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BIO-REINFORCEMENT OF SLOPES

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Abstract

The influence of vegetation on mechanical soil behaviour represents a significant factor to be considered in erosion control. This type of erosion control process is named bio-reinforcement and it is an environmentally friendly engineering method for shallow slope stabilization. The mechanical reinforcement made by roots has effect in shallow soil, where the most root biomass exists. Vegetation plays an important role in stabilizing settlements and infrastructures from hazards produced by water energy. The new trend named sustainability has forced engineers to rediscover vegetation as an engineering solution for shallow slope protection. This review paper presents various species of plants with an important role in slope stabilization applications. The need for a sustainable future creates a new engineering discipline, named Eco-geotechnics, which integrates knowledge from soil mechanics, botanics, engineering geology and atmosphere science.

Key words*: slope stability, bio-reinforcement, vegetation, roots tensile.*

INTRODUCTION

In order to prevent soil erosion on slopes it is very efficient to use bio-reinforcement using living plants. The utilization of vegetation as an environmentally friendly method to increase the stability of natural and artificial slopes is well known all over the world. In the scientific literature there are many papers on this topic, especially papers with authors from Asia (China, Indonesia, Malaysia, India, etc), Europe (Italy, Spain, France) and South America (Brazil, Peru).

The erosion process occurs when rainfall appears, especially on steep slopes that have a poor cover of vegetation or on non-vegetated slopes (Figure 1) besides the rainfall intensity, the erosion process depends on: relief, soil erodibility, water flows, climatic area and vegetation cover. Erosion produced by water (which presents interest for our paper) can occur by: splash erosions (or raindrop erosion), sheet erosion, rill erosion and gully erosion.

Sheet erosion is the soil particles movement from the upper part of the soil mass or topsoil produced by raindrop impact; along the slope and close to the base water will detach sheets and layers of soil from all the surface area.

Rill erosion represents small channels produced by runoff water concentrated down a slope. If the channel is up to 0.30 m it is rill erosion; if it is deeper, it is about gully erosion.

Gully erosion appears when the water flow is strong and can detach and move the soil particles. Gully erosion is visible on site and has a negative effect on soil productivity, roads, buildings, land and fences.

Splash erosion or raindrop erosion is caused by the splash of falling raindrops; and appears due to the rough splashes of water.

According to Touze-Foltz and Zanzinger (2016), an important achievement when we speak about surface erosion control on construction sites (steep slopes human made, fences, embankments, slopes around roads) is to stabilize soil and seed on slopes until the seed can germinate and fix in the topsoil.

MATERIALS AND METHODS

This paper it is a review article, which present the influence of bio-reinforcement made by vegetation on shallow slope stability applications, it was used some conclusions from a series of experiments from the scientific literature. The materials and methods used in various papers are presented below.

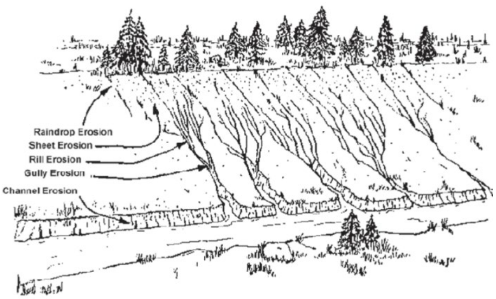

Figure 1. Types of soil erosion (Rimoldi, 2016)

The type of vegetation

Singh et al. (2021) studied trees and woody shrubs stabilization by their reinforcing properties and they concluded that the root systems transmit stability to slopes, subjected to mitigate soil erosion or landslides. The heart-root system of the shrubs and grass-roots provide a more significant increase in soil cohesion than tap-root system; the grass-roots protect the topsoil and reduce shallow landslides.

For a right solution of bio-stabilisation, it is important to take into account natural vegetation which can be found on site. These plants are naturally adjusted to the climate and soil from the region.

Woody plants used in studied papers are: *Chimonobambusa* sp. (it is a small bamboo of about 1.10 m height), *Pseudosasa japonica* (a type of bamboo, perennial, with a height of about 1.00 m), *Indigofera amblyantha* (a perennial deciduous shrub with a horizontally developed root system), *Ligustrum vucaryi* (a shrub with roots of 0.50-0.70 m), *Fumana thymifolia* (a shrub, medicinal plant which can grow to 30 cm tall), *Tamarix canariensis* (a shrub or small tree up to 4 m tall), etc.

Grass used in studied papers are: *Cymbopogon* sp. (Lemongrass - a tropical perennial grass with a length of roots of 0.35 m), *Chrysopogon zizanioides* (Vetiver grass is a common used plant in bio-stabilisation; it is a graminaceous plant, the roots can grow to 1.00 m in 3 months), *A fruticosa* (a plant used for ecological restoration for tailing ponds), *Limonium supinum* (it is a perennial herb, very common in saline areas from Iberian Peninsula; it is a plant used for the restoration of arid zones*),* *Stipa tenacissima* (it is a common plant from Mediterranean countries; it is very efficient in ecological domain because prevents desertification), etc.

The most common plant used for bio-reinforcement is *Medicago sativa*, also called alfalfa. It is a widespread perennial flowering plant; it is a forage crop in many countries from the world. Once it is established, this plant doesn't require cultivation, being a sustainable solution on slopes where it is difficult to reach with agricultural machinery. The root system reaches a depth of 3.00-5.00 m. According to Wang et al. (2022), the deep and root system of *Medicago sativa* go into the soil; the root system creates spaces and channels in depth allowing water infiltration.

Figure 2. The climatic areas in Romania (GE 027-1997)

In Romania, the bio-reinforcement of slopes with different plant is made depending on the climatic areas. In National Guide 027-1997, the surface of Romania is divided into 3 main areas; for each area it is proposed a mixture of perennial plants in order to protect the slopes for erosion (Figure 2).

The proposed mixtures for vegetalization of slopes are composed by the following plants: *Bromus inermis, Agropyrum cristatum, Medicago sativa, Dactylis glomerata, Festuca pratensis and Trifolium pratense.* These plants are known to have beneficial effects in erosion control, but unfortunately *Bromus inermis* and *Agropyrum cristatum* seeds are no longer produced and sold in Romania.

According to De Baets et al. (2009), in a study from Mediterranean part of Spain, the root characteristics to predict the erosion-reducing potential of vegetation depend both on the site conditions and on the erosion process of interest. In order to prevent rill and gully erosion it is mandatory to prevent the initiation of concentrated flow erosion.

Soil used in studies

In many laboratory studies, the soil was chosen in order to be a very erodible one or a difficult foundation soil. In the category of very erodible soil are coarse sands, fine sands, silty sands or silty soils. Difficult foundation soils used in analyzed scientific papers are: loessoid soils and expansive soils.

Preparing the samples

A series of studies were carried out on samples remodelled in the laboratory, samples in which vegetable fibbers were added (Figure 3).

Figure 3. Samples remodelled in laboratory (Badhon et al., 2021; Guo et al., 2020)

The most relevant studies are those carried out on soil samples where the plants grew, where the roots are naturally distributed in the soil mass (Figure 4). The relation between roots and soil can be schematic view in Figure 5.

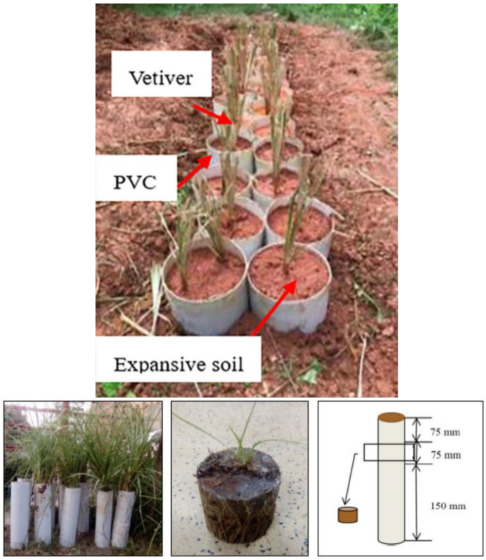

Figure 4. Preparation of undisturbed rooted soil samples (Badhon et al., 2021; Wang et al., 2020)

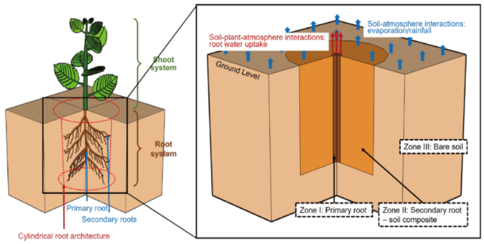

Figure 5. A schematic 3D root system (Ng et al., 2022)

Rainfall tests

In laboratory studies, have been used rainfall simulator with nozzles in order to apply various rainfall intensities for different period of time.

In the case of field experiments, rainfall was measured using automatic weather stations installed in the vicinity of the experimental plots.

Strength parameters

Researchers Waldron (1977) and Wu (1979) made the first attempts to quantify soil reinforcement due to roots using a simple perpendicular root model. This model in well known as Wu/Waldon Model - WWM and show that the increase in soil shear strength appears as an increase in soil cohesion, c_r (kPa). The roots cohesion it is expressed as:

$$c_r = 0.4 (\sin\delta + \cos\delta * \tan\varphi') * T_r * RAR$$

where: δ - shear distortion angle of roots, φ' - effective friction angle of soil; T_r - root tensile strength and RAR - root is ratio.

In a simple manner, the effect of root reinforcement on slope stability can be measured directly in terms of the additional shear strength given by plant roots in reinforced soil (Gao et al., 2020).

According to Wu (2013), for woody plants it can be measured the Young's modulus (E) and tensile strength. The tensile strength provided by the roots in soil mass (σ_{rt}) can be measured by performing a tension test on a root segment.

RESULTS AND DISCUSSIONS

A study from South-East part of Spain, made by De Baets et al., in 2009, presents a visual interpretation on the impact of 25 species of grass, forbs, reeds, rushes, shrubs and trees on slope stabilisation, erosion control, sediment obstruction potential or bending by water flow. They grouped the plant species into 8 categories; depending on the bio-stabilizing function they perform (Table 1).

Table 1. Plant species grouped according to their effect on bio-stabilization (De Baets et al., 2009)

Plants used in tests	Bio-stabilization effect
Fumana thymifolia *Teucrium capitatum*	Concentrated flow erosion - low resistance Sediment obstruction potential - low Bending by water flow - not resistant Improve slope stability - no potential
Nerium oleander *Rosmarinus officinalis*	Slope stabilization - low potential Prevent erosion by concentrated runoff - medium potential Bending by water flow - high resistance Sediment obstruction potential - medium
Anthyllis cytisoides *Retama sphaerocarpa* *Salsola genistoides* *Tamarix canariensis* *Atriplex halimus*	Slope stabilization - high potential Bending by water flow - very resistant Sediment obstruction potential - low Potential to prevent concentrated flow erosion - medium to high
Thymus zygis *Artemisia barrelieri* *Lygeum spartum* *Avenula bromoides* *Piptatherum miliaceum*	Prevent erosion by concentrated runoff - medium to high Slope stabilization - low Sediment obstruction potential - medium Bending by water flow - low
Stipa tenacissima *Thymelaea hirsuta* *Dittrichia viscosa* *Ononis tridentata* *Dorycnum pentaphyllum*	S lope stabilization - low Prevent incision by water flow - low Bending by water flow - medium to high Sediment obstruction potential - low
Plantago albicans *Limonium supinum* *Helictotrichon filifolium* *Brachypodium retusum*	Prevent concentrated flow erosion - medium to high Slope stabilization - low Sediment obstruction potential - high
Juncus acutus	Prevent concentrated flow erosion - high sediment obstruction potential - high Bending by water flow - medium
Phragmites australis	Bending by water flow - medium Sediment obstruction potential - medium Prevent concentrated flow erosion - low

The effect of the root characteristics in the reinforced soil according to Guo et al. (2020) shows that the values of cohesion of the soil-root system increase under consolidated - drained and consolidated - undrained condition, under unconsolidated - undrained condition it presents a complicated change. By the fact that the plant roots can be fully in contact to the soil particles it is registered an increase of the contact area while the root content increases. Some studies have shown that for an optimal root content the shear strength increases with root content until a peak value is achieved. When the root content continues to increase, the plant roots are not effectively connected with the soil particles and plant roots are in contact to each other's; in this case, the lateral restraint of the root system in the soil is no longer strengthened.

Studies on tree roots shows that the tensile strength reaches values of 5 to 60 MPa and the Young's modulus is between 200 to 600 MPa (Wu, 2013). In the same time, experiments made on woody roots shows that root tensile strength decrease exponentially with increasing root diameter.

A relation between shear strength and shear deformation is shown by Meijer et al. (2022). The experiments show that peak root reinforcements occurred at large shear deformations; this has a significant indication for the definition of the root reinforcement peak value. Peak root reinforcement is always defined as the difference between the peak shear strengths of rooted and bare soils and is named "apparent reinforcement". If the root reinforcement is calculated by WWM, it is called "actual reinforcement" and the author's shows in Figure 6 that it is a major difference between apparent and actual reinforcement (measured vs. estimated).

Experiments performed in direct shear test made by Badhon et al. (2021), on samples with and without *Vetiver* roots, shows that adding roots increases the shear strength of soil (Figure 7). The used soil in tests was a sandy soil, known as a very erodible soil.

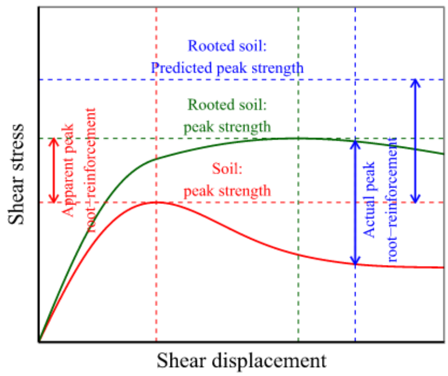

Figure 6. Different definitions of root-reinforced shear strength (Meijer et al., 2022)

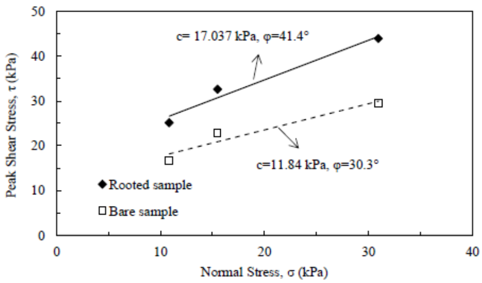

Figure 7. Shear strength parameters on bare soil and rooted soil sample (Badhon et al., 2021)

CONCLUSIONS

The aim of this review paper was to make a synthesis on the existing data in the field of stabilization by using living plants, plants known for their erosion control benefits.

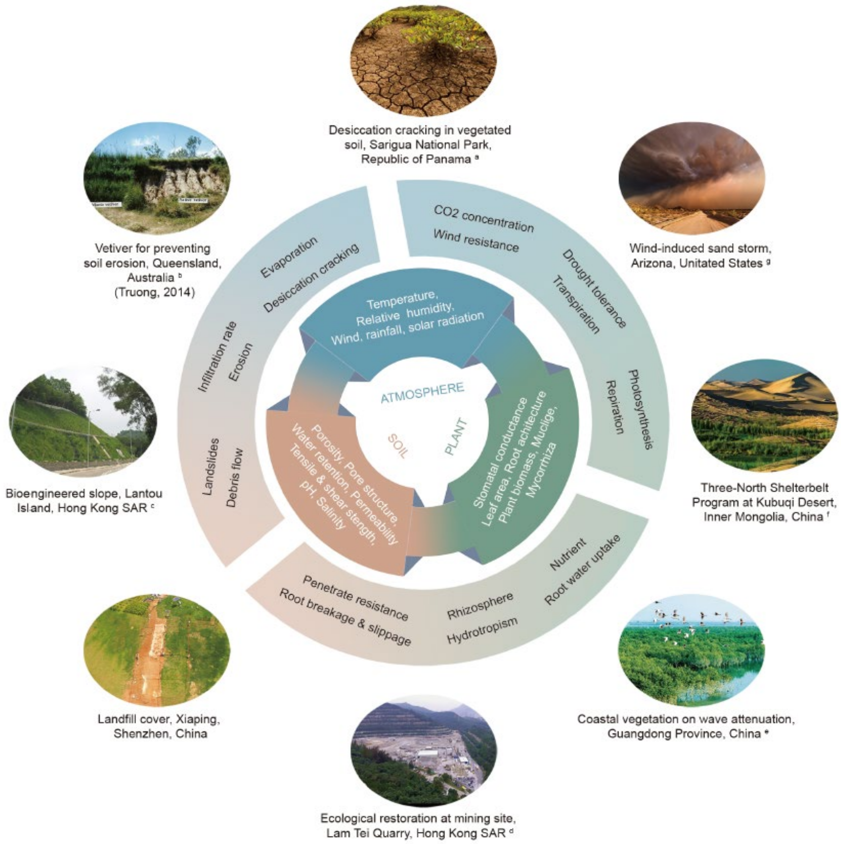

Figure 8. Eco-geotechnics - a sustainable discipline (Ng et al., 2022)

Using vegetation for shallow slope stability application is a sustainable method and creates a new discipline in Geotechnical Science. According to Ng et al. (2022), Eco-geotechnics is an emerging discipline and has gained recognition in the field of sustainable development in recent years. Eco-geotechnics should integrate knowledge from soil mechanics, ecology, rock mechanics, botanic, engineering geology and atmosphere science (Figure 8). In this context, geotechnical processes and ecological behaviour are inter-related to achieve overall sustainability.

For an efficiency of bio-reinforcement it is recommended to use geosynthetic materials for erosion control. These materials provide a protection for the topsoil cover, until the germination process occurs. According to Rimoldi (2016), some of geosynthetics are biodegradable materials or photodegradable; other geosynthetics remain in place for an extended period, or even permanently, and work in concert with the vegetation that grows up through them.

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