Chapter 7

The Use of Bamboo for Erosion Control and Slope Stabilization: Soil Bioengineering Works

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Abstract

The potential of bamboo in erosion control and slope stabilization has been proven worldwide. Bamboos are being used as living plants as well as construction material in different soil bioengineering techniques in many countries. The soil and water bioengineering approach is combined with bamboo traits and mechanical properties. The existing accumulated experiences of using bamboo in soil and water bioengineering works, along with the existing standards and design guidelines, make bamboo species an essential and cost-effective material for erosion control and slope stabilization works. In this chapter, all the necessary aspects to be taken into account for an appropriate use of bamboo in soil bioengineering works are addressed, and the design approaches for soil bioengineering works using bamboos are presented.

Keywords: bamboo, soil bioengineering, erosion control, slope stability, soil strength

1. Introduction

Bamboo is a globally distributed group of plants with more than 1400 species distributed worldwide in tropical, equatorial and semitropical biomes.

It builds important and diversified habitats with different specificities, according to the nature of the species and the general ecological conditions.

Most bamboo species show a very strong development and colonization ability, determining that in some temperate habitats, they can assume an invasive character.

The nature and characteristics of some bamboo communities can present an important ability to soil and slope protection and stabilization, as one can easily confirm by observing developed bamboo forests in mountainous areas with very steep slopes.

On the other hand, the structural characteristics offered by some woody bamboo species make bamboo a valuable basic construction material in many regions (e.g. India, China and Southeast Asia).

These characteristics determine that these species and communities can be of high interest for soil and slope protection and reinforcement works, particularly in areas where the bamboo is native. They can be used integrated and fostering natural communities, ensuring efficient soil cover and reinforcement functions through their high, lightly dense culms and their dense and resilient root systems.

These functions are also of particular interest for soil bioengineering because bamboo has biological characteristics such as a high vegetative propagation ability (making its reproduction very easy) and a rapid growth (allowing for a quick effect on soil cover and root consolidation). Moreover, the structural and physical characteristics of the stems of certain bamboo species turn them into a very effective construction material for complementary soil bioengineering support structures.

Therefore, bamboo in its different forms and associated communities, and also in terms of particular species, is of high interest for nature and biodiversity protection (and therefore ecosystem restoration) as well as for slope protection and stabilization.

2. Principles of soil bioengineering

Soil bioengineering comprises a diversified group of techniques and land management systems developed by mankind throughout the millennia to use natural systems and elements in order to ensure the safety and functionality of land uses in a context of restricted availability of materials and, particularly, energy.

Soil bioengineering techniques have been used throughout the world with the available plants and construction systems, many times replicated in different continents due to its efficiency and easy construction.

Only in the first decades of the twentieth century, this set of building and land management techniques has been recognized as an integrated engineering approach to many soil stabilization problems, and they started to be systematized, studied and developed.

This situation led to the development of an engineering discipline where 'soil bioengineering has set itself the aim of designing our environment in a "living" way by applying construction methods which are close to nature (…) based on materials which are found in nature and which are combined with technical building materials' [1].

This engineering domain developed from the rediscovery of traditional building and management techniques that use predominantly living plants and vegetation communities as building

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materials, nowadays, presents a strong evolution with the development of new materials and plant/material combinations, building techniques and innovative domains of application. This domain of engineering combines classical areas of civil engineering (e.g. structures, materials, construction, geological engineering) with biology, integrating a wide diversity of disciplines and specialization domains. The aim is to achieve feasible, efficient durable, self-repairing, resilient, evolving and ecological functional engineering structures that, within strict technical and geotechnical limits, normally fulfil their planed functions with higher efficiency and lower cost [2].

The European Federation for Soil Bioengineering (EFIB) defines soil and water bioengineering as:

> *'Typically, plants and parts of plants are used as living building materials, in such a way that, through their development in combination with soil and rock, they ensure a significant contribution to the long-term protection against all forms of erosion. In the initial phase, they often have to be combined with non-living building materials, which may, in some cases, ensure more or less temporarily, most of the supporting functions.*
>
> *The use of organic materials is preferred, because parallel to the development of the vegetation and its increasing stabilization ability, these materials will rot and be reincorporated in the natural biogeochemical cycles. Also preferred are indigenous (autochthonous) and site-specific plants, as they promote a biodiversity suited to the landscape. The planning and construction objectives are the protection and stabilization of land uses and infrastructures as well as the development of landscape elements'* [3].

Soil bioengineering aims, therefore, at ensuring an efficient nature-based solution to the protection of infrastructures. This can be helpful in situations of conflict between opposite needs: the human demand for larger spaces for activities and infrastructures and the natural systems intrinsic need for development space.

Soil bioengineering systems use plants and parts of plants as living building materials as well as introducing and developing functional living communities that are able (*per se* or complemented by a wide variety of materials and structures) to effectively ensure the desired soil and slope protection and consolidation targets. Its goal, as referred therewith, is mainly functional in terms of protecting and integrating within the infrastructure, as well as landscape protection and restoration. Its particular characteristic is the fact that the result of its application is not an inert structure, but a dynamic, resilient living community able to restore itself after disturbances and, if adequately maintained, to ensure a long-term, non-decaying, effective intervention with permanently developing efficiency.

Due to the nature, characteristics and properties of vegetation, it is important to note that bioengineering strategies also have limitations in terms of their effectiveness and application limits. The first one is that only a limited available number of plants from a given habitat have the necessary technical characteristics constraining the potential use of the aimed technical solutions. Secondly, plants, as living organisms, do not behave in a standardized way, limiting the ability to precisely calculate the technical effectiveness of the interventions. Finally, plants have limited ability in terms of root growth, hindering their capacity to stabilize soils to depths larger than 1.5–2 m, depending on the species. It is also important to note that there is a lack of a systematized knowledge on the physical behaviour of plants and particularly of their roots and root systems, when exposed to external forces, despite the promising results of an ever-growing research effort.

These limitations imply the need for the use of complementary structures to help overcome—temporarily or permanently—the local adverse conditions. This situation determined the development of a particular segment of the industry related to complementary materials (e.g. organic geotextiles) aimed at reducing the impact of water and soil erosion in the initial development phases of the construction and interventions and to the conception of construction techniques using classical civil engineering approaches and materials in combination with the advantages brought by vegetation.

The main concerns for soil bioengineering are related to soil support, cover, and consolidation, as well as the regulation of the forces and processes (mainly hydrological, hydraulic, and wind-related) that act as disturbance factors.

The main functions fulfilled by the bioengineering approach are the following:

- Support functions, in terms of building or fostering the development of structures able to stabilize slopes affected either by an increase on their slope angle or by an increase of the external or internal acting forces
- Cover functions in terms of protection against erosion and trampling
- Consolidation functions in terms of soil protection, structuring, and reinforcement
- Regulation functions in terms of hydrological processes such as interception, evapotranspiration, infiltration, and runoff control

These functions are performed mainly through the action of plant aerial parts and roots as well as the associated soil biota, through their action in soil anchoring, structuring, aggregating, draining, buttressing, and reinforcement. All of these functions, mainly ensured by living autochthonous vegetation, have the complementary advantages of promoting biodiversity and strongly reducing the CO_2 emissions, not only through its capture during construction but also because the techniques and the nature and quantities of the complementary materials used imply a lower production of greenhouse gases and natural resource consumption.

3. Use of bamboo in soil bioengineering techniques

The strength of bamboo culms and roots and their straightness, lightness combined with hardness, range and size of hollowness make them potentially suitable for a variety of both structural and nonstructural applications. With good physical and mechanical properties, low shrinkage and good average density, bamboo is well suited to replace wood/timber in soil bioengineering applications but also to act on its own as a living material providing rapid ground coverage and sediment trapping, increasing surface roughness, increasing soil strength and decreasing pore-water pressures in the soil by evapotranspiration.

The selection of appropriate techniques is based on a specific site assessment and design criteria. Local climate conditions (precipitation regimes, seasonal variation, averages and extremes of temperature and rainfall), topography (slope gradient, terrain shape, elevation, sun exposition), soil (types, permeability, moisture and nutrient conditions), hydrological conditions and the most relevant erosion processes define the set of feasible techniques for a particular site. In a following step, the evaluation of the existing surrounding vegetation is most important for the design, in terms of project limitations, opportunities and potential long-term achievements. Even when bamboo is the main vegetal constructive element, the long-term success of any bioengineering implementation work is based on a wide range of plant species. It is also important to take into account the bioengineering-specific local logistical and economic constraints. Finally, all this gathered and specific site information forms the basis for selection of the appropriate bioengineering technique, plants and materials to use.

The use of bamboo to make retaining structures for soil mass or for stream bank erosion control has been practiced in traditional way in various places around the world for long time. Live bamboo stakes, wattle fence, hedge brush layering techniques and bamboo crib walls are most commonly used bioengineering techniques. Several handbooks describe these techniques and can be used as references [4]. However, an engineering design of bamboo retaining structures, such as bamboo crib wall, has not been detailed so far. For this reason, this section is focused on this bamboo bioengineering technique.

A live bamboo crib wall is a three-dimensional structure created from untreated bamboos, fill material and live cuttings. Morgan and Rickson [5] described the crib wall as 'a specialized form of gravity-retaining structure using on-site fill material, held within a constructed framework, to provide most of the necessary mass to resist overturning by the weight of both the slope and the materials'.

This crib structure, once filled, acts as a retaining structure and supports the slope. The bamboo and other installed plants provide immediate protection and stability to the structure. However, it has to be taken into account that the structure stability and resistance to failure will be gradually decreasing as its construction materials decompose. As the bamboo elements of a crib wall decompose, the live cuttings of plants or bamboo clumps will grow and proliferate. The resulting root mass will then bind the fill material and the parent soils of the slope into a single continuum, which will have enhanced strength and contribute towards the stability of the slope. **Figure 1** shows the construction steps from a practical application of a bamboo crib wall in Nepal [6, 7].

3.1. Live bamboo crib wall materials and construction specification

Both freshly cut and seasoned bamboos can be used in the construction of crib walls. Additionally, lime-treated or chemically treated bamboo stems can also be used. However, the bamboo treatments can make the crib wall construction very expensive. Therefore, it is suggested either to use freshly cut green bamboo or air-dried bamboo for crib construction.

The twig and large knots need to be trimmed although it is not necessary to make the stem smooth. Based on the size of the bamboo stems available at the site, it can be used as single stem or a bundle of three bamboos to make the header and stretcher elements in the crib construction. If larger diameters are used, the bamboo crib wall will resemble a wooden log crib wall, and the crib construction procedure will be similar to wooden log crib wall. If single bamboo stem is used for the header and stretcher elements, it is recommended to use uniform-sized bamboo stems to ensure a uniform thickness of the crib layer.

Figure 1. Crib wall construction steps in Thankot (Nepal) 2002 [7].

To secure the bamboo stems together in a bundle or to make the crib form, suitable binding wires, binding materials or nails should be used so that the bamboo stems will not tear apart or break/bend along their length.

In addition to the bamboo and binding wires, the live cuttings or rooted plants (if possible and according to the nature of the plant, longer than the depth of the crib wall to allow penetration into the soil at the back) and suitable fill materials are also required for the construction of crib walls. Generally, locally available slope or cut material is used as fill material for the crib wall construction. However, if the material contains very coarse gravel where roots cannot develop, a layer of fine, organic-rich material or humus material should be placed around the cuttings to promote the root growth. Large stones and boulders are not recommended as fill materials. The fill material should allow some degree of compaction, so that there will be no large voids within the body of the crib structure.

Before starting the crib wall construction, bamboos, binding wires and cuttings should be stockpiled near the construction site. After setting out the layout of the wall, the foundation for the crib wall construction should be prepared according to the requirement of designed dimensions of the crib wall. The depth of foundation trench shall be between 0.3 and 0.5 m, depending upon the height of the bamboo crib wall. The foundation should be inclined at about 10–15° inwards (in-slope) to increase the stability against sliding. It is recommended to have at least one layer of cribs below the existing ground level to prevent the structure from sliding and the foundation from getting undermined by any seepage water.

3.1.1. Construction procedure

First, the header and stretcher elements should be prepared by making bundles of three bamboo stems of uniform size. The header elements are cut according to the designed length, which defines the total width of the crib wall. After the stretcher and header crib elements are prepared, the first two stretcher elements should be laid on the prepared foundation trench, parallel to each other. The spacing of these stretcher elements will be controlled by placing the header elements in a specified interval as per the design drawings and specifications. After laying the header and stretcher elements, they should be firmly bound together to make a crib frame. The first layer of the crib frame should then be secured by bamboo pegs of appropriate sizes and should be bound with a peg.

After the completion of the first layer of the frame, fill materials should be placed inside the crib frame and compacted by using hand rammer. The fill material should be compacted to about 50–70 mm above the crib elements. After placing the fill, cuttings or seedlings of rooted plants should be placed horizontally on the top of the fill material. The spacing of cuttings should vary between 100 and 300 mm depending upon the size of cuttings and species of the plants used. While placing the second crib layer, the second crib frame should be set inwards to maintain the designed front batter. In this way, a stable vegetative bamboo crib wall can be constructed. After the completion of the topmost layer, an additional layer of soil should be added to ensure flush finish with the existing slope of the ground.

3.1.2. Maintenance

After the crib wall construction, in dry weather and low soil moisture, it is recommended to irrigate the cuttings and other plants. After the successful establishment of the cuttings, during the initial growing stages, they should be protected from grazing, so that the young plants can grow undisturbed. If some cuttings do not thrive, additional cuttings should be inserted or planted on the wall to ensure green cover of the front face of the wall and stop the washing out of the structure's fill material. If the crib wall settles due to consolidation, an additional fill material should be added on the top of the wall. The vegetated crib wall should be well maintained for at least the first 2 years after construction (**Figure 2**).

In this bioengineering technique, bamboo and plant materials are used as structural elements to take some load and resist earth pressure. This type of crib wall could be used as an alternative to gabions or masonry retaining walls.

Figure 2. View of slide at Badikhel/Lalitpur, Nepal, in May 2003 and August 2003 [7].

4. Biotechnical properties of bamboo

The plants' biotechnical properties are those plant traits contributing to a good performance and effectiveness of the bioengineering work.

4.1. Biomass growth: aerial and root system characteristics

Bamboo belongs to the grass family and has an aerial part characterized by a jointed stem called a culm. The culms are typically hollow with the exception of certain bamboo species which have solid culms. Each culm segment begins and ends with a solid joint called a node. It is in these nodes that the vegetative parts of the culm able to develop the culm vertically, produce branches and develop roots and stems if stacked or laying in the ground can be found. The underground part of the plant is built from rhizomes growing normally at a shallow depth (up to a maximum of 150 mm) from where the roots develop. These roots can grow deep into the soil up to 500 mm. The rhizomes are the main form of spreading of the plant by growing horizontally away from the plant and, because they have a similar structure as the culm with vegetative nodes developing either roots or buds, originate new shoots and new individuals.

Bamboo is the fastest growing perennial, evergreen, arborescent plant with a resulting high productivity: the dry weight yield per hectare could total as much as 32–38 or even 47 tons of biomass per hectare per year but averaging 8–18 tons per ha per year in normal conditions according to the different species and locations [8].

This productivity, expressed both for the aerial and the root parts of the plant, illustrates the ability of bamboo to cover the terrain very rapidly, to develop a dense network of subsuperficial rhizome and root system which would structure and consolidate the upper soil layer. The growth rate of each plant varies, but there are references of a 900 mm culm elongation in 1 day. The growth rate (both of the culm, the rhizome and root system, buds and shots) corresponds to a vegetative cycle that varies with the species and the climatic conditions. The growth factors (like starch reserves on the culm and the rhizome) vary with the evolution of the growth season but are maximal before sprouting, meaning a high resilience to disturbance and regeneration ability. The biomass production is very intensive both above and below ground with values of above ground dry weight varying between 0.8 and 1 tons per ha in some references [9].

The bamboo stands act as an important factor in water and nutrient conservation, as well as soil protection and runoff control. There are references of reduction in nutrient loss higher than 50% and similar values for runoff retention. This shows that bamboo stands, although having little geotechnical ability in terms of slope stabilization (due to the low depth of rooting), could have a very important role in local water cycle regulation and, therefore, soil consolidation and stabilization, preventing erosion and reducing infiltration [10].

4.2. Bamboo natural distribution

The use of native plant species is inherent to the bioengineering work approach and philosophy. Moreover, the use of indigenous species is a compulsory feature of the living material used in these works. Hence, the knowledge of bamboo natural distribution is necessary for its use.

Published literature notes approx. 1400 different species (grouped in one herbaceous and three woody types) identified and designated as bamboo (https://www.eeob.iastate.edu/research/bamboo/index.html).

Bamboo is globally distributed between 51°N and 47°S, particularly in subtropical, tropical and equatorial regions. It also covers a high altitude range, reaching up to 4000 m above sea level and thriving at temperatures as low as −20°C. The main area of occurrence is Asia where the largest number of species can be found.

This wide distribution does not mean that all species or even natural stands thrive without problems. Many forest stands are being intensively exploited, endangering a high number of species, namely, several mammal, bird and even bamboo species all classified as 'endangered' by IUCN. Several hundred species of bamboo occupy remaining natural forest stands not bigger than 2500 km^2 [11].

Due to its versatility, physical characteristics, rapid growth, and easy establishment, it is intensively exploited, not only in terms of harvesting natural forests but also in growing areas of cultivation, where there is a selection of the economically more attractive species (few dozens). The exploitation is mainly located in China, India and Southeast Asia (but also, with increasing importance, in Central and South America) and predominantly aimed at species with applicability in construction or other industries (e.g. paper pulp or laminated and other composite productions, biomass production) [12].

There is also a growing interest for bamboo as an ornamental plant, which brought the spread of several species to areas outside their natural ecological areas. This also raised some problems such as turning into invasive species and threatening natural habitats [13].

4.3. Mechanical properties of bamboo for soil bioengineering applications

The strength of bamboo culms, their straightness and their lightness combined with hardness, range and size of hollowness make them potentially suitable for a variety of both structural and nonstructural applications. With good physical and mechanical properties, low shrinkage and good average density, bamboo is well suited to replace wood/timber in soil bioengineering applications.

For example, from more than 100 bamboo species native to India, only around 20 have been systematically tested, and 16 have been found to be adequate for use in construction (**Table 1**, [14]).

The compressive strength of bamboo ranges between 35 and 70 N/mm^2 which is twice to four times the value of most timber species. The range can be explained by the different test methods and used samples. Bamboo with low moisture content has a higher compressive strength than bamboo with high moisture content (https://www.bambooimport.com/en/blog/what-are-the-mechanical-properties-of-bamboo).

The average tensile strength of bamboo is approximately 160 N/mm^2 which is around three times higher than most conventional construction grade timber materials (https://www.bambooimport.com/en/blog/what-are-the-mechanical-properties-of-bamboo).

Species	Properties							
	In green condition				In air dry condition			
		Modulus of rupture	Modulus of elasticity	Max. compressive strength	Density	Modulus of rupture	Modulus of elasticity	Max. compressive strength
	kg/m^3	N/mm^2	N/mm^2	N/mm^2	kg/m^3	N/mm^2	N/mm^2	N/mm^2
Bambusa auriculata	594	65,1	15010	36,7	670	89,1	21410	54,3
B. balcooa	783	65,4	7310	46,7				60,6
B. bambos	559	58,3	5950	35,3	663	80,1	8960	53,4
B. burmanica	570	59,7	11010	39,9	672	105	17810	65,2
B. glancescens	691	82,8	14770	53,9				
B. nutans	603	52,9	6620	45,6	673	52,4	10720	47,9
B. pallida	731	55,2	12900	54				
B. tulda	658	51,1	7980	40,7	722	66,7	10070	68
B. ventricisa	626	34,1	3380	36,1				
B. vulgaris	626	41,5	2870	38,6				
Cephalostachum pergracile	601	52,6	11160	36,7	640	71,3	19220	49,4
Dendrocalamus longispathus	711	33,1	5510	42,1	684	47,8	6060	61,1
Dendrocalamus strictus	631	73,4	11960	35,9	728	119,1	15000	69,1
Melocanna baccifera	817	53,2	11390	53,8	751	57,6	12930	69,9
Oxytenanthera abyssinicia	688	83,6	14960	46,6				

Table 1. Physical and mechanical properties of Indian bamboos (in round form) [14].

Shear stress parallel to grain is 6–12 N/mm^2 which is approximately 10 times lower than compressive strength and up to 20 times lower than the tensile strength of the same bamboo species. However, the shear strength of bamboo is often twice the value of popular timber species. (https://www.bambooimport.com/en/blog/what-are-the-mechanical-properties-of-bamboo). The bending strength of most bamboo species varies between 50 and 150 N/mm^2 (**Table 2**) and is, on average, twice the magnitude of most conventional structural timber materials. Interspecies variations can be caused by different test methods, sample quality and moisture content of the tested bamboo. (https://www.bambooimport.com/en/blog/what-are-the-mechanical-properties-of-bamboo).

When bamboo is used in green condition, the mechanical values that should be used for design are shown in **Table 3** (adapted from [14]).

Laboratory testing of material properties [15, 16] showed that the compressive and shear strength parallel to the grain were most significantly affected by moisture content, followed by longitudinal tensile modulus and then bending modulus. Age had little effect on the sensitivity of the tensile modulus and bending modulus to moisture content change, while young

Category	Modulus of rupture (R)	Modulus of elasticity (E)	Max. compressive strength ($f_{c,max}$)
	N/mm^2	N/mm^2	N/mm^2
A	>70	>9000	>35
B	50-70	6000-9000	30-35
C	30-50	3000-6000	25-30

Table 2. Material properties of different categories of structural bamboo (adapted from BIS [14]).

Category	Species	Extreme fibre stress in bending N/mm²	Modulus of elasticity N/mm²	Allowable compressive stress N/mm²
A	Bambusa glancescens	20,7	3280	15,4
	Dendrocalamus strictus	18,4	2660	10,3
	Oxytenanthera abyssinicia	20,9	3310	13,3
B	Bambusa baicooa	16,4	1620	13,3
	B. pallida	13,8	2870	15,4
	B. nutans	13,2	1470	13
	B. tuida	12,8	1770	11,6
	B. auriculata	16,3	3340	10,5
	B. burmanica	14,9	2450	11,4
	Cephalostachum pergracile	13,2	2480	10,5
	Molocanna baccifera	13,3	2530	15,4
	Thyrsostachus oliveri	15,5	2160	13,4
C	Bambusa arundinacea	14,6	1,32	10,1
	B. ventricosa	8,5	0,75	10,3
	B. vulgaris	10,4	0,64	11
	Dendrocalamus longispathus	8,3	1,22	12

Table 3. Safe permissible stresses of different categories of green bamboo for structural design (adapted from BIS [14]).

bamboo was more sensitive to moisture content change for shear strength and less sensitive for compression strength [17].

The experimental results show that the tensile strength of bamboo roots decreases with the increase in diameter through a power function. The tensile strength of the tested bamboo roots ranges between 18 and 30 N/mm² at ultimate strains of 14–18% [18].

4.4. Bamboo natural durability

Bamboo, like most lignocellulosic materials, has very low resistance to biological degrading agents. The culms are liable to attack by insects and termites, and above the fibre saturation point, they can be deteriorated by strain and rotting fungi [19].

Bamboo is more susceptible to decay than timber, due to a lack of natural toxins and its typically thin walls. This means that a small amount of decay can mean a significant percentage change in technical capacity [20].

The high sugar and starch content of the bamboo culm explains its low natural durability. There is not much data available on the natural durability of different bamboo species. The natural durability of raw bamboo is low and varies between 1 and 36 months depending on the species, age of culms and climatic conditions [21]. Bamboo is generally destroyed in about 1–2 years when used in the open and in contact with the ground. According to durability classification [22], bamboo falls in class III (non-durable category) with little variation among species. Data about natural durability of some bamboo species obtained from tests of untreated bamboo poles can be found in [21].

The most popular traditional treatment for enhancing bamboo natural durability is soaking the bamboo in running water for a period of time [19]. This treatment has a significant effect in enhancing durability against decay fungi because it washes off the starch content of the culms [19]. This treatment has little effect on termite attack because these organisms depend merely on cellulose rather than on starch as food source [23]. Traditional techniques for controlling starch content in felled bamboo include [21]:

- Felling of bamboo during low-sugar content season
- Felling of bamboo at maturity when sugar content is low
- Postharvesting transpiration of bamboo culms
- Water soaking of bamboo

When bamboo is used as an inert construction material, seasoning (drying) processes are important in order to carefully bring down its moisture content to levels closer to the in service equilibrium moisture content. Seasoning improves bamboo's resistance to biological attack and limits the amount of drying shrinkage in service [20].

The low natural durability of bamboo material can be perfectly accommodated in the bioengineering approach since, in this type of work, just an initial rigidity is pursued and, hence, only temporary structures are usually included in the work design. Once the introduced living plants become established, the vegetation gradually takes over the structural functions of the wooden supports [24, 25]. As time progresses, the inert bamboo culms will deteriorate, and the live bamboo pegs (or poles) will grow and assume the strengthening effect of the initial structure.

In the bioengineering design approach, the load transfer between the initial structural elements and the evolving structural vegetation elements can be calculated using an eco-engineering design scheme for durability [26]. The rapid growth pattern of bamboo species make them very suitable for this kind of work approaches and strategies.

5. Bamboo effects at the slope stability level

The reinforcement effect ensured by bamboo roots (**Figure 3**) can be expressed in engineering terms as an 'additional cohesion' added to the strength of the non-rooted soil Eq. (1) [27]. Therefore, the total cohesion of a rooted soil will be the sum of the unrooted soil cohesion plus the cohesion increase due to the presence of roots in the soil [27].

The 'additional cohesion' (ΔS; Eq. (1)) can be calculated for a known root tensile strength and root area ratio (RAR; the ratio of the surface area of roots crossing the shear plane and shear plane area [28, 27], Eq. (1)) assuming that all the roots cross the shear plane perpendicularly and break during the shearing process. The rooted soil strength value is then used in traditional slope stability analysis methods (e.g. limit equilibrium methods) to determine the overall slope stability:

$$\Delta S = 1.2\, t_R \;\mathrm{RAR} \tag{1}$$

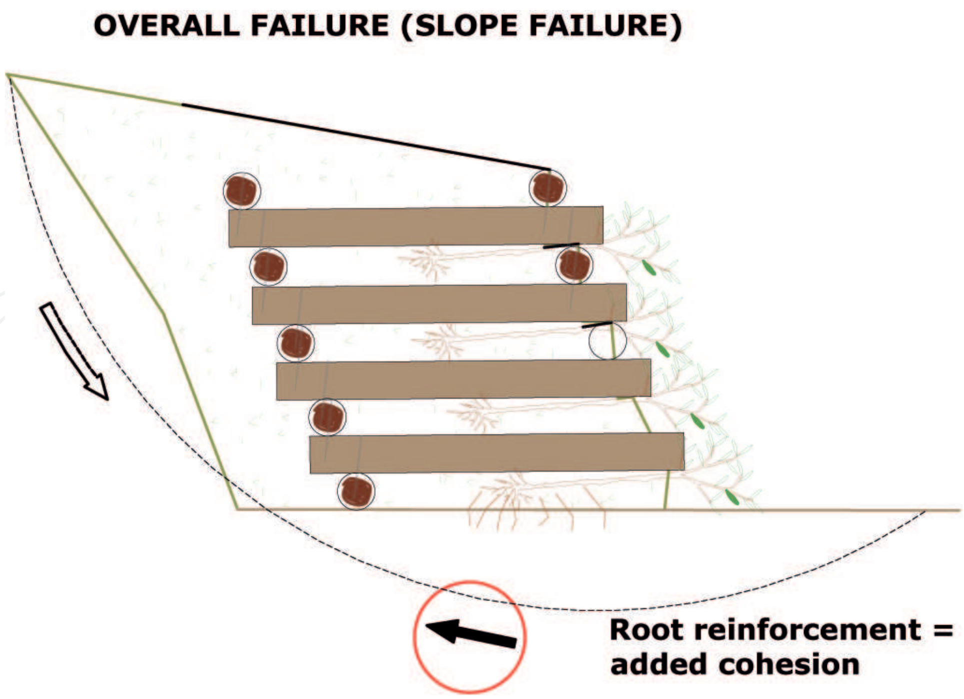

Figure 3. Overall stability check for a bamboo crib wall.

where ΔS is added cohesion or increase in shear strength due to the presence of roots in the soil [KN/m^2], t_R is average tensile strength of roots per unit area of soil [KN/m^2], and RAR is the ratio of area of roots crossing the shear plane and the shear plane area.

The bamboo capacity to improve overall slope stability is limited by its shallow root system. Important effects can be found within the first 0.3–0.5 m depth. Examples of assessment of soil strength increase by bamboo living culms roots can be found in [29].

At the end of the construction stage, when the bamboo culms roots are not yet developed, the slope must be kept stable exclusively by the action of the inert elements and structures used in the bioengineering work. As time progresses, bamboo roots will increase the overall slope stability, and this process can be assessed by using Eq. (1) and traditional slope stability analysis methods.

6. Design standards for bamboo structure calculations

The current bamboo construction standards published in 2004 by the International Organization for Standardization (ISO) were the first step in the attempt to standardize the use of bamboo in construction [15, 16, 30]. These standards are essentially based on the existing traditional knowledge with an adaptation of the existing ISO timber and timber testing standards for bamboo [31]. These standards cover the basis for design and testing of bamboo and bamboo products and can be used as a basis for further standardization of bamboo as a structural material used in soil bioengineering. ISO 22156: Bamboo, structural design [30], provides basic design guidance for full culm bamboo construction. This standard is supported by ISO 22157-1 Bamboo, determination of physical and mechanical properties, part 1: requirements [15], which specify the test methods necessary for design, and ISO 22157-2 [16], which is essentially a laboratory manual for determining the structural properties of bamboo.

6.1. ISO 22156: bamboo: structural design

This international standard is based on limit state design and on the structure's performance; it is only concerned with the requirements for mechanical resistance, serviceability and durability of structures [30]. Execution (work on-site and fabrication of components off site and their erection on-site) is covered to the extent that is necessary to indicate the quality of construction materials and products which should be used and the standard of workmanship on-site needed to comply with the assumptions of the design rules. Bamboo construction design concepts shall be based on calculations, relevant permissible stresses verifying that no relevant limit state or no stress is exceeded. Exclusions are made for design based on previous generations' experience or design based on evaluation reports on structures that survived natural disasters (e.g. hurricanes, earthquakes, etc.) undamaged. In this standard, the limit state design is based on the characteristic value of a material property (5 percentile property, estimated from test results [15], with 75% confidence that it represents the sampled population). The standard advises that special attention is given to differences between materials originating from different sites to account for natural variability. The standard assumes that bamboo will behave as a linear elastic material with service classes dependent on the local environmental conditions (e.g. temperature, humidity) during the structure lifetime. This means that bamboo material is expected to behave elastically until failure, while the plastic behaviour is considered insignificant. In terms of schematization; the bamboo culms are supposed to be analysed as not perfectly straight, tapered, hollow-tube structures with variable thickness.

Similarly as for timber structures, the design shall be verified if no possible limit state is exceeded when partial safety factors and loads/actions relevant to the location of the structure have been applied. Alternative to this approach, allowable stress approaches can be adopted with suitable modification for differences between laboratory and in situ results (0.5), duration of the load (1.0–1.5) and a default value of the factor of safety of 2.25. In these analyses, the conventional structural analysis methods can be used with the bamboo initial curvature, diameter and wall thickness as inputs. The joints/supports of bamboo structures should be located near the nodes (which, in reality, are not spaced at constant intervals) and should be considered to act as a hinge, unless substantive data exist to justify a spring or a fixed joint.

Reflecting the use of bamboo structural members in bioengineering, this standard prescribes the design of beams (predominantly loaded in bending), columns (predominantly axially loaded), joints and assemblies (trusses). All beam elements should be symmetrically loaded, and the loads should be applied preferably close to or at the nodes. All axially loaded bamboo elements should preferably be constructed using the best available straight bamboo culms to avoid buckling. For both types of elements, standard structural calculation methods apply, taking into account the effects of any combination of stresses that may occur during the structure/element lifetime. The joints between the elements should be rigid and provide structural continuity between them, including force transmission and deflection limitation.

In the section on sound construction practices, this standard advises that the designer is in charge of ensuring that 'sound construction practices are taken into account', covering mostly the moisture content change of structural bamboo. It also suggests that special care should be taken to ensure the workmanship (on-site and for products coming from the factory) is according to the assumptions listed in the appendix of the standard. Special provision is made

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for the use of bamboo elements as soil reinforcement, providing that there is an appropriate evidence (test results) that the bamboo will function as reinforcement during the structure's expected service lifetime, with special attention to the lifetime of the bamboo in the organic environment. Types of tests and the frequency of testing are not specified in this standard.

The environmental conditions (temperature, humidity, moisture content, soil/water characteristics and composition, surrounding flora/fauna, etc.) must be taken into account at the design stage to assess their effect on the durability of the structure but also to enable the design of material protection techniques. The durability of each structure is expected to vary based on the particular materials and the environmental conditions. The standard does not prescribe methods for assessing the durability but suggests considering a range of factors (e.g. environment, service life, use, performance criteria, workmanship, maintenance, etc.) when making such assessments.

In terms of quality assurance, the design with bamboo structural elements should be carried out by suitably qualified and experienced personnel. Similarly, qualified and experienced personnel should carry out the supervision and quality control during construction. The structures should be used as per the design briefly and adequately maintained. This standard specifies quality control for mainly factory-produced bamboo and products using a quality assurance manual (QAM). For the purposes of eco-engineering works, the standard can be interpreted including material specifications (including incoming material, inspection, and acceptance requirements), quality assurance inspection testing and acceptance procedures, sampling and inspection frequencies and procedures to be followed upon failure to meet specifications or upon out-of-control conditions. The QAM should be supplemented by relevant records, including inspection and test records, test data, corrective actions, etc.

6.2. ISO 22157-1 bamboo: determination of physical and mechanical properties: part 1: requirements

This standard specifies the test methods for evaluating the following characteristic physical and strength properties of bamboo: moisture content, mass per volume (density), shrinkage, compression, bending, shear and tension. This data is needed for establishing characteristic strength functions and determination of allowable stresses, as well as for establishing the relationship between mechanical properties and factors for quality control functions.

The standard prescribes the acceptable precision of testing measurements, the sampling and storage of test samples and reporting requirements. The measurements specified in the standard include determination of moisture content, mass (by volume), shrinkage, strength in compression (including nominal modulus of elasticity), strength in bending (including load-deflection curves and modulus of elasticity), strength in shear and strength in tension. The principles, apparatus, preparation of test specimens, procedure, calculation and expression of results and test report requirements are specified for each test.

6.3. ISO 22157-2 bamboo: determination of physical and mechanical properties: part 2: laboratory manual

The purpose of this standard, originally written as a technical report is to disseminate best practice test methods in order to make these globally available but also to outline the 'how to' for the tests specified in ISO 22157-1 [15, 16]. On a number of issues, this standard refers to existing national and supranational standards which should be followed, especially for bamboo application in temperate climates (e.g. W. Europe, Canada). This standard contains a number of examples, templates and backgrounds to the tests specified in [15].

The above ISO standards provide the basis for design with bamboo culms. However, they do not include content relating to living bamboo (design and testing) and the use of a combination of living and inert bamboo in a structure. The existing standards need to be updated and expanded to reflect the growing research on test methods and material characterization of both living and inert bamboo, especially covering the durability and evolution of load transfer mechanisms with time. This update could be partially covered by an attempt to use the existing timber-based test methods for characterization and design [29] which could be beneficial in engaging engineers and architects [31] in the use of bamboo for bioengineering purposes.

7. Stability checks for bamboo retaining structures

The analysed structures can be classified as soft engineering structures [24] with a certain durability and change in stress transfer mechanism over the lifetime of the structure. The durability of the structure will depend on the used bamboo species and the biological activity of local degrading mechanisms but also on air temperature, humidity and soil moisture variability. In the bioengineering design approach, the load transfer between the initial structural elements and the developing structural vegetation elements can be calculated using a bioengineering design scheme for durability [26]:

- Determination of the mechanical properties of the wooden elements
- Determination of the stress diagrams of the different structural elements
- Determination of the decay rate of the wooden element and their design service life
- Determination of the plant root system growth and the roots' mechanical properties
- Stability assessment of the structure at different periods of its design lifetime reflecting the progression of decay and development of the live elements in the structure [26]

7.1. External stability checks

As with any stabilization structure, soil bioengineering solutions must be checked from a structural point of view to ensure that both external (sliding, overturning, bearing capacity and slope failure; **Figure 1**) and internal stability conditions are satisfactory. These checks must include both decay and living plant effects, in order to reflect the changes during the lifetime of the bioengineering solution. The external stability checks are usually performed in line with existing geotechnical engineering design standards and the stability is expressed in terms of a factor of safety (FoS; e.g. [32]). In this book chapter, both the FoS expressions for bare and vegetated soil [24] and the use of lumped global FoS for the sliding and overturning checks are proposed. The resistance to sliding (FoS_s) will be affected by the evolution of the RAR value with time across the sliding plane [33], while the resistance to overturning (FoS_o) will

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be affected by the pull-out force evolution with time due to root growth (**Figure 4**). As shown before, the overall slope stability of a bioengineered slope can be assessed using existing slope stability analysis methods [34] taking into account both long-term (drained) and short-term (undrained) conditions.

7.2. Internal stability check

Internal stability analysis consists of checking the mechanical capacity of the bamboo culms which are fulfilling structural functions within the ground bioengineering work.

The characteristic strength values should be obtained according to ISO 22157 [15, 16]. Suggested characteristic strength values for any bamboo species can be found in [35]. These values should be adapted to the bamboo moisture content by using the moisture content correction factor included in [35] which is based on NSR [36] and EN 384 [37]. Bamboo live pole (pegs) strength characteristic values have been shown in preceding epigraphs (see **Table 3**). The values for the material factor of safety are specified in ISO 22156 [30]. Recommended values for this factor can also be found in [35].

In soil bioengineering works, bamboo culms work under Service Class 3 conditions (relative humidity >85%) and in-ground conditions. This situation can be reflected by means of the service class and load duration factor (K_{mod}) which can be determined from the existing standards [30, 35].

Other factors making allowance for other conditions (e.g. earthquakes, connection between elements of different rigidity, etc.) can also be found in [35].

Bamboo structures' internal stability checks follow Eurocode 5: Design of timber structures. This design scheme is detailed in ISO 22156 [30] and in [38]. Because of the specific bamboo culm shape, the cross-sectional area to be used in the design calculation is the following:

$$A = \frac{\Pi}{4}(De^2 - (De - 2t)^2) - \sum area\ of\ any\ holes \quad (2)$$

where A is the net area of section; De is the bamboo culm outer diameter; t is the bamboo culm average thickness.

Accordingly, the elastic section modulus ($S_{elastic}$) for the bamboo case will be.

$$S_{elastic} = \frac{\Pi(De^4 - (De - 2t)^4)}{32De} \quad (3)$$

By comparing the existing stress values with the element bending capacity, shear, axial tension or axial compression, the internal stability check can be fulfilled.

Additionally, Eqs. (2) and (3) can also be useful for determining the minimum bamboo culm dimeter fulfilling the internal stability condition [29].

The forces exerted on the bamboo culms can be determined by using traditional structural calculation theory (**Figure 5**). Typically, the moment, shear and axial stress diagrams should be generated and their maximum values used for internal stability checks [29].

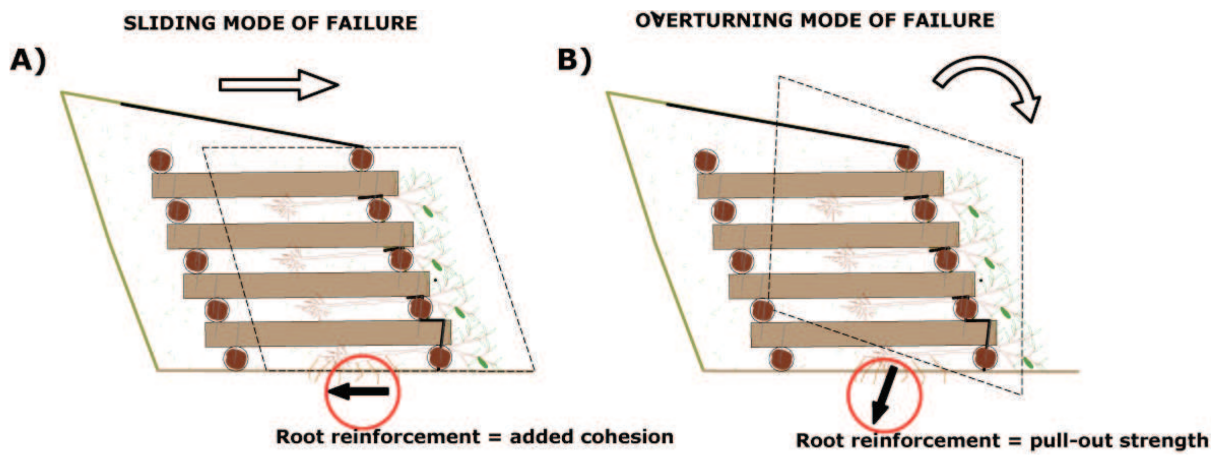

Figure 4. (A) Sliding check and (B) overturning check. The bamboo root effect (if applicable) is highlighted within the circle (adapted from [26]).

Given the low natural durability value of bamboo species, an adapted design scheme making allowance for the wooden element deterioration process can be adopted [26]. In order to give answer to cross-sectional losses because of decay processes at the internal stability design level, different strategies can be followed:

- Increase of the initial diameter of the bamboo culms used in the work
- Reduction of the elements bending span length
- Reduction of the height of the retaining structures

In the last two cases, lower forces will be exerted on the bamboo culms, and, therefore, lower diameters will be able to withstand them and ensure the internal stability of the bamboo structure. A complete example of the preceding design approach can be found in [26, 29].

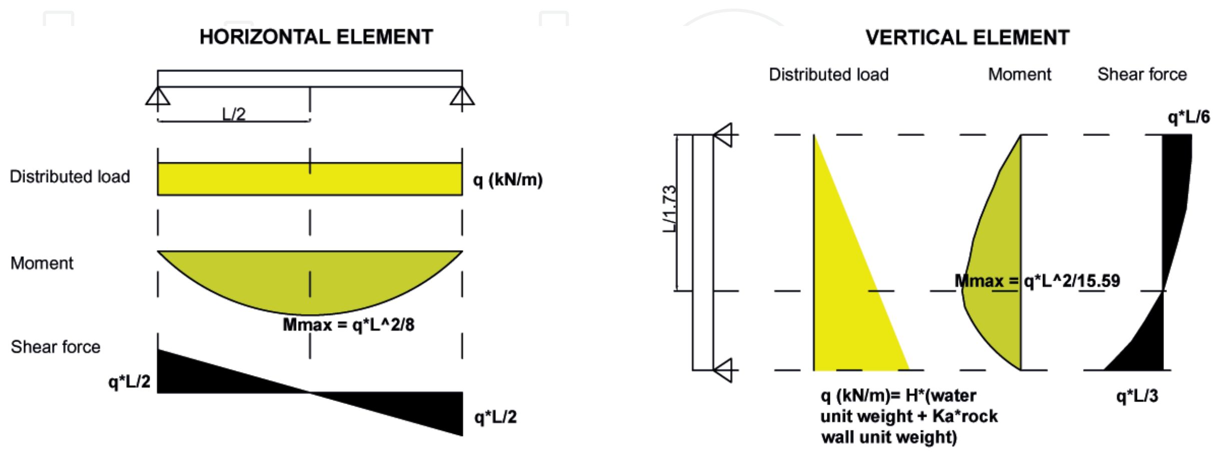

Figure 5. Example of stress diagrams for the vertical and horizontal elements in a bamboo palisade [29], where q is the distributed load (kN/m^2), L is the length of the element (m), H is the height of the vertical element and Ka is the coefficient of active earth pressure (dimensionless).

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8. Plant material quality control, maintenance and monitoring of bamboo structures in soil bioengineering

Quality assurance manual (QAM) covering the bamboo application and approved by the overseeing organization should form an integral part of soil bioengineering project documentation [30]. For the purposes of soil bioengineering works, the QAM should record the control of plant material (including incoming material, inspection and acceptance requirements), personnel, design, construction, quality assurance testing and acceptance procedures, sampling and inspection frequencies and procedures to be followed upon failure to meet specifications or upon out-of-control conditions. The QAM should be supplemented by relevant records, including inspection and test records, test data, corrective actions, etc.

8.1. Plant material quality control

There are a large number of species of bamboo native to different world regions, mainly in the warm and moist tropical and warm temperate climates. Current standards recognize that methods of identification of bamboo through anatomical characteristics have not been perfected. To mitigate against the risk of selecting inadequate/untested species, experienced sorters should be employed in identification through morphological characteristics on full standing culm and the results recorded in the QAM.

Quality control must ensure that only matured bamboo of at least 4 years of age shall be used in construction, preferably after at least 6 weeks after felling. Experienced quality assessors should ensure that solid bamboo culms or culms with thicker walls and closely spaced nodes are selected for structural use. Conversely, the quality assurance control must ensure that any broken, damaged or collapsed bamboo shall be rejected while dead/immature/infected bamboos shall be avoided.

If living bamboo is to be used in the structure, the origin/provenance of the bamboo seeds/seedlings/plantings should be recorded in the QAM together with the species name(s), application/planting rate/density, fertilizer, mulching, soil preparation and maintenance requirements. This must be supported by certificates relating to type, origin, quality and validity of seeds/plants and quality of fertilizers.

Knowing that the natural durability of bamboo is relatively low (12–24 months when used in the open and in contact with the soil but depending on the species and environmental conditions), and its strength decreases rapidly with the onset of fungal decay, suitable treatment (traditional treatments if possible) for preserving bamboo must be applied considering the environmental impact and health aspects of labour and all users of the structure. The samples for testing the effect of preservatives must be cut from treated bamboo for chemical analysis (e.g. a weight of approx. 100 g per 100 kg bamboo treated).

Air-dried bamboo should be used whenever possible in order to ensure it deteriorates more slowly. QC should ensure that, if the bamboo delivered to site is wet, there is an opportunity to dry again before it is applied in the soil bioengineering structure.

8.2. Personnel

Bamboo structure should be designed and constructed by personnel having appropriate skills and experience. Similarly, qualified and experienced personnel should carry out the supervision and quality control during construction. The expertise and skills of the personnel involved must be recorded at an early stage as part of the quality management submission of the contractor and then updated periodically throughout the duration of the project.

8.3. Design

Design tasks (e.g. load analysis, calculations, specifications, drawings, detailing) and/or modelling should be carried out as per the existing current standards (see Section 6 above) and the design brief. Here it is acknowledged that traditional experience rather than precise calculations may generally govern the detailing but the experience has to be based on evidence in form of reports on the structural damage to similar structures after they have sustained the severity of earthquakes, hurricanes, etc. as criteria for recommendations by the evaluation by competent engineer/builder with adequate experience in the field. Independent design check should be carried out in accordance with the quality management demands and methods of the client and the contractor.

8.4. Laboratory and in situ testing

Laboratory and in situ testing of material properties, structural stability and general performance of the structure should be carried out in accordance with the existing current relevant standards (see Section 6) and design brief [15, 16]. The quality control should ensure that due care is taken to maintain and calibrate the testing equipment on a regular basis and minimize the scatter in the test data by the use of appropriate numerical techniques, a representative number of tests is carried out for determination of each property and that the personnel performing the tests and the analysis of results are suitably qualified and skilled. The records covering the above should be kept as part of the QAM and periodically updated throughout the duration of the project.

8.5. During the construction stage

The quality control should ensure that the workmanship of the labour force is according to the design and testing assumptions. Regular periodic inspections should be carried out by a designated quality assessor or manager who will record any defects stemming from the workmanship and allow the project manager or site supervisor suitable time to correct them before proceeding. The inspection records should be kept as part of the QAM, with a special emphasis of the following defects when using inert bamboo culms:

- Damage caused by bamboo Borer/ghoon beetle (*Dinoderus* spp. *Bostrichidae*), which attacks felled culms.
- Crookedness of the bamboo culms in terms of a localized deviation from the straightness in a piece of bamboo.

- Discoloration of the bamboo demonstrated as a change from the normal colour of the bamboo which does not impair the strength of bamboo or bamboo composite products.
- Collapse of the culm occurring on account of excessive shrinkage, particularly in thick-walled immature bamboo, and causing a reduction in structural strength. This defect is demonstrated as a development of a wide split resulting in a depression on the outer surface of the culm.
- Splitting at the end of a bamboo as an effect of drying which occurs both from outer and interior wall surfaces of bamboo as well as the end at the open ends.
- Surface cracking demonstrated as fine surface cracks not detrimental to strength which can reduce the structural strength if it occurs at the nodes.
- Wrinkles and deformation in cross section, during drying, which occurs in immature round bamboos of most species; in thick-walled pieces, besides this deformation the outer surface becomes uneven and wrinkled. Very often the interior wall can develop a crack below these wrinkles, running parallel to the axis and decreasing the structural strength of the culm
- If the engineer has identified a **fire risk**, the QA should check if the necessary treatment has been applied to the bamboo prior to construction/commission.

The client should ensure that the structure will be **used and operated** in accordance with the design limit briefs. Periodic inspections and monitoring of the use of the structure and the loads experienced should be carried out and the records kept in the QAM during the lifetime of the structure. Emergency action plan should also be prepared by the designer/engineer in order to cover the mitigation measures to be put in place during or after the application of accidental loads or in the event of structural failure.

8.6. Maintenance

The existing standards [30] specify that adequate maintenance is required for the structure without providing definition of adequacy and the quality control procedures associated with it. Knowing that one of the main characteristics of soil bioengineering works is that their full efficiency is only reached once the living plants have rooted and active growth has commenced [39], it is critically important that the maintenance is planned and controlled in order to accelerate the establishment process and shorten the time between construction and reaching full operational capacity. In this respect, the quality control should cover maintenance during the plant establishment phase (recording the percentage of ground cover, application of fertilizers and mulches, survival/failure rate of plantings/seedlings, inspection and acceptance/rejection of all live and inert plant materials), aftercare during the plant establishment phase (replacement of inadequate/dead plant material, fertilization, weeding, cultivation, mulching, irrigation, protection/preservation, staking/tying) and aftercare during development stage (periodic inspections during 2–5 years after construction and, if needed, replacement of any inadequate materials, fertilization, irrigation, ground preparation, mulching, mowing, pruning, staking/tying, pest disease control [14, 40], coppicing and pollarding).

8.7. Monitoring of bamboo structures and applications

As a result of working with materials possessing relatively large natural variability, the soil bioengineering design with bamboo has to account for some uncertainty. To mitigate against the uncertainties and risks, monitoring will be vital throughout the lifetime of the bamboo-based structure. Current standards do not specify or regulate which monitoring should be conducted as a step-by-step engineering process starting with a definition of objectives and end with application of mitigation measures if warranted by the monitoring data [41]. A monitoring programme should be included in the design and periodically updated as part of the QAM in the project file throughout the duration of the project. The programme should detail the specification of instrumentation and methods for monitoring and should be cross-referenced to the risk assessment register of the project.

The monitoring of a soil bioengineering structure can be carried out in accordance with the existing current guidelines (e.g. [42]) with an addition of monitoring of the bamboo-related parameters critical to the stability and resilience of the structure. Depending on the form of bamboo used (live or inert) in the structure, the monitoring of the following parameters should be adopted as a minimum:

- Survival rate and/or percentage ground cover
- Height above ground or length of culms
- Displacements (horizontal, vertical, tilt) of the bamboo elements and the whole structure
- Root spread (horizontal and vertical)
- Root density
- Moisture content (air and soil)
- Temperature
- Culm diameter range
- Tensile strength of the roots
- Suction stress due to the presence of roots
- Groundwater levels
- Changes in soil organic content
- Precipitation
- Runoff
- Soil loss to erosion
- Diameter deterioration and rates of deterioration
- Bamboo strength [15, 16]

A sustainability assessment framework can be used to benchmark the sustainability performance of the bamboo-based soil bioengineering applications for the purpose of monitoring their performance. In this context, an attempt to cover the socioeconomic, environmental and engineering performance of the application can be performed, and the framework can be used as part of the existing QA/QM procedures with a number of KPIs already being measured as part of the other QA processes [43]. The advantage of such a framework would be its use to assess the performance of the application after construction. The graphical output of the assessment makes the framework easier to use also throughout each project stage as a planning and decision-making tool.

9. Case studies: analysing accumulated experiences

The following shows a case study conducted under a research project from the University of Natural Resources and Life Sciences Vienna (BOKU) and the Tribhuvan University Kathmandu, Nepal [44].

The research work was focused on field investigations to develop technical standards of soil bioengineering systems. Among other research activities, one site in Kusunti in Kathmandu was selected for the implementation of a bamboo crib wall. A vegetated bamboo crib wall was compared with a conventional slope stabilization method (gabion) by means of different parameters.

At Kusunti site, that half portion of the site was treated with the gabion retaining wall, and the other half with the bamboo crib wall to compare two retaining wall systems from a technical as well as an economic point of view. One layer of gabion retaining wall was constructed for the whole stretch as a base. The total designed height of the wall is 3 m.

The actual construction work at this site was started on November 11, 2006 and ended on November 23, 2006. A supervisor was appointed to control the quality of the work. Students from the Pulchowk Campus and one student from Switzerland (University of Applied Sciences Wädenswil (HsW)) were also directly involved in this work. The before and after construction photographs and the work evolution are shown in **Figures 6** and **7**, respectively.

From the various project activities and critical study and monitoring of project sites, the following general conclusions on the use of bamboo crib walls can be made:

- Vegetative crib walls are comparatively cheaper than gabion or stone masonry wall (construction costs only ¼ of gabion and 1/5 of masonry wall) but provide the same technical stability.
- Although there is more vertical settlement in the case of vegetative crib wall, compared to gabion/masonry walls, vegetative crib walls have better attachment with the slope.
- Vegetative crib walls keep minimum soil moisture, avoid cracks in soil and provide better interception during rainfall.

Figure 6. Before and after construction photographs, Kusunti, Lalitpur (November 2007) [26].

Figure 7. The vegetated bamboo crib wall just after construction (November 2006) and after 1 year of construction (Kusunti, Lalitpur, November 2007) [26].

- More stability through increased cohesion and soil reinforcement is provided in the case of vegetative crib walls.
- The vegetative crib wall made of wood or bamboo is more suitable (also sustainable and environmentally friendly alternative) for solving slope stability problems or for road embankment protection in Nepal.

10. Conclusions

The existing accumulated experiences of using bamboo in soil and water bioengineering works, together with the existing standards and design guidelines, make specific bamboo species an essential and cost-effective material for erosion control and slope stabilization works where these species are native.

The integration of the bioengineering particularities at the design stage demands the integration of the plant evolution and the deterioration processes into the bioengineering design

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scheme. The existing design routines can be adapted for making allowance of the preceding features. The analysis of other works, the accumulated experiences of monitoring and field works and tests (e.g. bamboo root depth, root tensile strength, bamboo culm deterioration processes, bamboo culm mechanical testing, etc.) will support the specialization process for this type of interventions in the future.

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