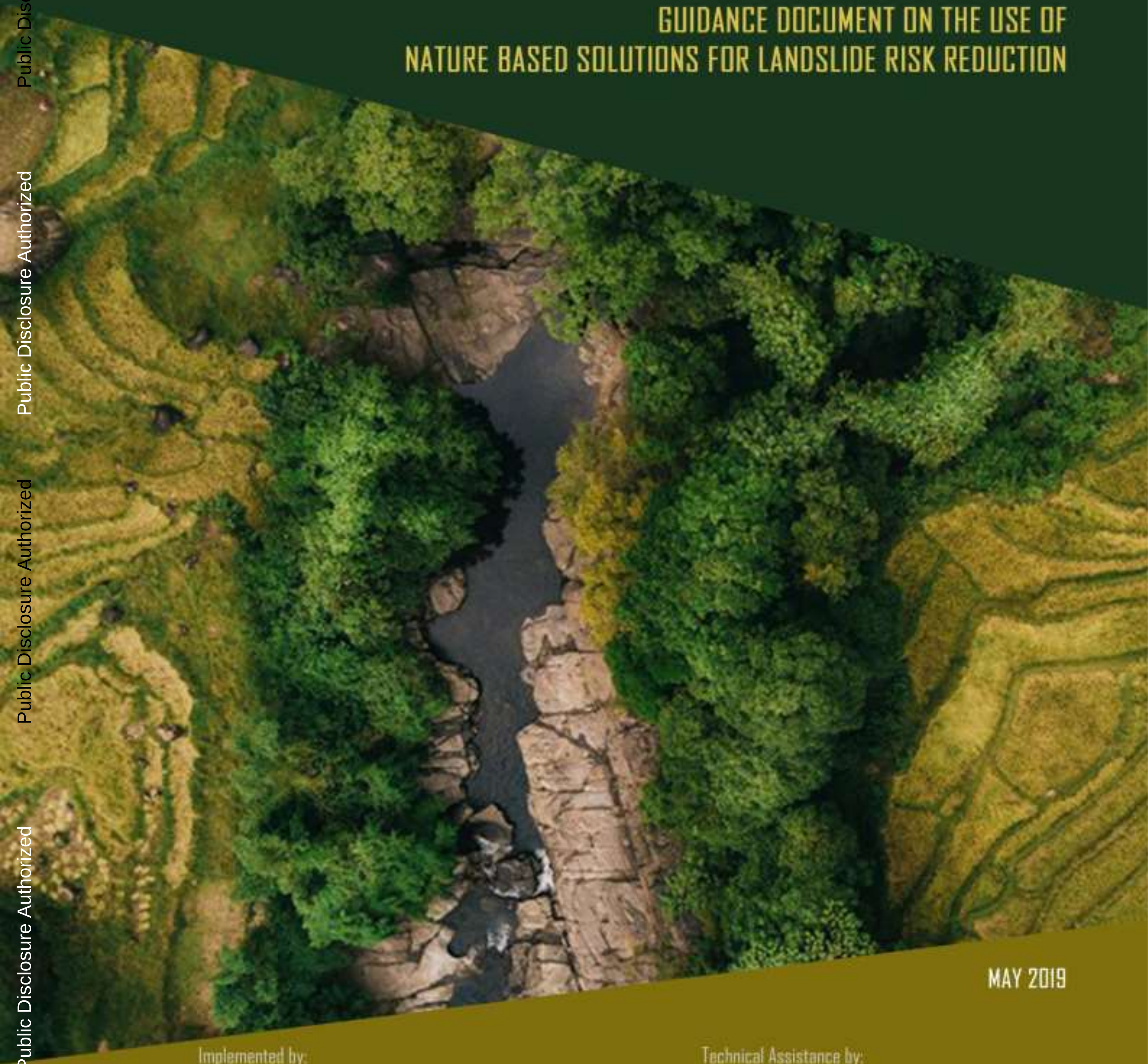
Nature Based Landslide Risk Management Project in Sri Lanka

GUIDANCE DOCUMENT ON THE USE OF NATURE BASED SOLUTIONS FOR LANDSLIDE RISK REDUCTION



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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 (engineering in combination with nature based) approaches for landslide risk management has been 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 associated impacts of such landslides.

This Manual on “Nature Based Solutions for mitigation of Landslide risk” is an outcome of the World Bank funded Nature Based Landslide Risk Management Project in Sri Lanka, implemented by the 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 manual 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 the mitigation project designs. It is not possible to replace the technical advice of experts in the subject through a manual of this nature and it is not intended. It is our expectation that this manual will provide those involved in designing the landslide risk mitigation projects with some understanding and technical guidance in application of bio-engineering measures in slope stabilization.

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.

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ACRONYMS

ADB	: Asian Development Bank
AD	: Agriculture Department
ADPC	: Asian Disaster Preparedness Center
CRIP	: Climate Resilience Improvement Project
DCS	: Department of Census and Statistics
DoM	: Department of Meteorology
DMC	: Disaster Management Center
DRM	: Disaster Risk Management
DRR	: Disaster Risk Reduction
DS	: District Secretary
DSD	: Divisional Secretariat Division
FD	: Forest Department
GoSL	: Government of Sri Lanka
GND	: Grama Niladhari Division
GN	: Grama Niladhari
ID	: Irrigation Department
IUCN	: International Union for Conservation of Nature
JICA	: Japan International Cooperation Agency
LHMP	: Landslide Hazard Mitigation Program
MOH	: Ministry of Health
MoDM	: Ministry of Disaster Management
PG	: Provincial Government
NBRO	: National Building Research Organization
RDA	: Road Development Authority
SD	: Survey Department
UDA	: Urban Development Authority
UNDP	: United Nations Development Program
UNCHS	: United Nations Center for Human Settlements (UNHABITAT)
TNGA	: Training Needs and Gap Assessment
WB	: World Bank

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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

According to Wikipedia, the term landslide or, less frequently, landslip, refers to several forms of mass wasting that include a wide range of ground movements, such as rock falls , deep-seated slope failures, mudflows and debris flows. 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.

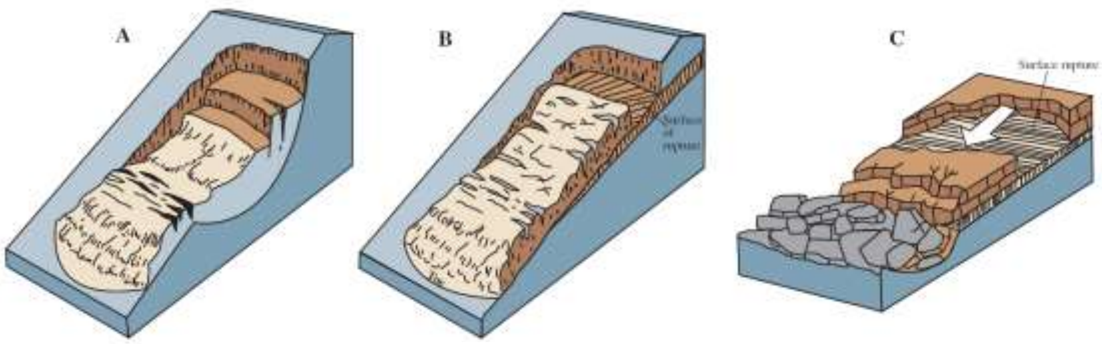
Many of the existing classifications on landslides are done in considering specific mechanics of slope failure and the material types involved. Hungr et al. (2013) indicated that the system of landslide classification devised by late D. J. Varnes in 1978 is the most widely used system globally. Hungr 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
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. The types of movement observed in landslides



(A) Rotational Slide (B) Translational Slide (C) Lateral Spread

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

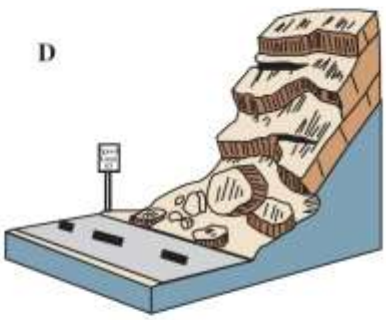
A topple is a block of rock that tilts or rotates forward on a pivot or hinge point and then separates from main mass, falling to the slope below, and subsequently bouncing or rolling down the slope.

Slides

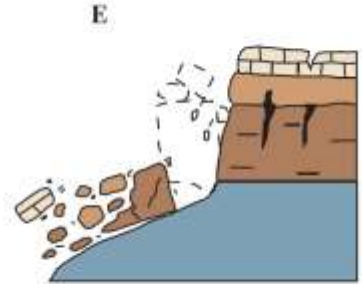
Although many types of mass movements are included in the term of “landslides”, the more restrictive use of the term refers to movement of soil or rock along a distinct surface of rupture which separates the slide material from more stable underlying material. The two major types of landslides are rotational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

Rotational slide

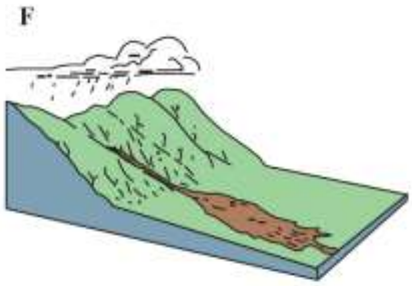
Rotational slide is one in which the surface of rupture is curved concavely upward (spoon shaped) and the slide movement is more or less rotational about an axis that is parallel to the contour of the slope. A “slump “is an example of a small rotational slide.



(D) Rockfall



(E) Topple



(F) Debris Flow

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

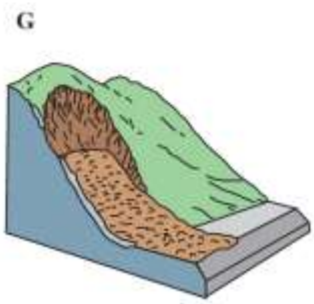
Lateral spreads are a result of nearly horizontal movement of geologic materials and are distinctive because they usually occur on very gentle slopes. The failure is caused by liquefaction, the process whereby saturated, loose, cohesion less sediments (usually sands and silts) are transformed from a 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.

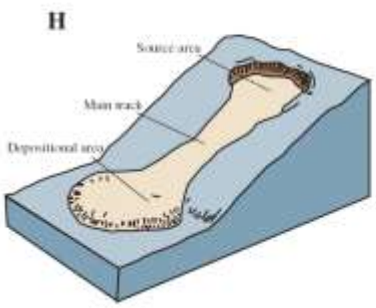
Creep

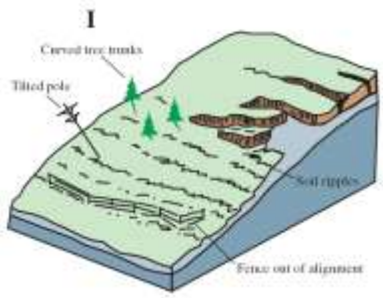
Creep is the imperceptibly slow, steady downward movement of slope-forming soil or rock. Creep is indicated by curved tree trunks, bent fences and small soil ripples or terracettes.

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.







(G) Debris Avalanche (H) Earth Flow (I) Creep

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 the 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, Rathnapura, 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 the 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 tend 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 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 seems 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.

Example of Debris flows

a

b

Figure 1.1: Landslide at Aranayake (a) and landslide at Meeriyabadda (b) (Dulanjalee, 2018)

Example of a cutting failure

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)

Example of a location with rock fall threat

Figure 1.3: Location with rockfall threat. Kandy - Mahiyangana – Padiyathalawa road between culverts 55/3 and 55/6
(**[*http://nbro.gov.lk/index.php?option=com_content&view=article&id=130:crip&catid=2&Itemid=101&lang=en*](http://nbro.gov.lk/index.php?option=com_content&view=article&id=130:crip&catid=2&Itemid=101&lang=en)**)

1.5. Factors that contribute to triggering of 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 Maps prepared by NBRO

The NBRO implemented Landslide Hazard Mapping Program (LHMP) is continuing since 1990. The LHMP was initially funded by the UNDP/UNHCR and since 1996 the program has been funded by the government. It identifies spatial distribution of landslide hazard and as an outcome of the project it is expected to produces hazard maps. At present maps are available in 1:50,000 scale and 1: 10,000 scale. 1:50,000 scale maps are available for Badulla, Nuwara Eliya, Kegalle, Rathnapura, Kandy, Mathale, Kalutara, Galle, Matara, Monaragala districts and 1:10,000 scale maps for selected areas of the above districts. Currently the mapping team is engaged in developing hazard maps in selected areas of Kurunagala, Nuwara Eliya and Matale districts.

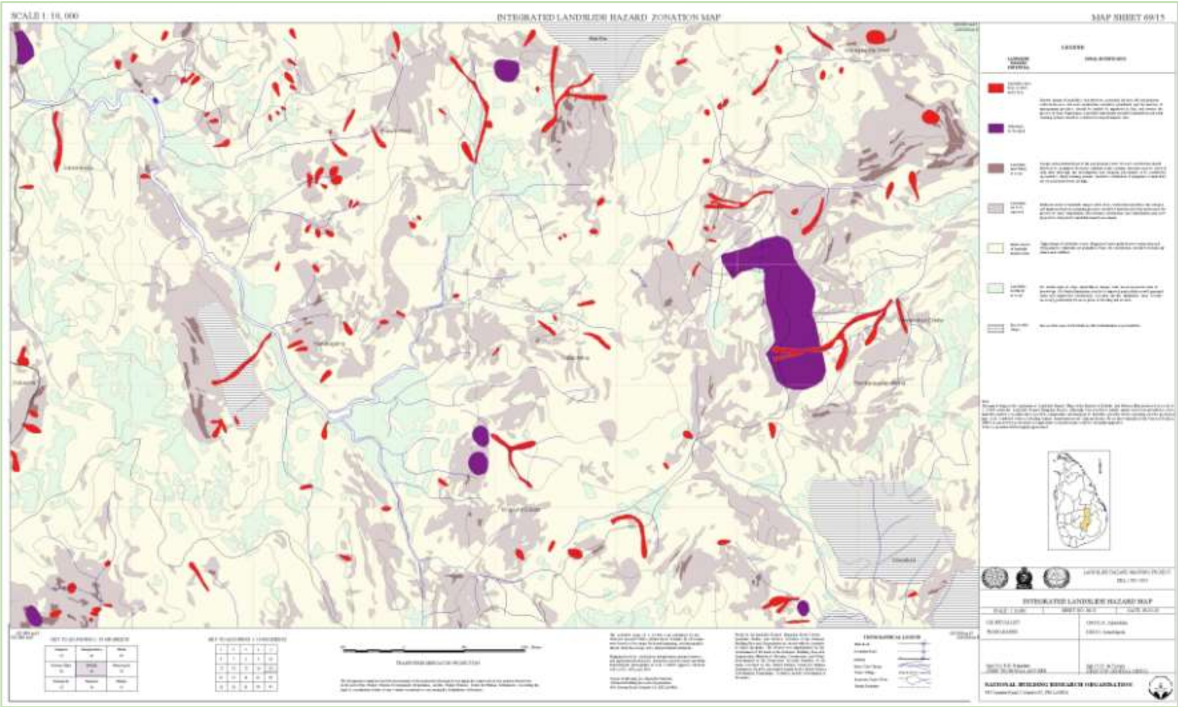


Figure 1.4: Sample of 1:10,000 LHZ Maps: Badulla District - Sheet No.6915

The maps produced by this project are used in the 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 and 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).

CHAPTER 2 :

Classification of Mitigation Measures

2.1. Framework for landslide risk management

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 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. (2008) on behalf of the JTC-1 Joint Technical Committee on Landslides and Engineered Slopes (Safe Land, 2012).

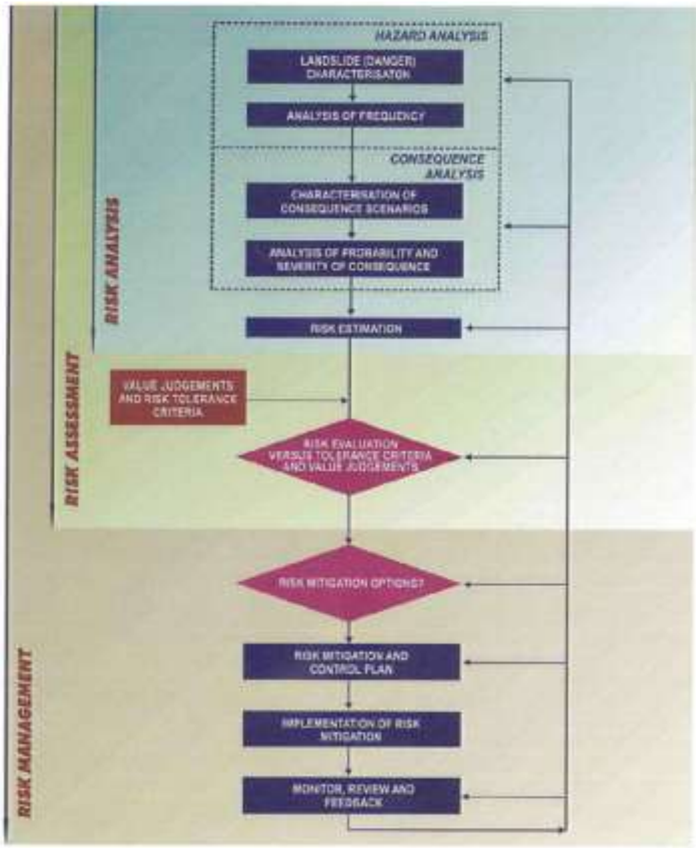


Figure 2.1: Framework for landslide risk management (Fell et al., 2008 as cited in Safe Land, 2012)
Extracted from the Compendium of tested and innovative structural, non-structural and risk transfer mitigation measures for different landslide types.

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, 2006; Evangelista et al., 2008 as cited in Safe Land, 2012), in relation to whether the mitigation measures “actively” pursue an improvement s.s. 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., 2003a, b 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 behaviour 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., 2003a, b as cited in Safe Land, 2012), relating to their relevance to different stages of movement (see Leroueil, 2001 as cited in Safe Land, 2012).

2.2. General approach for mitigation of landslides

The general approach for mitigation of landslides as described in the Compendium of tested and innovative structural, non-structural and risk transfer mitigation measures for different landslide types, is presented in the Table 2.1 below.

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

2.3. Criteria for Selection

The selection of the most appropriate mitigation measures to be adopted in specific situations must take into account 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, hystorical and visual/landscape value of the locale;
- preexisting structures and infrastructure that may be affected, directly or indirectly;
- capital and operating cost, including maintenance.

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 are 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, 2001 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, 2009 as cited in Safe Land, 2012)

Physical process	Brief description
Surface protection; control of surface erosion	• Vegetation (hydroseeding, turfing, trees/bushes) • 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. (*) 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 the unstable mass	• Substitution • Compaction • Deep mixing with lime and/or cement • Permeation or pressure grouting with cementitiuous or chemical binders • Jet grouting • Modification of the groundwater chemistry

Physical process	Brief description
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)

2.4. Examples of mitigation measures at landscape level

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. Some examples of such mitigation measures from several sites in Sri Lanka are provided below as figures 2.2, 2.3, 2.4, 2.5 and 2.6.

Figure 2.2: Slope protected with berm drains, cascade drains and surface protecting measure - Different surface protecting measures; shot-creating or vegetation had to be used based on the prevailing conditions, (Southern Transport Development Project - Sri Lanka)

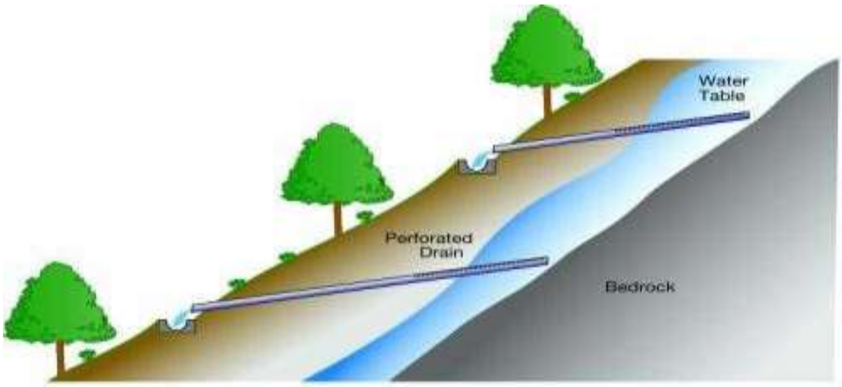


Figure 2.3: Sub horizontal drains

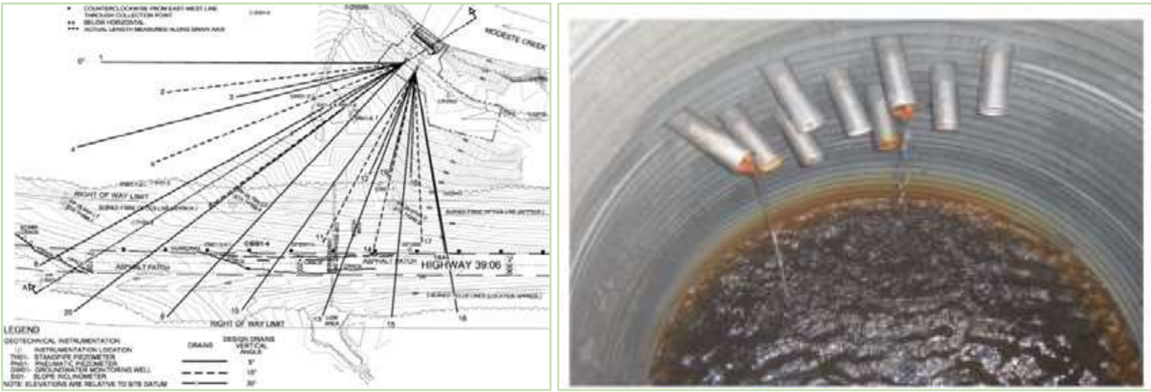


Figure 2.4: Sub horizontal drains installed from a drainage well

Figure 2.5: Nail heads connected by high tensile strength steel mesh and vegetation introduced by hydro-seeding with the help of coir mesh

Figure 2.6: Different surfacing options – Full face shotcreting or/and application of bio-engineering after connecting nail heads with beams

CHAPTER 3 :

Services that vegetation can provide in improving the stability of slopes and in preventing surface erosion

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.

3.1. Purpose and importance of a nature-based landslide risk management strategy

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; Schiechtl & Stern, 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:

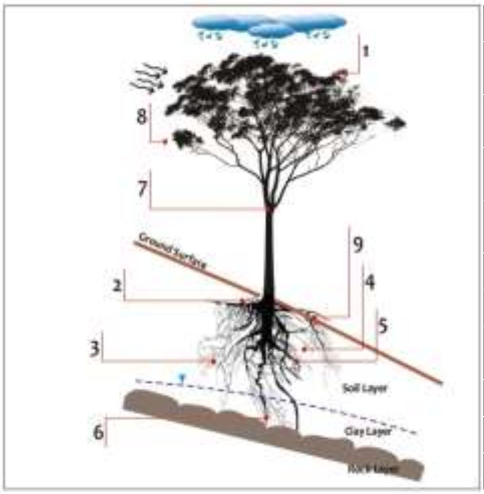
- **Catching Material:** When material moving down the slope (due to erosion or shallow sliding) the catching is done by the stems of vegetation. Movement can cause due to gravity alone or with the aid of water

- **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 large 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. The 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 (Ibid.).

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 (Ibid.). 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

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
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 (Ibid.). 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).

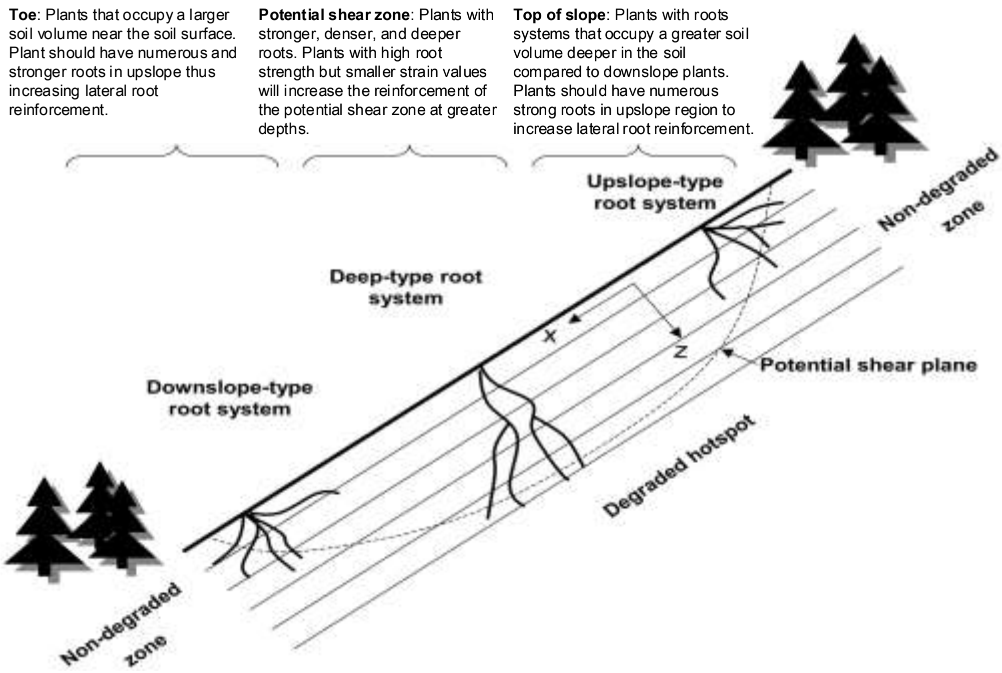


Figure 3.2: Simplified scheme for root trait-based plant species selection for bioengineering (modified after Ghestem et al., 2014a, 2014b)

3.5. Comparison between Geo-engineering slope protection measures with some of the Bio -engineering functions of vegetation.

Both geo-engineering and bio-engineering measures can perform certain engineering functions to support slope stabilization and prevent erosion. However, vegetation cover or plants cannot emulate the all the functions of geo-engineering measures could offer as there is a significant limitation in the growth of plant roots in particular the depth can reach only several meters. Therefore, various plant types depending on their architecture of the root system, its depth and circumference etc. can offer various functions that geo-engineering measures can offer but has its own limitations. A comparison between bio-engineering and geo-engineering measures is provided below:

Table 3.2: Engineering functions of vegetation (Department of Roads. His Majesty's Government of Nepal, 2002)

BIO - ENGINEERING FUNCTIONS	REQUIREMENT	EXAMPLE IN CONFIGURATION OF THE VEGETATION COVER	GEO-ENGINEERING EQUIVALENT	HYBRID OR 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

BIO - ENGINEERING FUNCTIONS	REQUIREMENT	EXAMPLE IN CONFIGURATION OF THE VEGETATION COVER	GEO-ENGINEERING EQUIVALENT	HYBRID OR COMBINATION OF BOTH
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 about 0.5 meter, this is achieved only by large woody plants with big vertical roots (tap roots)	Plants with deep roots. Strong, Long, vertically oriented roots.	Shrubs and trees which are deeply rooting.	Soil anchors	Combination of anchors and trees.
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	Extensive, deep and wide-spreading root systems. Many strong fibrous roots.	Large clumping bamboos; most trees	Retaining walls	Retaining wall with bamboos above

BIO - ENGINEERING FUNCTIONS	REQUIREMENT	EXAMPLE IN CONFIGURATION OF THE VEGETATION COVER	GEO-ENGINEERING EQUIVALENT	HYBRID OR COMBINATION OF BOTH
buttresses and arches of a building have the same engineering functions.				
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 pore-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 4 :

Assessments of potential for applying NBSs and hybrid solutions

4.1. Introduction to principals in application of Nature-based solutions or bio-engineering solutions

Nature-based solutions or bio-engineering solutions are defined as techniques that uses live plants or plant parts to fulfill engineering functions and it is proven as an appropriate, cost effective and nature friendly practice appropriate for stabilization of slopes mainly in South/ East Asian region of the world. This is 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 nature-based solutions (NBS) principles which is highlighted in Box 1.

Box 1
IUCN has proposed 8 nature-based solutions (NBS) principles as follows:

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. Are an integral part of the overall design of policies, and measures or actions, to address a specific challenge.

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 provide 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. The 8 principles, mentioned in the Box 1 provide some guideline for defining factors for short-listing of sites that are suitable for application of nature-based solutions and hybrid solutions that can be applied to improve the slope stability.

4.2. Developing a site selection criteria for short listing of sites that are suitable for application of Nature Based Solutions and/or hybrid solutions

Unstable sites with landslide symptoms must be studied in detail considering the factors such as socio-economic, geo-engineering, scientific, risk escalating factors, in order to understand the socio-economic conditions, level of risk and the nature of failure mechanism before implementing nature based solutions and hybrid solutions. Mostly such solutions would be ideal for shallow & slow moving landslides and generally would not be very effective for rock fall sites or very deep or rapid moving landslides.

Hence, there is a need for a developing a criteria for shortlisting the sites in order to select the most appropriate location for the implementation of Nature Based Solutions and Hybrid Solutions. In the project currently being implemented by NBRO with technical assistance from ADPC, the methodology described below is used for site selection for implementing Nature Based Solutions (NBSs) and Hybrid Solutions.

4.2.1. Description of the selection criteria

Seven key criteria are being utilized in short listing of sites for application of NBSs and hybrid solutions. Each of them is assigned with a weightage factor depending on their contribution towards positive implementation of NBSs and hybrid solutions in landslide risk management. The weighting of the criteria is done based on subjective experience and expert judgment within a scale from 0 to 5. Table 4.1 indicates weightage factors assigned to each criteria.

Table 4. 1: Weightage factors assigned to each criteria

Name of criteria	Weightage Factor
Depth to failure plane	5
Rate of potential movement	5
Slope range & category (in degrees)	5
Suitability for creating a vegetation cover	5
Sustainability/maintenance challenges	3
Geotechnical data availability	3
Probable loss considering the exposure elements at risk within impact zone	5

Depth to failure plane

The criteria has five categories and marks (from 0 to 4) are allocated to each category as shown in the Table 4.2. “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 4.2: Scores allocated for depth to failure plane

Name of category	Possibility of implementing NBSs	Suggested marks
Surficial (<0.5 m)	Very High	4
Shallow (0.5 – 3 m)	High	3
Medium (3 – 8 m)	Medium	2
Deep (8 - 15 m)	Low	1
Very Deep (>15m)	Very Low	0

Rate of potential movement

Nature based solutions are more favorable for slow moving landslide sites.

Table 4.3: Marks allocated for rate of movement

Name of category	Possibility of implementing NBSs	Suggested marks
Slow (Creep effect; site observations include tilting of trees)	High	3
Moderate to fast	Very low	0

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. Moreover, as per the Soil Conservation Act of Sri Lanka, perennial crops are not allowed on slopes having more than 60 degree angles and above 1,500m above MSL. Hence, taking into account the factors described above, marks are suggested for each slope category as shown in table 4.4.

Table 4.4: Marks allocated for slope range

Name of category	Possibility of implementing NBSs	Suggested marks
Slope category I (>40)	Very Low	0
Slope category II (31-40)	Low	1
Slope category III (17-31)	Medium	2
Slope category IV (11-17)	High	3
Slope category V (0-10)	Very high	4

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 4.5: Marks allocated for planting ability

Name of category	Possibility of implementing NBSs	Suggested marks
Category I (Greater extent of the site covered with boulders)	Very Low	0
Category II (Soil thickness lower than 0.5 m) and longer dry periods in existence	Low	1
Category III (Soil thickness greater than 0.5 m and ecosystem with average rainfall)	Medium	2
Category IV (Soil thickness greater than 0.5 m and ecosystem with reasonable rainfall)	High	3

Sustainability/ maintenance challenges

More attention must be paid to the possibility of implementing the “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 NBSs are not very conducive, hence, the score can be very low. Further, the possibilities must be look into whether an economic benefit can be generated from the proposed landslide prevention measure.

Marks can be assigned under this criteria considering the above mentioned factors and grouping them under Very low (0), Low (1), Medium (2), High (3) and Very High (4)

Geotechnical data availability

This parameter could be used as a complementary data when selecting sites for the application of Nature Based Solutions. Hence, the criteria has been given a lesser weightage than others (Table 4.1) since, all sites with landslide threats do not have geotechnical data during early stages of investigations. If relevant geotechnical data are available, then a factor of safety can be calculated and marks can be assigned as follows;

Table 4.6: Marks allocated for factor of safety considering the current state of stability of the slope

Name of Criteria	Possibility of implementing NBSs	Suggested marks
Category I (1-1.1)	Very Low	0
Category II (1.1-1.3)	Low	1
Category III (1.3-1.5)	Medium	2
Category IV (>1,5)	High	3

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

Scores can be assigned under this criteria considering the magnitude of loss considering the exposure elements within the impact zone (the size of the community, number of residential building units, commercial institutes etc.) and grouping them under Very low (0), Low (1), Medium (2), High (3) and Very High (4)

Method of calculating the Final Score for each site

The scores allocated under each sub category must be multiplied by the corresponding weightage factor shown in Table 4.1. 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. The site with the highest score against a threshold value of 2.0 is considered as suitable for the implementation of NBSs and hybrid solutions.

4.3. Conducting a site specific detail landslide Risk assessment considering the flow distance.

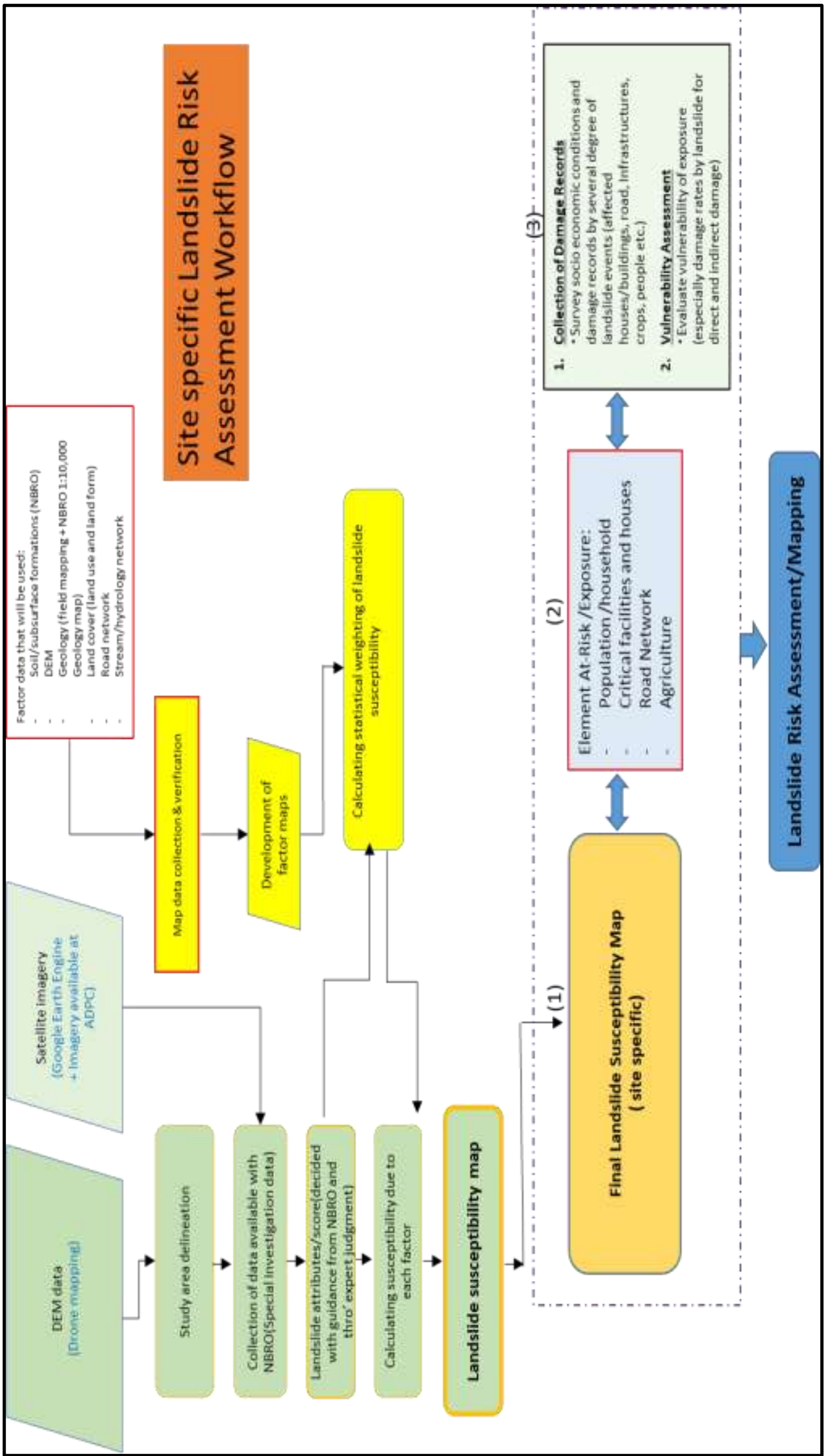


Figure 4.1: Framework for susceptibility mapping for short listed sites

For all short listed locations, location specific technical (Drone mapping data or DEM, Geotechnical information: borehole data, GPR survey data, Geophysical survey data etc.) and 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 framework that will be used for susceptibility mapping is provided in the diagram presented in Table 1 below. 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

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 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 sort listed sites.

4.3.1. The results obtained for the two short listed sites under the Nature Based Landslide Risk Management project is presented below:

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

At present, a network of surface and subsurface drains was constructed in order to improve surface drainage of water, minimize infiltration of storm water and lower the ground water level in order to arrest any further ground movements. NBRO has been performing continuous monitoring of the activity of the landslide using extensometers, inclinometers, strain gauges and ground water level monitoring gauges.

Figure 4.3: Arial View of the failed mass which is delineated with a red polygon

Socioeconomic analysis was carried out on the community at risk due to the landslide. The necessary data was obtained from the Database maintained by NBRO.

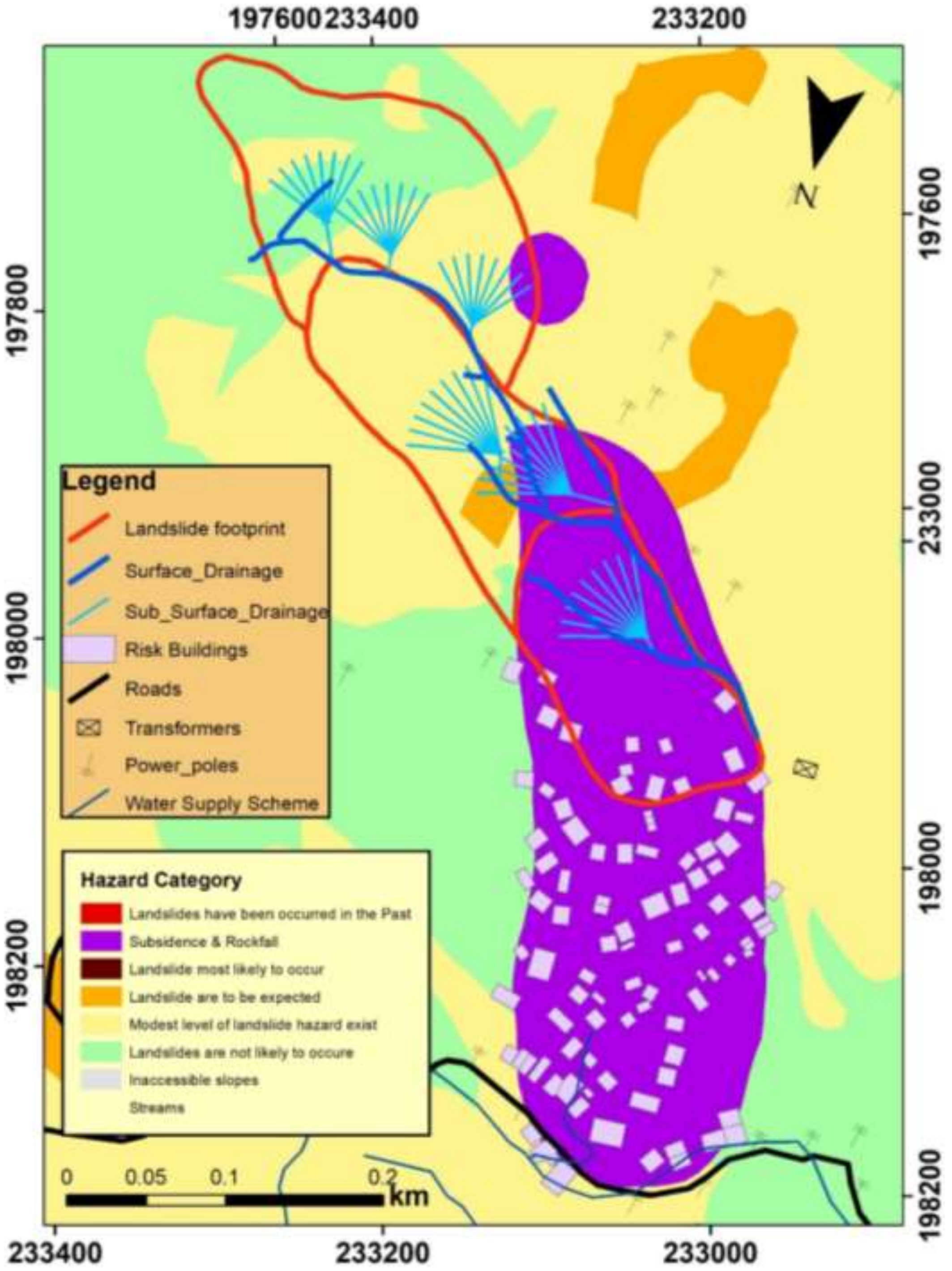


Figure 4.4: Map showing the spatial distribution of elements at risk in the study area overlaid on the landslide hazard zonation map

Table 4.7: 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

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.

Site at Galabada in Rathnapura

The site is located in Ratnapura 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.

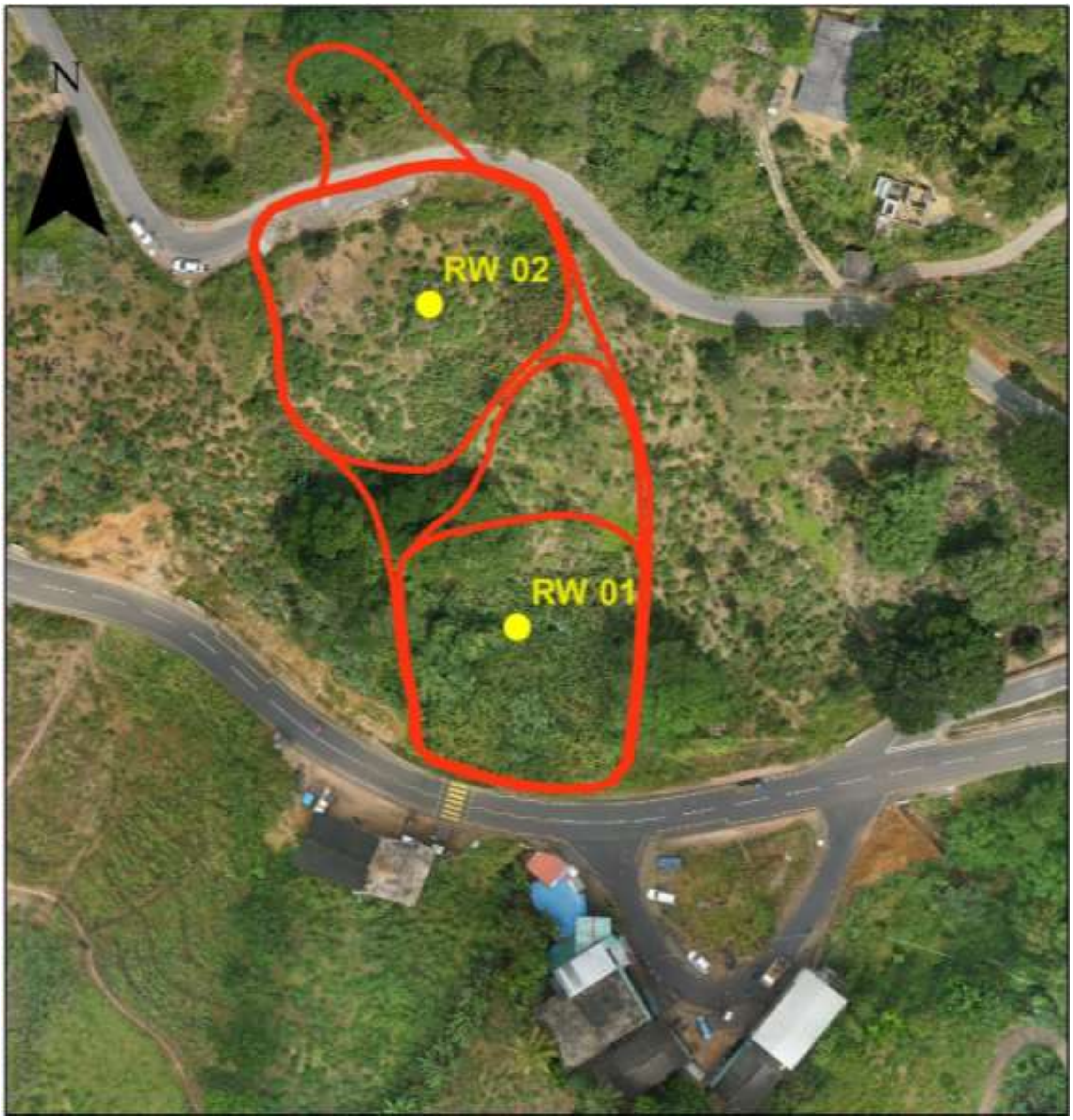


Figure 4.5: Landslide foot print at Galabada

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 JAICA in the year 2018. Accordingly Figure 4.6 shows the land area vulnerable to landslide hazard delineated by a red dotted line. 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.

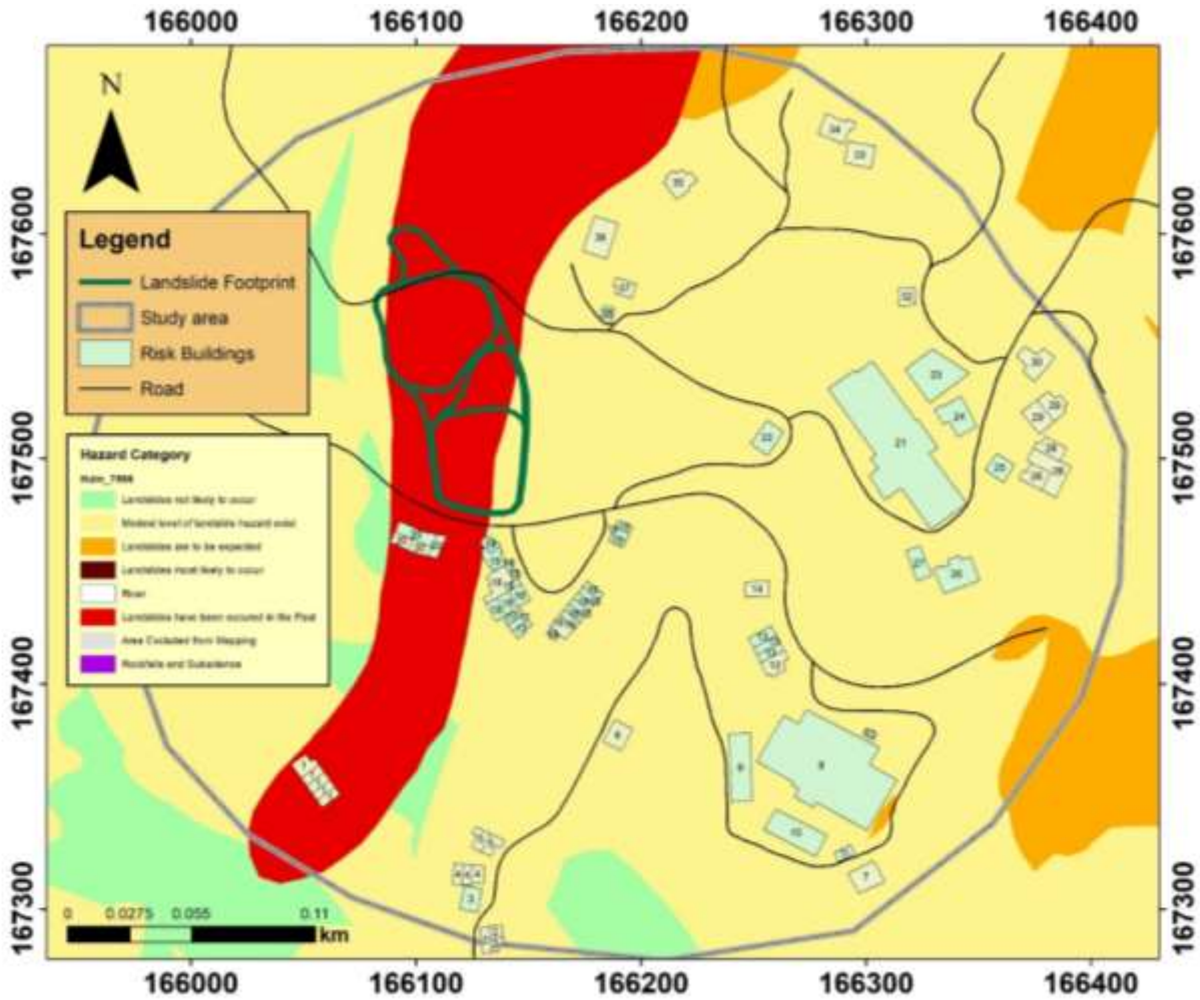


Figure 4.6: Map showing the spatial distribution of elements at risk in the study area overlaid on NBRO landslide hazard zonation map

Table 4.8: 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

4.4. Conducting a geo-technical assessment for the selected site.

Slope stability assessment will provide the necessary checks for the suitability of a particular slope against any possible instability.

Slope stability is dependent on the following:

a) Material involved including:
    - Material properties (cohesion and the internal friction)
    - Fracture density and quality
    - Weathering of the material

b) Geometry of material

c) Slope angle

d) Weight distribution

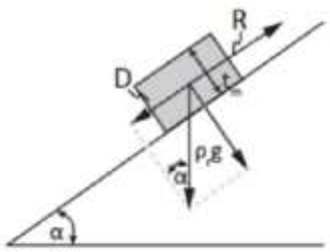
e) Water content

f) Vegetation

g) External impulsive forces (such as earthquakes)

4.4.1. 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. There are multiple methods for calculating the factor of safety of a slope. The calculation of the safety of a sliding block on a plane (a layered slide with preferential failure along pre-existing weaknesses) is shown below in figure 4.7. This calculation considers the slope angle, friction, cohesion, and water content. Increasing water content and slope angle decreases the factor of safety. Increasing friction and cohesion increases the strength and therefore increases the factor of safety. The method of calculation pertaining to sliding plane and corresponding factor of safety cannot be applied to homogenous soils where there is no preferential weak layer for failure. The failure surface in homogenous soils is sub-spherical, resulting in a rotational slide.



$$FS = \frac{R}{D} = \underbrace{\frac{C}{t_m}\frac{1}{(\rho_r g)\sin(\alpha)}}_{\text{cohesion term}} + \underbrace{\frac{\tan(\varphi)}{\tan(\alpha)}}_{\text{friction term}} - \underbrace{\frac{m(\rho_w g)\tan(\varphi)}{(\rho_r g)\tan(\alpha)}}_{\text{water pressure term}}$$

D are driving forces
R are resisting forces
φ is the internal angle of friction
α is local hillslope gradient

C is cohesion
t_m mean landslide thickness
ρ_r density (rock)
ρ_w density (water)
m The ratio of saturated thickness to total landslide thickness

Figure 4.7: Factor of safety calculation

Material properties control the strength of a rock or soil and are an important control on the type of failure. The intrinsic strength of a rock or soil comes from cohesive strength and the internal friction. Cohesion is the resistance force per unit area, and is measured in Pascals. In fine-grained soils, cohesion is a result of electrostatic bonds between clay and silt particles and is on the order of a few kPa. Sands and gravels are effectively cohesion-less. Rock has much greater cohesion due to interlocking particles and cement. Cohesion values for rock may be 1000s of 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, while clayey soils tend to have a friction angle 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 samples in the lab using a tri-axial compression test 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 take into account 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. Multiple failure criterions to evaluate the stability of a slope accounting for large-scale discontinuities have been developed. All require careful study of a field site, and are difficult to apply broadly.

The above factor of safety calculation does not take into account the geometry of the slope, the distribution of weight, or the vegetation. Geometry of a slope includes the strike and dip of the potential failure planes (bedding, joints, etc.) and the orientation of the failure planes with respect to the slope. Discontinuities that "daylight" and are dipping at a lower angle than the slope angle are capable of failure along the weakness plane. Planes that are steeper than the slope angle will not slide, though they may undergo toppling failure.

Changes in the center of gravity of a potential failure can trigger failure or serve to stabilize a slope. Adding weight to the top of a potential failure will decrease stability while adding weight to the base of the same potential failure can increase 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 decreases the water content of a slope via evapotranspiration. Vegetation further reduces the energy of rain drops due to its leaves/canopy and controls erosion too. However, vegetation also adds weight to a potential slide, and can decrease stability. All of these factors must be evaluated for each potential slide, and considered when analyzing a slide that has already occurred.

4.4.2. Engineering characterization of vegetation effect on slope stability

Shear strength (τ) equation for a soil with root reinforcement can be expressed as:

$$\tau = c^r + c' + \sigma_n tan\emptyset^{/}$$

Where

$c^r - root\ cohesion$

$c' - effective\ cohesion$

$\sigma_n - normal\ stress$

$\emptyset^{/} - effective\ angle\ of\ friction$

c', and $\emptyset^{/}$ can be found by performing direct shear tests in soil specimen at the soil laboratory.

The root cohesion c^r can be found by adopting the following approach:

Step 1:
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.

Step 2:
Root cohesion which is needed for design and analysis of the stability of slopes was obtained from the formula given. It was obtained from the study carried out by Schwarz et al. (2010);

$$Cr = 0.48 * Tr * (RAR)$$

$$\mathrm{RAR} = \frac{A_r}{A} = \frac{\sum_{i=1}^{n} \pi d_i^2/4}{A}$$

d – diameter of the root
A – effective soil cross section area

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:
As the next 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 the formula for testing vetiver plants:

$$\bar{c}_r = \frac{c_r l_r}{l_r + l_s}$$

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

After finding the root cohesion, the stability of the slope can then be estimated by using known Limit Equilibrium methods taking into account the slope gradient and soil properties.

CHAPTER 5 :

Plant selection and planning process for selection

5.1. 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).

5.2. 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. The plant manual(attachment ..) 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 (Annex I) provides a review of existing knowledge in the form of literature, expert interviews, field visits, and preliminary laboratory studies.

5.3. 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.

5.4. 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.

5.4.1. Strength of plant roots in landslide prone areas

Under the WB 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 5.1). 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 5.1: 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) (Figure 5.2). 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 5.2: 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.

5.5. 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 5.3). 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.

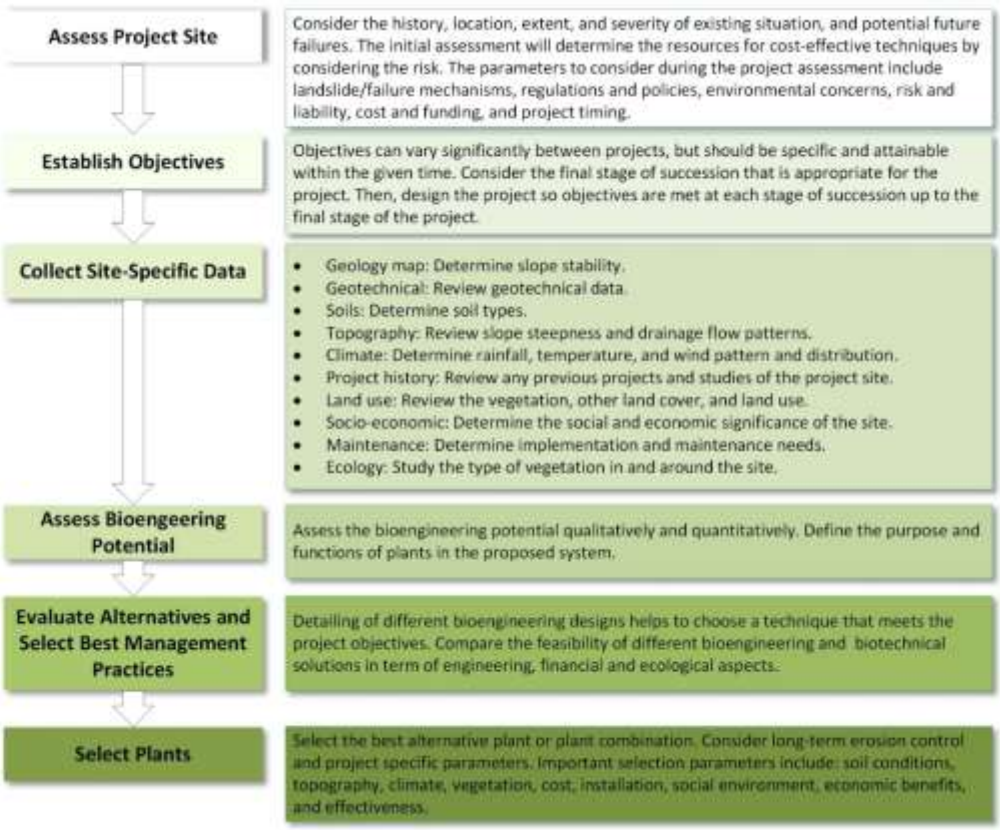


Figure 5.3: The six steps of the plant selection process

5.6. 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.

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.

5.7. 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.

5.7.1. 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.

5.7.2. 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.

5.8. 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. The following table details some criteria that may assist plant selection from the list of plants shown in Annex II.

Table 5.1: 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.

5.9. 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 taken into account 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

5.9.1. 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 5.2).

Table 5.2: 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.	

5.9.2. 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.

5.9.3. 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/m^3 on clay soils and above 0.7 Mg/m^3 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.

5.9.4. 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.

5.9.5. 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 produce directly earn an income. The soil stability improvement, erosion control, aesthetics, and environmental benefits are key indirect considerations.

5.9.6. Simplified scale for plant species characterization

In order to compare species, the specific characteristics of each plant were scored. The scores ranged from 0 to 5, as illustrated in Table 5.3 The transition from one score to another was fixed when there was an uncertainty due to lack of information/data. A higher score for a given characteristic (e.g. hydrological significance) indicates that the considered plant has preferable features with respect to characteristics. The procedure of scoring is discussed in Table 5.3.

Table 5.3: Scaling the desired plant characteristics

Score	Plant type and structural characteristics	Hydrological significance	Root strength characteristics	Ecological significance	Economic value
0	Herbs	Insignificant	Shallow, low strength	Invasive	Unimportant
1	Creepers	Low	Shallow, medium strength	Introduced, non-invasive	Indirect only
2	Shrubs	Moderate	Moderate depth, medium strength	Introduced, non-pioneer, agricultural	Indirect and low direct benefits
3	Small trees	High	Moderate depth, high strength	Native, pioneer, agricultural	High indirect and direct benefits
4	Large trees	Very high	Deep, high strength	Native/endemic, pioneer, agricultural	Very high indirect and direct benefits

CHAPTER 6 :

Planting Techniques and selecting an appropriate configuration in utilization of appropriate services provided by vegetation for stabilization of slopes

6.1. 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.

6.1.1. 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.

6.1.2. 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.

6.1.3. 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.

6.2. Selection of Planting configuration

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 techniques 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 have 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.

6.3. Vegetative techniques

The Roadside Bio-engineering Reference manual published by the Department of Roads, His majesty's Government of Nepal (2002) has suggested a set of main bio-engineering techniques in the Nepal road sector and their respective engineering functions which is given below:

Table 6.1: The main bio-engineering techniques used in the Nepal road sector and their engineering functions

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

SYSTEM	DESIGN AND FUNCTION
	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 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.

6.4. 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 below table and it is based on the information extracted from Roadside Bio-engineering Reference manual published by the Department of Roads, His majesty's Government of Nepal (2002).

Table 6.2: Comparative assessment of different Vegetative techniques

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 possibility	On any slope. On cultivated slopes 35 horizontal lines can be used to minimize loss of soil and help conserve moisture	• 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 create small slump and gully features.	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.
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	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

Technique	Function	Sites	Advantages	Disadvantages	Timing	Care and maintenance
			solid palisade			
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 require 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 better using this technique.	• 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.
Bamboo planting	The planting of large bamboo to reduce movement of material and	Any fill site can be planted. Any cut slope with an angle of 45 except in very dry and stony	• No nursery space is required • The rhizome will give a large new shoot	• Requires a lot of material and is damaging to the parent clump • Involves a large	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

Technique	Function	Sites	Advantages	Disadvantages	Timing	Care and maintenance
	stabilize slopes	sites. Best for stabilizing the lower part of a slope	relatively quickly • Proof against grazing animals	operation at a busy time of the year		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 appearanc e	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 construction s	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 undermine d 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 construction	Fences made out of live cuttings are placed across the slope so	Non-farmland on gentle slopes maximum up to 35.	Can be placed as pegs at intervals of 25 cm by hammering cuttings in to	• Require a large amount of cutting stock • Although most of the cuttings should stay alive and grow	Because of the large amount of exposed cuttings, installation should only	There seems to be a large failure rate and weak areas of the fence should

Technique	Function	Sites	Advantages	Disadvantages	Timing	Care and maintenance
	that debris and water moving down the slope are trapped behind.	Very limited success elsewhere.	the ground. Pegs should protrude about 30 com	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	take place once the monsoon rains have broken	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.

6.5. 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 6.3 provides a set of sample Techniques required to fulfil the engineering functions of slope stabilization at different scales of seriousness.

Table 6.3: Techniques required to fulfil the engineering functions of slope stabilization at different scales of seriousness

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
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 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 7 :

Evaluating the enhancement effects of vegetation on slope stability through modeling the related factors

7.1. Introduction

Numerous research studies have demonstrated that vegetation can have positive influences on stability of slopes (Ali et al. 2012, Chok et al. 2015, Leung et al. 2015). Pallewatta et al. (2019) used the term "Green Corridor" concept whereby ground conditions are improved 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 has been tried 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 efficient use of this method in practice.

7.2. Modeling factors that help in mechanical strengthening of subsoil formations through vegetation

The Green Corridor concept 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.

7.2.1. 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 to 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, but 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. Operten and Friedmen (2000), Natasha Pollen (2007) and Wang (1974) developed different root models by considering different root behaviors.

Development of 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 7.1.

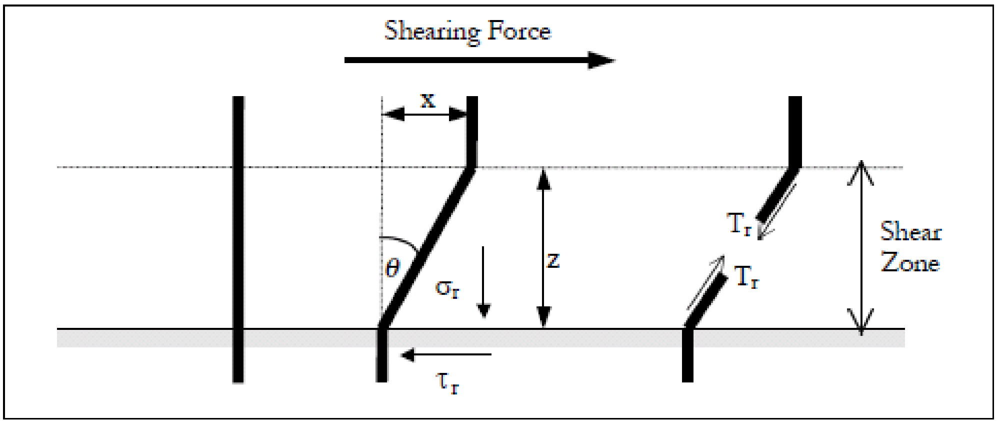


Figure 7.1: Schematic Diagram to show root deformation under shearing (after Waldron 1981)

As Figure 7.1 shows, soil is sheared as the tensile force Tr 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.

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

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. Figure 7.2 explain the impact of the friction angle and cohesion on the shear stress in a reinforced and unreinforced situation.

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

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.

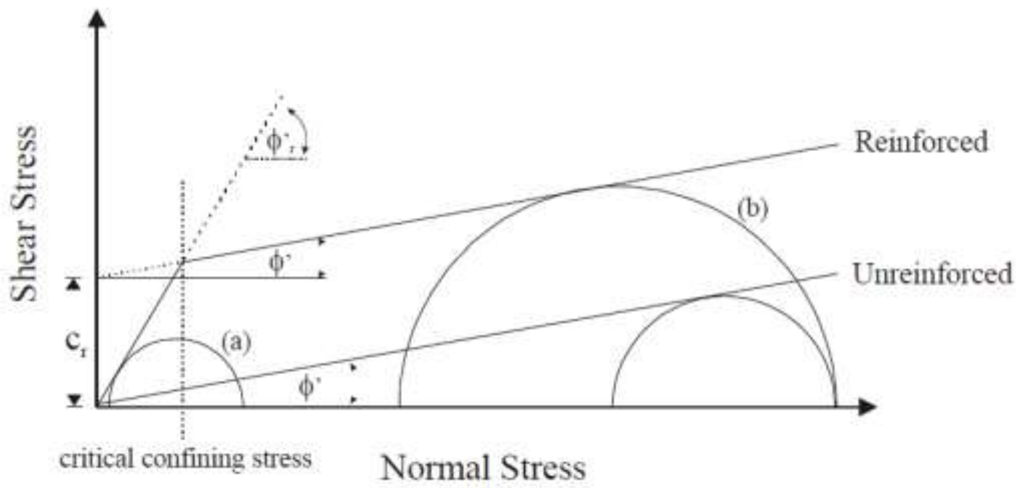


Figure 7.2: Mohr-Coulomb envelopes for reinforced and unreinforced soils with circles describing failure by (a) slippage and, (b) reinforcement rupture

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 (ΔS) is then given by Equation 3

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

Figure 7.3 shows a schematic diagram on the progressive failure of roots in the event of a landslide.

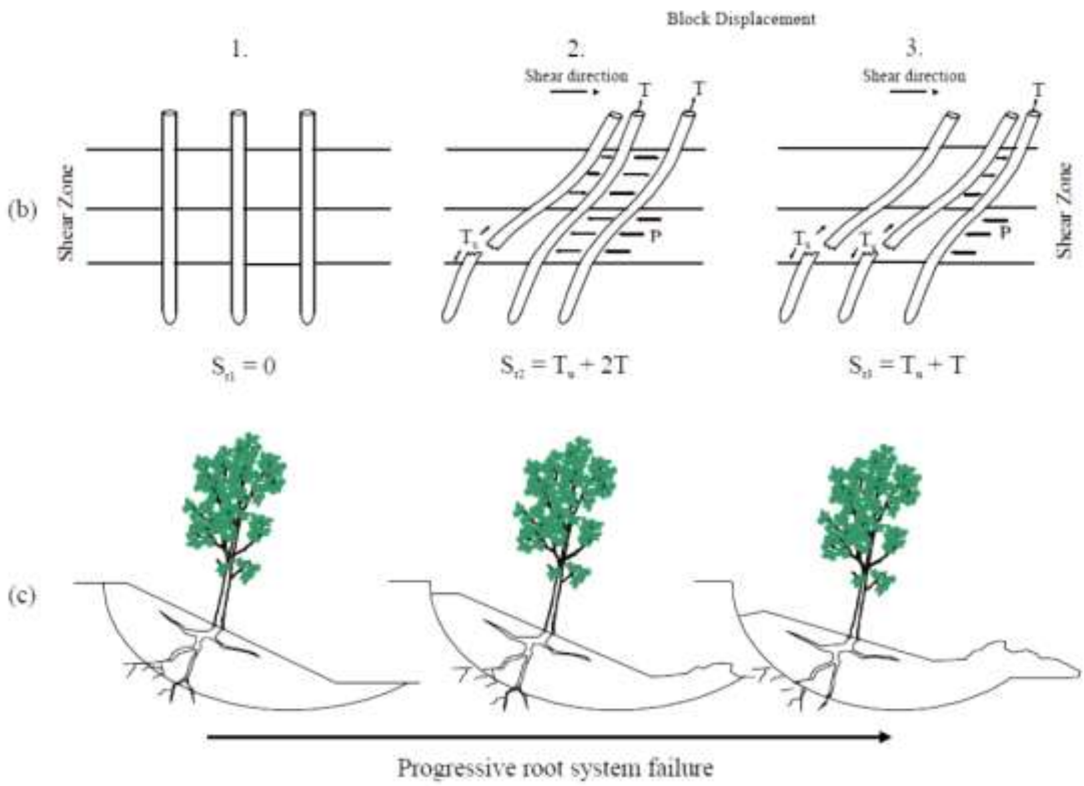


Figure 7.3: Schematic diagram to show the progressive root failure of roots (after Docker and Hubble 2001)

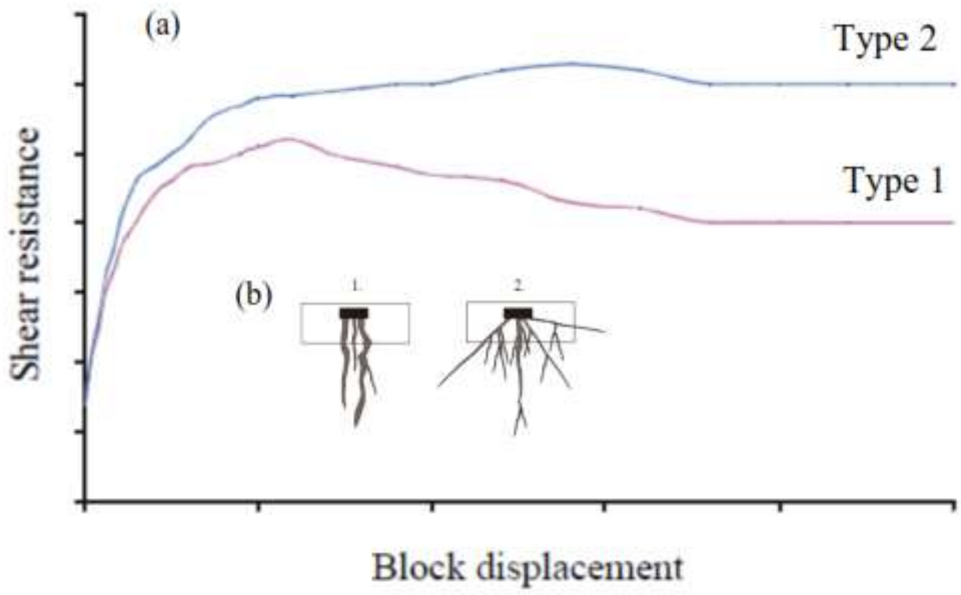


Figure 7.4: Shear resistance over block displacement for two types of spatial distribution of roots

In Figure 7.4, 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 contributes to soil reinforcing more than all the other factors.

7.3. Modeling factors that help in improving the hydrological regime of the slope through vegetation.

The root water uptake of trees increases the matric suction of adjacent soil due to a reduction in the moisture content, which therefore makes the tree-soil matrix unsaturated for a certain period. 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. (1974), $F(T_P)$ is the factor related to the potential transpiration by referring to the relationship developed by Nimah and Hanks (1973), as represented in equation 5.

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

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

Considering all the relationships shown above, it is understandable 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 7.5, a soil model, gives 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.

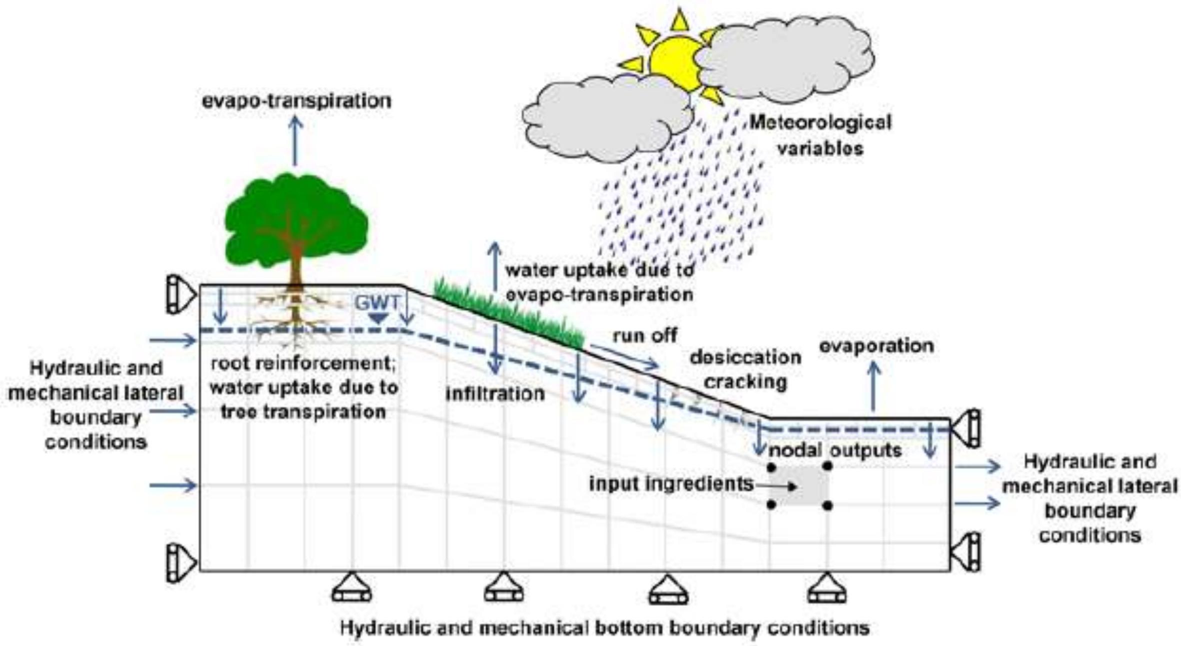


Figure 7.5: Schematic slope model and potential slope-vegetation-atmosphere interaction phenomena. (Elia et al. 2017)

7.4. Experience of the WB funded Nature Based Landslide Risk Management project in Sri Lanka.

In this project a computer model is used to evaluate the positive impacts of vegetation and hybrid solutions on slope stability. Data from Pilot site at Badulusirigama in Badulla district was used for the analysis. General information about this pilot site is described under chapter four.

7.4.1. Numerical analysis of the slope

The conditions of the slope was 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 JAICA team of investigation and the test results available at NBRO. Different strength properties assigned for each subsurface layer is summarized in table 7.1.

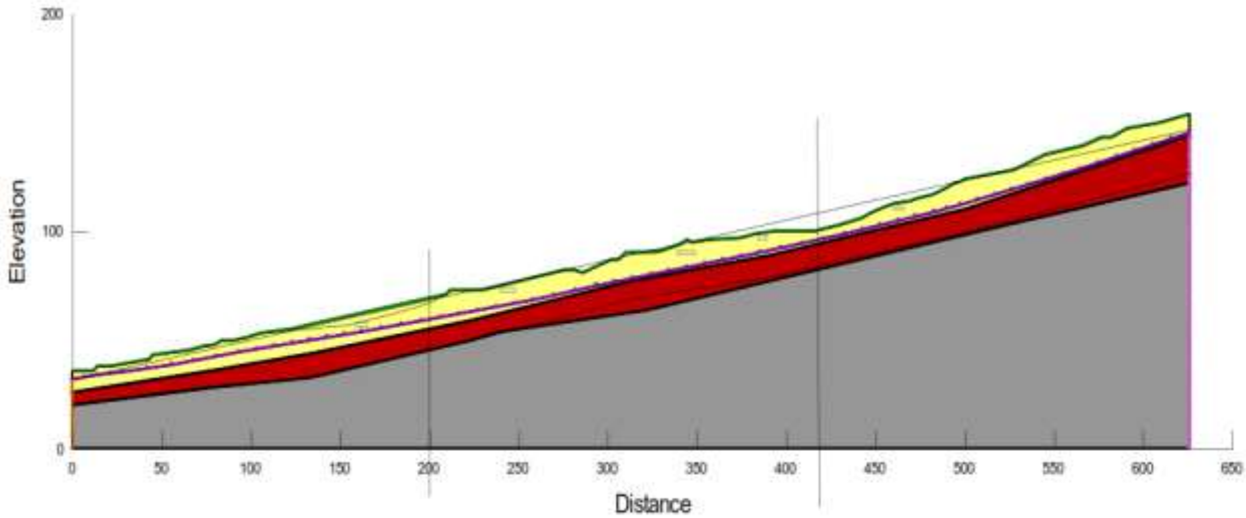


Figure 7.6: Idealized subsurface profile

Table 7.1: Geotechnical parameters assigned for each subsurface layer

Layer	Colour code	Cohesion (kPa)*	Phi (deg)*	Phi b (deg)**	Unit weight (kN/m²)
Colluvium		7	12	10	15
Completely weathered rock (soil)		7	14	-	16
Mod. Weathered Rock		20	40	-	19

*Monitoring Report No. 08 Published by JICA and NBRO Studies

**Kankanamge et.al (2018)

The subsurface profile shown in figure 7.6 was divided into three zones after studying the results of the geophysical investigations carried out by JAICA team of experts. Figure 7.7 shows the division of zones. In the stability analysis, each zone was modelled separately.

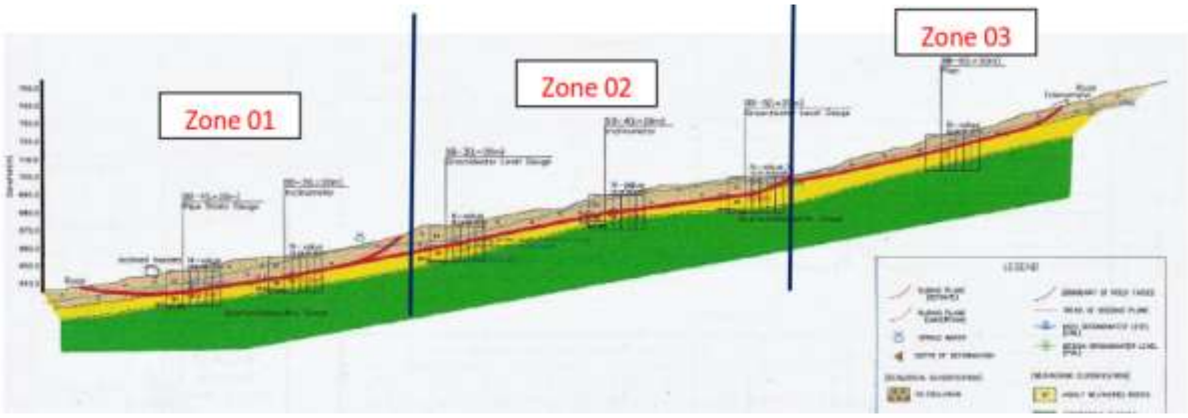


Figure 7.7: Division of three zones for stability analysis

7.4.2. Results and Discussion

Case 1: Slope without any mitigation measures

Table 7.2: Factor of safety of 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 analysis 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. Therefore, appropriate mitigation measures need to be applied 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 7.3.

Table 7.3: Factor of safety improvement after drainage improvement

Zone	FoS before drainage improvement	FoS after drainage improvement
01	1.001	1.281
02	0.959	1.256

03	0.913	1.218

Table 7.3 indicates that stability has increased upon the introduction of subsurface drainages. The highest increase of factor of safety is on zone 3.

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

The effect of vegetation was incorporated to slope stability by calculating soil cohesion due to presence of roots which is defined as root cohesion. This value was treated as an additional cohesion provided to the soil layers.

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

Step 1:

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.

Step 2:

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

$$Cr = 0.48 * Tr * (RAR)$$

$$\mathrm{RAR} = \frac{A_r}{A} = \frac{\sum_{i=1}^{n} \pi d_i^2/4}{A}$$

d – diameter of the root

A – effective soil cross section area

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:

As the next 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 the formula for testing vetiver plants:

$$\bar{c}_r = \frac{c_r l_r}{l_r + l_s}$$

l_r – width of the plant row

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

For the pilot analysis, Eugenia caryophyllus species which is commonly known as Clove was used. Its properties were given in the table below.

Table 7.4: Properties of the Clove root

Crop name	Scientific name	Age (yrs)	Average root cohesion (MPa) for different spacing (m)			
			2.0	1.5	1.0	0.5
Clove	Eugenia caryophyllus	20	0.038	0.048	0.064	0.096

The shear strength parameters of Colluvium soil layer was adjusted accordingly due to presence of Clove roots. The amended values are given in table 7.5.

Table 7.5: Revised geotechnical parameters upon application of vegetation (Clove)

Layer	Colour code	Cohesion (kPa)	Phi (deg)	Phi b (deg)*	Unit weight (kN/m^2)
Colluvium after 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 after vegetation" by considering the average root depth zone of Cloves which is around 2m to 3m.

Afterwards, variation of factor of safety was analyzed for shallow slip surfaces upon introduction of subsurface drainages and vegetation (hybrid solution). The results are given in table 7.6.

Table 7.6: Variation of factor of safety after applying subsurface drainages with vegetation (Hybrid solution)

Zone	FoS before drainage improvement	FoS after drainage improvement	FoS after drainage improvement and applying vegetation for shallow slip surfaces
01	1.001	1.281	1.464
02	0.959	1.256	1.261
03	0.913	1.218	1.232

This analysis shows that the factor of safety values could be increased further by introducing vegetation. However, it is to be noted that more no. of results of root cohesion data are needed for different plant species in order to quantify the degree in increase of safety factor accurately.

7.4.3. Important issues to be considered

- Nature based landslide mitigation measures can be integrated with structural measures in slope rectification to form a hybrid system.
- Main objective of introducing vegetation is to enhance the stability against shallow failures and also controlling the surface run off.
- Selection of vegetation should be based on number of factors such as, anchoring effect, control of surface erosion and draining of excess water etc.
- Grasses or small shrubs like species can be used in to control the surface erosion.

7.4.4. Limitations of the study

- Limited data availability
- Some testing needs long term observations
- Used reasonable assumptions
- High contribution from literature to final output

CHAPTER 8 :

Establishment of Plant Nurseries

It is necessary to establish Plant Nurseries to serve as the sources 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 NBSs and Hybrid solutions for landslide risk mitigation.

8.1. Establishment

It is desirable to establish plant nurseries for all the sites where the NBSs 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 NBSs 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.

8.2. Other factors that will be useful to consider during establishment of Plant Nursery.

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 team 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.

8.3. Construction

During construction there are number of facts that need to be considered. The usual understanding is that all plants that are required for the NBSs 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. 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.

8.4. Providing 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.

8.5. Water supply

It is essential to have a direct water supply to the plant nursery. Within the premises of the Nursery a suitable arrangements 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.

8.6. 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.

8.7. 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 multification, weed removal, removal of decease attracted plants, pest and 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

Figure 8.1: "Vetiver" Plant Nursery

CHAPTER 9 :

Work plan preparation and budgeting

All the requirements for comprehensive landslide risk mitigation planning and execution including post implementation care and maintenance work need to be provided in a work plan. Those responsible for supervising the implementation of the plan should ensure that the requirements that will be mentioned in the plan are fully understood and design requirements are fulfilled while executing the plan. However during the course of execution of the plan there might be some final adjustments to be made to suit actual site conditions depending on the actual 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.

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

Table 9.1: Sample set of activities planned under the assignment

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

Major tasks	Sub-tasks
	• 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 • 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 provided 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.

9.1. Sample budget

Table 9.2: 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			

	Task	Sub-tasks	Unit	Rate	Quantity	Cost (SLR)
		• 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 cuttings, erosion protection mats etc.) as per the design of the mitigation plan	Labour days			
		• 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				

	Task	Sub-tasks	Unit	Rate	Quantity	Cost (SLR)
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.	Monitoring and Instrumentation	• Automatic rain guage	No			
		• Stand pipe	No			
		• Strain guage	No.			
		• Suction sensors/Tensiometer	No.			
		• Moisture sensor	No.			
		• Installation of sensors	LS			
		• Monitoring for one year period	LS			
8.	Cost of material					
9.	Higher of equipment & machinery					
10.	Transportation					
11.	Electricity					
12.	Water supply					
13.	Communication					
14.	Miscellaneous					
	Total					

9.2. Sample work plan

Table 9.3: 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																								
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																								
6	Instrumentation and monitoring of slope movement																								

9.3. Proposed monitoring and evaluation plan to assess the performance of nature based solutions in-situ.

Parameters to be monitored:

Daily precipitation

Ground water level

Soil suction levels

Moisture levels

Slope movement

Set of instrumentation:

Rain gauge

Vibrating wire piezometer

Suction sensor/ tensiometer

Moisture sensor

Strain guage

Monitoring Plan:

Data shall be obtained from two locations, namely, locations with nature based solutions and locations with out. This is for the purpose of comparing the two sets of data in order to assess the improvements gained from implementing nature based solutions.

Suction sensor/ tensiometer and moisture sensor shall be installed at different depth levels considering the depth of plant roots zone. Some of the suggested depth levels can be: 0.5m, 1m, 1.5m and 2m

Strain gauges shall be installed at a depth between 1.5m to 2m in order to monitor the shallow slope movement.

Vibrating wire piezometers shall be installed to intercept the ground water level.

Monitoring Sequence:

Hourly measurements of precipitation

Daily measurements from suction sensor/ tensiometer and moisture sensors

Groundwater level shall be monitored daily during rainy seasons and once a week during dry periods.

Analysis of Acquired data:

Data from monitoring instruments shall be analyzed once a month or every after fifteen days to assess the effectiveness of nature based solutions.

CHAPTER 10 :

Case studies from South Asia, East Asia & the Pacific & lessons learnt

10.1. 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), conducted an assessment of 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, specially 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.

10.2. 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 1 and 10 mm. 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.

Chen et al. (2014) discussed the mechanisms of forest restoration in landslide treatment areas. They investigated a landslide area in Sule watershed in northern Taiwan. Investigation results from the study showed that tree islands and soil-seed banks are suited to reforestation in landslide regions. Trees in a tree island change the micro-climate of the landslide region, and they gather as many nutrients and as much moisture as possible, enabling vegetation to expand around the tree island. Germination of plant seeds from a soil-seed bank (i.e., seeds in soil covered with leaves) indicated that more woody plant species existed around the tree island than in other areas in the landslide region.

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.

10.3. Lessons learnt

A summary of Salient features/lessons learnt is given in Table 10.1

Table 10.1: Summary of Salient features/ lessons learnt

Country	Authors	Salient features/ 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
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.
Taiwan	Chen et al (2014)	Mechanisms of forest restoration in landslide treatment areas
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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