchors and evaporators	Deep root system with M-type architecture	Seeds	Primary and secondary forests	Wet zone
16	Indocalamus tessellatus	Poaceae	Katu-una	Grass	Clay loam, sandy clay and sandy loam	Anchors	Rhizomatous which enables its spread	Divisions	Gardens, ridgetops and along water courses	Dry, intermediate and wet zones
17	Chrysopogon zizanioides	Poaceae	Savandara	Grass	Silty clay and clay loam		Massive finely structured root system can grow very fast	Seeds, divisions	Floodplains, bank of streams and rivers, rich moist soil	
18	Cymbopogon nardus	Poaceae	Citronella	Grass	Silty clay and clay loam		Stout rootstock	Seeds, divisions of established clumps	Grassland, open woodland	
19	Paspalum dilatatum	Poaceae	Miti-paspalum tana	Grass	Silty clay and clay loam	Anchors and evaporators	Short creeping rhizomes and deep thick fibrous roots	Seeds	Gardens, footpaths, closed forests, open woodland, waste areas	
20	Panicum maximum	Poaceae	Gini tana	Grass	Variety of soils except heavy clayey	Ground cover and prevent soil erosion	Fibrous	Seeds, vegetative	Road and railway sides, natural forests, crop plantations, natural grasslands and scrubland at low and mid elevations	Most ecological zones
21	Cymbopogon citratus	Poaceae	Lemmon grass	Grass	Sandy soil, hard clay soil not suitable	Ground covers and soil stabilizers	Fibrous	Seeds and suckers		Wet zone
22	Dillenia retusa	Dilleniaceae	Godapara	Medium to large tree		Anchors and evaporators	Taproot system up to 1.0m; H type roots	Seeds	Disturbed sites, scrub	Wet zone
23	Hemerocallis fulva	Asphodelaceae	Orange day-lily	Herbaceous plant	Clay loam, sandy loam and sandy clay loam	Ground covers and soil stabilizers	tuberous roots	Seeds	Roadside, home-gardens	
24	Ageratina riparia	Asteracea	Mistflower,	Herbaceous	Clay loam, sandy loam	Ground covers and soil stabilizers	Its stems produce r	Seeds	Mountain and cloud forests of sri lanka,	

#	Scientific Name	Family	Local Name	Type	Soil Type	Stabilization Method	Root System	Propagation	Available Site	Agro Ecological Region
		e	creeping croftonweed	plant	and sandy clay loam		oots at joints that touch the ground		and in pastures, roadsides, wastelands and bushlands	
25	Mimosa pudica	Fabaceae	Nidikumba	Herbaceous plant	Sandy loam and	Anchors	Bark-fibrous	Seeds and vegetative methods	Open-spaces, especially road side, cultivated land, and waste area	Dry, wet, intermediate zones
26	Elettaria cardamom	Zingiberaceae	Cardamom	Herbaceous perennial plant	Loamy and loamy clay	Prevent soil erosion	Fibrous, rhizome	Seedlings, suckers	Central hill country, Galle	
27	Termiinalia arjuna	Combretaceae	Kumbuk	Large tree	light (sandy), medium (loamy) and heavy (clay) soils and prefers well-drained soil	Helping to reduce soil erosion on the banks through its root-mass	Taproot	Seeds, root-suckers, stumps and air-layering	Along water courses of monsoon forest	Dry, intermediate zones
28	Sapindus emarginatus	Sapindaceae	Penela	Large tree	Wide range of well-drained soils, including those that are dry, stony and nutrient deficient	Firmly hold on to soil, hold soil tightly, wind barrier, prevent erosion	Taproot	Seeds, greenwood cuttings	Monsoon forest canopy	Dry zone
29	Alnus nepalensis	Betulaceae	Alder	Medium-sized tree	Tolerate clay, flooding, fog, gravel, sand, shade, slope, water-logging	Firmly hold on to soil, hold soil tightly, wind barrier, prevent erosion	Extensive lateral root system	Seeds, cuttings of mature wood	Forests in ravines, on stream banks	
30	Terminalia chebula	Combretaceae	Aralu	Medium-sized tree	Any moderately fertile, well-drained soil from sandy to clayey	Firmly hold on to soil, hold soil tightly, wind barrier, prevent erosion	Taproot	Seeds, cuttings	Monsoon forest canopy, savannah	Dry zone, intermediate zone
31	Bischofia javanica	Phyllanthaceae	Bishop wood	Medium-sized tree	Deep loose soils, such as sandy, rocky or loamy soils, with sufficient water content	Firmly hold on to soil, hold soil tightly, wind barrier, prevent erosion	Taproot	Seeds, stem cuttings	Savannah tracts, especially on riverbanks and shady ravines	
32	Arachis pintoi	Fabaceae	Perennial peanut, Pinto peanut	Plant	Sandy loam and	Anchors	Distinct taproot, dense network of fibrous roots, up to 20cm long, with nodules	Stem cuttings, seeds	Occurs under open forests	
33	Mussaenda frondosa	Rubiaceae	Mussenda	Scandent shrub	Soil with a pH around 7, lightly amend heavy clay or sandy soils with organic matter	Ground covers and soil stabilizers	Taproot	Seeds, air layering, cuttings of half ripe wood	Scrub, roadsides	Wet zone
34	Atalantia ceylanica	Rutaceae	Yakinaran	Shrub	Well-drained soils, fertile loamy soils	Ground cover and prevent soil erosion	Taproot	Seeds	Monsoon, intermediate and rain forest understory, scrub	Dry, intermediate, wet zones
35	Morus alba		Mulberry	Shrub	Rich loamy	Ground covers	longest	Seeds,	Home gardens,	Intermediate,

#	Scientific Name	Family	Local Name	Type	Soil Type	Stabilization Method	Root System	Propagation	Available Site	Agro Ecological Region
		Moraceae			soil, clay loam, sandy loam	and soil stabilizers	lateral root extension was 42 feet, most lateral roots occurred in the upper 1 to 3 feet	stem cutting	plantations	wet zones
36	Breynia retusa	Euphorbiaceae	Wal murunga	Shrub	Sandy loamy soil, granite or basalt derived sandy soil, limestone	Ground covers and soil stabilizers	Taproot	Seeds	Monsoon, intermediate, rain forest understory	Dry, intermediate and wet zone
37	Phyllanthus myrtifolius	Euphorbiaceae	Ganga-werella	Shrub	Any well drained soil	Ground covers and soil stabilizers	Taproot	Cuttings	Along water courses in forest; gardens	Intermediate zone, wet zone
38	Strobilanthes Sp.	Acanthaceae	Blooming nelu	Shrub	Clay loam, sandy loam and sandy clay loam	Ground covers and soil stabilizers		Softwood cuttings	Horton plains	Central high land
39	Lamiaceae Sp.	Lamiaceae	Val-seneha kola, maagandi, kapparawalliya	Shrub	Clay loam, sandy loam and sandy clay loam	Ground covers and soil stabilizers		Stem cuttings		
40	Austroeupatorium inulifolium	Asteraceae	Sudda, valsudda	Shrub	Clay loam, sandy loam and sandy clay loam	Ground covers and soil stabilizers		Seeds, cuttings	Forest, plantations and perennial crops, roadsides	
41	Bambusa guangxiensis	Poaceae	Chinese dwarf bamboo	Shrub	Clay loam, sandy clay and sandy loam	Anchors	Rhizomes with fibrous root	Seeds, rhizomes, culm and branch cuttings	Gardens	Wet zone, mid country
42	Ochlandra stridula	Poaceae	Bata	Shrub	Clay loam, sandy clay and sandy loam	Anchors	Fibrous	Seeds	Understory, gaps and fringes of rain forest	Wet zone
43	Osbeckia octandra	Melastomataceae	Heen bowitiya	Shrub	Clay loam, sandy clay and sandy loam	Anchors		Seeds, vegetative	Montane and rain forest gaps and fringes, secondary forest, scrub and grasslands	Mid country, wet zone, dry zone
44	Osbeckia lanata	Melastomataceae		Shrub	Clay loam, sandy clay and sandy loam	Anchors		Seeds	Mountains of southern, montane forest understory	Mid country
45	Osbeckia aspera	Melastomataceae	Bowitiya	Shrub	Clay loam, sandy clay and sandy loam	Anchors		Seeds	Forest understory, secondary scrub	Wide spread
46	Agave vera-cruz	Asparagaceae	Pathok, hana	Shrub	Silty clay and clay loam			Seeds, in vitro propagation	Waste places, roadsides and railway embankment	
47	Tabernaemontana divaricata	Apocynaceae	Wathu sudda	Shrub	Fertile, moist but well-drained soil	Ground covers and soil stabilizers	Taproot	Seeds, cuttings	Home gardens, parks	Wide spread
48	Lantana camara	Verbenaceae	Ganda pana	Shrub	Variety of soil types	Ground covers and soil stabilizers	Taproot	Stem cuttings	Naturalized, scrub, roadsides, home gardens	Wide spread
49	Murraya paniculata	Rutaceae	Etteriya	Shrub to small	Alkaline, clayey, sandy , acidic and	Ground covers and soil stabilizers	Taproot	Cuttings, seeds	Monsoon forest understory, rocky outcrops, limestone	Dry zone

#	Scientific Name	Family	Local Name	Type	Soil Type	Stabilization Method	Root System	Propagation	Available Site	Agro Ecological Region
				tree	loamy soils				scrub	
50	Premna latifolia	Verbenaceae	Maha midi	Shrub to small tree	Sandy loam with good organic content		Taproot	Stem cuttings	Monsoon forest understory, scrub	Dry, intermediate zones
51	Camellia sinensis	Theaceae	Tea	Shrub to small tree	light (sandy) and medium (loamy) soils and prefers well-drained soil	Ground covers and soil stabilizers	Taproot, primary to 3 meters deep	Seeds, cuttings of firm wood	Home gardens, plantations	Wet, intermediate zones
52	Dichrostachys cinerea	Leguminosae	Andara	Shrub to small tree	Many types of soils, including lateritic or clayey soils	Ground covers and soil stabilizers	Taproot	Seeds, root suckers, root cuttings	Thorn scrub	Dry zone
53	Pliotinia integrifolia	Rosaceae	Lunu warala	Shrub to small tree	Acid and neutral soils	Ground covers and soil stabilizers	Taproot	Seeds	Montane forest understory, gaps and fringe	
54	Theobroma cacao	Malvaceae	Cocoa	Small tree	fertile, moisture-retentive but well-drained soil	Firmly hold on to soil, hold soil tightly, wind barrier, prevent erosion	Taproot	Seeds, leaf-bud cuttings, grafting	Under-story plant of evergreen rainforest, home gardens	
55	Psidium guajava	Myrtaceae	Guava	Small tree	Varied types of soils from heavy clay to very light sandy soils	Firmly hold on to soil, hold soil tightly, wind barrier, prevent erosion	Taproot	Seeds, cuttings and grafting	Agricultural areas, forest edges, natural forests	
56	Neolitsea cassia	Lauraceae	Dawul kurundu	Small tree	Moist soils, well-drained soils	Firmly hold on to soil, hold soil tightly, wind barrier, prevent erosion	Taproot	Seeds	Montane and rain forest understory	Mid country, low country, up country wet zone
57	Streblus taxoides	Moraceae	Gongotu	Small tree		Firmly hold on to soil, hold soil tightly, wind barrier, prevent erosion	Taproot	Seeds	Rocky, dry places, monsoon and intermediate forest understory	Dry, intermediate zones
58	Zizyphns jujuba	Rhamnaceae	Masan	Small tree	Well drained most soil types/ prefer open loam	Firmly hold on to soil, hold soil tightly, wind barrier, prevent erosion	Taproot	Seeds, stem and root cuttings	Montane forest understory	Mid country
59	Barringtonia acutangula	Lecythidaceae	Ela-midella	Small tree	Wide range of soils including heavy clay	Firmly hold on to soil, hold soil tightly, wind barrier, prevent erosion	Taproot	Seeds, stem cuttings	Around tanks, water ways, flood plains	Dry zone
60	Pandanus odoratissimus	Pandanaceae	Pandan, mudu keiya	Small tree	Light to heavy soil types/ wide range	Firmly hold on to soil, hold soil tightly, wind barrier, prevent erosion	Long aerial roots	Stem cuttings, suckers	River banks, alluvial	
61	Leucaena leucocephala	Leguminosae	Ipil-ipil	Small tree	Shallow limestone soils, coastal sands and seasonally dry soils	Firmly hold on to soil, hold soil tightly, wind barrier, prevent erosion	Taproot	Seeds, stem cuttings	Roadsides, plantations	Dry, wet, intermediate zones
62	Cycas circinalis	Cycadaceae	Madu	Small tree	light (sandy) and medium (loamy) soils and prefers well-drained soil	Firmly hold on to soil, hold soil tightly, wind barrier, prevent erosion	Fibrous r oots	Seeds, offsets	Savannahs, home gardens	Intermediate zone
63	Dillenia indica	Dilleniaceae	Hondapara	Small tree	Loamy, sandy	Firmly hold on to soil, hold soil tightly, wind barrier, prevent erosion	Taproot	Seeds, cuttings	Roadsides, disturbed sites close to water	Wet zone

#	Scientific Name	Family	Local Name	Type	Soil Type	Stabilization Method	Root System	Propagation	Available Site	Agro Ecological Region
64	Rhododendron arboreum	Ericaceae	Maha rath mal	Small tree	Clay loam and sandy clay loam	Anchors and evaporators	Root ball is kept intact	Seeds, layering, cuttings	Montane forest gaps and fringes, wet patana grassland	Mid country
65	Artemisia argyi	Asteraceae	Thora	Tree	Clay loam, sandy clay and sandy loam	Anchors	Tonic and anti-spasmodic	Seeds	Waste places, roadsides, slopes, hills, steppe and forest	
66	Calliandra calothyrsus	Fabaceae	Calliandra	Tree	Sandy clay loam	Anchors	Well-developed lateral root system, deep root and extensive fibrous root	Seeds, stem cuttings	Secondary vegetation, roadsides, open slopes	
67	Adenanthera pavonina	Fabaceae	Madatiya	Tree	Silty clay and clay loam		Taproot	Seeds, nodal cuttings	Deciduous forest at low elevations, roadsides, dry open forest	
68	Gliricidia sepium	Fabaceae	Gliricidia	Tree	Silty clay and clay loam	Anchors and evaporators	Root system may improve soil fertility	Seeds, cuttings	Roadsides, gardens, tea plantations	Wide spread
69	Symbplocus sp.	Symplocaceae		Tree	Clay loam and sandy clay loam	Anchors and evaporators	Taproot	Seeds	Understory plant in upland and mountain rainforest	
70	Pinus roxburghii	Pinaceae	Pinus	Tree	Clay soil	Trees that prevent soil erosion using the fallen leaves or needles as a soil cover	Taproot	Seeds	Plantations	Wet zone, low country mid zone
71	Syncarpia glomulifera	Myrtaceae	Turpentine	Tree		Trees that prevent soil erosion using the fallen leaves or needles as a soil cover	Noninvasive root system	Seed	Plantations	Wet zone
72	Anacardium occidentale	Anacardiaceae	Cadju	Tree	Arid thickets in stony, sandy soils, can bear heavy, waterlogged clay soils or saline soils but with an extreme poor growth	Firmly hold on to soil, hold soil tightly, wind barrier, prevent erosion	Taproot	Seed, cuttings of ripe wood, layering	Sandy coastal thickets, home gardens	Dry, wet zones
73	Spondias dulcis	Anacardiaceae	Ambarella	Tree	limestone derived soils as well as on acid sands, but the soil should be well drained	Firmly hold on to soil, hold soil tightly, wind barrier, prevent erosion	Taproot	Seeds, layering, cuttings	Planted on roadside home gardens	Wet zone
74	Alstonia scholaris	Apocynaceae	Rukaththana	Tree	Tolerant of a range of soils, and have been grown successfully on shallow soils over coral	Firmly hold on to soil, hold soil tightly, wind barrier, prevent erosion	Taproot	Seeds, grafting	Particularly along stream ways in monsoon forest, rain forest	Dry zone, wet zone
75	Careya arborea	Lecythidaceae	Kahata	Tree	well-drained, sandy or even rocky	Firmly hold on to soil, hold soil tightly, wind barrier, prevent	Taproot	Seeds	Savannah, dry patana grassland	Wet, intermediate zone

#	Scientific Name	Family	Local Name	Type	Soil Type	Stabilization Method	Root System	Propagation	Available Site	Agro Ecological Region
					soil	erosion				
76	Artocarpus heterophyllus	Moraceae	Jackfruit	Tree	Prefers a deep, well-drained alluvial soil, wide range of soil types	control floods and soil erosion	Taproot, wide-ranging root system	Seeds, root cuttings	Home gardens	Wide spread
77	Gyrinops walla	Thymelaeaceae	Walla-patta	Tree		Firmly hold on to soil, hold soil tightly, wind barrier, prevent erosion	Taproot	Seed	Rain forest understory	Wet zone
78	Santalum album	Santalaceae	Sudu-hadun	Tree	Fertile, moist but well drained soil, slightly acid soil	Firmly hold on to soil, hold soil tightly, wind barrier, prevent erosion	Taproot	Seeds, branch cuttings, root suckers	Home gardens, scrub	Intermediate zone, wet zone
79	Hevea brasiliensis	Euphorbiaceae	Rubber	Tree	Wide range of soils, including clay, sand and loam	Firmly hold on to soil, hold soil tightly, wind barrier, prevent erosion	Taproot	Layering, seeds	Plantations, home gardens	Intermediate, wet zones
80	Cinnamomum zeylanicum	Lauraceae	Cinnamon	Tree	Loamy and lateritic gravelly, silver sands	Reduce the erosion	Long aerial roots	Seed, stem cutting	Rain forest subcanopy, home gardens, plantations	Wet zone
81	Ficus racemosa	Moraceae	Aththikka	Tree	Most soils that are reasonably moist but well-drained,	Firmly hold on to soil, hold soil tightly, wind barrier,prevent erosion	Taproot	Seeds, air layering, tip cuttings around 4 - 12cm long, taken from lateral branches	Riverbanks	Dry, intermediate zones
82	Horsfieldia iryaghedhi	Myristicaceae	Ruk	Tree		Firmly hold on to soil, hold soil tightly, wind barrier, prevent erosion	Taproot, stilt roots are sometimes	Seeds	rain forest subcanopy	Low country wet zone
83	Myristica dactyloides	Myristicaceae	Malaboda	Tree	Succeed on a range of soil types	Firmly hold on to soil, hold soil tightly, wind barrier, prevent erosion	Taproot/the bole often has stilt roots	Seeds	Intermediate and rain forest canopy and subcanopy	Low country mid zone, intermediate zone, wet zone
84	Myristica fragrans	Myristicaceae	Sadikka	Tree	Volcanic origin and soils with a high content of organic matter with a pH in the range 6.5 - 7.5	Firmly hold on to soil, hold soil tightly, wind barrier, prevent erosion	Taproot	Seeds, air layering, grafting	home gardens	Intermediate, wet zones
85	Diospyros insignis	Ebenacea	Porawa-mara	Tree	Fertile soil of clay and sandy	Firmly hold on to soil, hold soil tightly, wind barrier, prevent erosion	Taproot	Seeds	Rain forest understory	Wet, dry zones
86	Cinnamomum dubium	Lauraceae	Wal-kurundu	Tree	Well drained sandy, loamy, clay	Firmly hold on to soil, hold soil tightly, wind barrier, prevent erosion	Taproot		Rain forest understory	Wet zone
87	Mesua ferrea	Calophyllaceae	Ironwood	Tree	Well drained and deep fertile soil, stiff clay soil	Firmly hold on to soil, hold soil tightly, wind barrier, prevent erosion	Taproot	Seeds	Rocky hills, gardens	Dry zone
88	Macaranga peltata	Euphorbiaceae	Kanda	Tree		Firmly hold on to soil, hold soil tightly, wind barrier, prevent	Taproot	Seeds	Rain forest gaps and fringes, secondary forest	Wet zone

#	Scientific Name	Family	Local Name	Type	Soil Type	Stabilization Method	Root System	Propagation	Available Site	Agro Ecological Region
						erosion				
89	Dipterocarpus zeylanicus	Dipterocarpaceae	Hora	Tree		Firmly hold on to soil, hold soil tightly, wind barrier, prevent erosion	Taproot	Seed	Rain forest canopy, along	Intermediate zone, low country wet zone
90	Mangifera indica	Anacardiaceae	Mango	Tree	light (sandy), medium (loamy) and heavy (clay) soils and prefers well-drained soil	Firmly hold on to soil, hold soil tightly, wind barrier, prevent erosion	Taproot	Seeds, cuttings	Roadsides, home gardens	Dry, wet, intermediate zones
91	Artocarpus altillis	Moraceae	Del	Tree	sand, sandy loam, loam or sandy clay loam	Firmly hold on to soil, hold soil tightly, wind barrier, prevent erosion	Taproot	Seeds, stem and root cuttings	Wet lowland	Wet, intermediate zones
92	Syzygium aromaticum	Myrtaceae	Clove	Tree	Well-drained sandy, acid loams	Firmly hold on to soil, hold soil tightly, wind barrier, prevent erosion	Taproot	Seeds, cuttings of terminal leafy softwood	Home gardens	Wet, intermediate zone
93	Hopea jucunda	Dipterocarpaceae	Ratberaliya	Tree	Deep and shallow soil	Firmly hold on to soil, hold soil tightly, wind barrier, prevent erosion	Taproot	Seeds, cuttings and wildlings	Rain forest subcanopy	Wet zone
94	Cordia monoica	Boraginaceae	Lolu	Tree	Red clay soils	Firmly hold on to soil, hold soil tightly, wind barrier, prevent erosion	Taproot	Seeds, cuttings	Valley bottoms and watercourses on rocky areas, scrub on sandy seashore	Dry zone
95	Casuarina equisetifolia	Casuarinaceae	Kassa	Tree	Poor sandy soil conditions, wide range of condition	Firmly hold on to soil, hold soil tightly, wind barrier, prevent erosion	Taproot	Seeds, vegetative	Roadsides, coastal sands, plantations	Dry, wet zones
96	Garcinia mangostana	Clusiaceae	Mangosteen	Tree	Loamy and clay soil (prefers well-drained soil)	Anchors and evaporators	Taproot	Seedlings	Home gardens	Intermediate, wet zones
97	Anogeissus latifolia	Combretaceae	Dawul	Tree	Variety of soils but prefers deep alluvial soils	Firmly hold on to soil, hold soil tightly, wind barrier, prevent erosion	Taproot	Seedlings	Forest, savannah	Intermediate, dry zones
98	Dendrocalamus giganteust	Poaceae	Yodha-una	Tree-like clump	Clay loam, sandy clay and sandy loam	Anchors	Aerial roots occur up to the eighth node. The rootstock is stout	Seeds, culm and branch cuttings	home gardens, tea estates	Wet zone
99	Bambusa vulgaris	Poaceae	Kaha-una	Tree-like clump	Wide range, moist soils, well-drained soils	Ground covers and soil stabilizers	Narrow ring of roots and covered with brown hairs	Seeds, storage organs (rhizome)	Paddy field bunds, water courses	Dry, intermediate, wet zones
100	Michelia champaca	Magnoliaceae	Gini-sapu	Large tree	Wide range of soils	Anchors and evaporators	Well develop tap and lateral roots	Seeds	Home gardens and secondary forests	Dry, intermediate, wet zones
101	Chrysopogon zizanioides	Poaceae	Vetivergrass	Grass	Wide range of soils	Native grass for erosion control and soil	Dense fibrous root	Seed Division		

#	Scientific Name	Family	Local Name	Type	Soil Type	Stabilization Method	Root System	Propagation	Available Site	Agro Ecological Region
						improvement	penetrates to deep			
102	Hibiscus tiliaceus	Malvaceae	Belipatta	Medium to large shrub	Quartz sand, coral sand, limestone	Evaporators	Taproot system up to 2.0m; VH type roots	Seeds, cuttings	Coastal areas along rivers and lagoons	
103	Murraya paniculata	Rutaceae	Etteria	Small to medium shrub	Rich, moist, well-drained loam	Anchors and evaporators	Taproot system up to 1.0m; H type roots	Seed	Native tree, not a pioneer species	
104	Jatropha curcas	Euphorbiaceae	Theledaru	Small to medium shrub	Well-drained soils with good aeration	Plant makes an excellent hedge	Taproot system up to 2.0m; R type roots	Seeds, cuttings of half-ripe wood	Grassland savannah and thorn forests	
105	Vitex negundo	Lamiaceae	Nika	Small to medium shrub	Light well-drained loamy soil	Used as a contour hedge in sandy arid areas for soil retention and moisture conservation	Taproot system up to 2.0m; H type roots	Seeds, cuttings of mature wood and half-ripe wood	Native forest tree species	
106	Melastoma malabathricum	Melastomataceae	Bowitiya	Small shrub	Well-drained, fertile, humus-rich soil	Anchors and evaporators	Taproot system up to 2.0m; M type roots	Seed	Disturbed locations, on fallow land, or in grasslands	
107	Coffea arabica	Rubiaceae	Coffee	Medium size shrub	Deep friable soil on undulating land	Hold soil tightly, wind barrier, prevent erosion	Taproot system up to 1.0m; H type roots	Seeds, cuttings	Gardens, estates	Wet and intermediate
108	Michelia champaca	Magnoliaceae	Ginisapu	Large tree	Moist but well-drained, deep, fertile, loamy to sandy soil	Soil under tree cover shows an increase in pH, soil organic carbon and available phosphorus	Taproot system up to 2.0m; VH type roots	Seeds, cuttings	Scattered in primary lowland to montane rain forest	
109	Bauhinia racemosa	Fabaceae	Maila	Medium to large tree	Fertile, moisture-retentive but well-drained soil	Anchors and evaporators	Taproot system up to 4.0m; VH type roots	Seeds, cuttings of half-ripe wood	Dry, deciduous forests, frequent in grassy blanks and open spaces, and common also on dry hills	
110	Bauhinia purpurea	Fabaceae	Bauhinia	Medium to large tree	Fertile, moisture-retentive but well-drained, sandy, loamy or gravelly soil	Anchors and evaporators	Taproot system up to 2.0m; H type roots	Seeds, cuttings of half-ripe wood	Mixed deciduous forests	
111	Azadirachta indica	Meliaceae	Kohomba	Large tree	A well-drained soil in a sunny position	Anchors and evaporators	Taproot system up to 4.0m; VH type roots	Seeds, air-layering, Root cuttings.	Evergreen lowland forests	
112	Peltophorum pterocarpum	Fabaceae	Wal ehela	Medium to large tree	Prefers light to medium free draining alkaline soils although it also tolerates clay soils	Used as a hedge	Taproot system up to 2.0m; R type roots	Seeds	Forest areas	
11	Pterocarpus	Fabaceae	Amboyna	Large	A range of	Anchors and	Taproot	Seeds,	Widespread tree	

#	Scientific Name	Family	Local Name	Type	Soil Type	Stabilization Method	Root System	Propagation	Available Site	Agro Ecological Region
3	indicus			tree	soils from sandy loams to clays	evaporators	system up to 4.0m; VH type roots	cuttings		
114	Wendlandia bicuspidata	Rubiaceae	Wana-edala, rawan-edala	Evergreen small tree		Anchors and evaporators	Taproot system up to 2.0m; R type roots	Shoot cuttings and root cutting seems to be a promising propagation	Native forest species in secondary forest, pioneer	Wet zone
115	Eurya accuminata	Pentaphylacaceae		Small tree	A moderately fertile free-draining moisture retentive soil	Anchors and evaporators	Taproot system up to 2.0m; R type roots	Seeds, cuttings of half-ripe wood	Hill forests	
116	Trema orientalis	Cannabaceae	Gadumba	Medium to large tree	A well-drained, sandy soil	Improve the soil, growth rapidly on disturbed soils	Taproot system up to 2.0m; VH type roots	Seeds, Cuttings	Moist forests, dry scrub of open slopes	
117	Myristica fragrans	Myristicaceae	Nutmeg	Medium size tree	Deep well-drained loams and sandy clay loams	Firmly hold on to soil, hold soil tightly may help to reduce soil erosion	Taproot system up to 2.0m; R type roots	Seeds, Cuttings of half-ripe wood	Home gardens, Estates	Mid country areas
118	Areca catechu	Palmae	Areca	Large and tall mono cot tree	A diverse soil type	Anchors and evaporators	Dense fibrous root penetrates to moderate depth	Seeds	Home gardens, Estates	Wet zone and wetter part of the Intermediate zone
119	Cinnamomum verum	Lauraceae	Cinnamon	Medium size tree	A fertile, sandy, moisture-retentive but freely draining soil	Anchors and evaporators	Taproot system up to 2.0m; VH type roots	Seeds, Cuttings of semi-ripe side shoots and division of old rootstocks	Along the coastal belt from Negombo to Matara	
120	Dillenia indica	Dilleniaceae	Hondapara	Medium to large tree	A well-drained sandy loam and a sunny position	Anchors and evaporators	Taproot system up to 2.0m; VH type roots	Seeds, Semi-ripe cuttings	Roadsides, disturbed sites close to water	Wet zone

Implemented by National Building Research Organization

Technical Assistance by: adpc

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ISBN 978-624-5298-03-7