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Bamboo structures as resilient erosion control measure

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Abstract

Climate change means that fire damage and torrential rains are major issues in many parts of the world, stripping water courses and their ability to attenuate flow in ponds and weirs. Soil bio-engineering methods integrate civil engineering techniques with natural materials to obtain fast, effective and economic methods of protecting, restoring and maintaining the natural slowing of water run-off.

This study combines both the theory and the practical installation involving slope instability, erosion, soil hydrology, mountain plant ecology, and land use restoration to protect the slope against erosion and soil mass loss. Using a multidisciplinary approach, we explore the exchange of the stabilising role between an initially inert structure and the living material used in a bioengineering work to protect the slope against erosion and soil mass loss. From a case study investigation in Spain we investigate bioengineering structures installed within erosion gullies or on eroded slopes and propose a similar measure for a site in Nepal,. The know-how transfer between eco-engineering works from different geo-climatic conditions is considered where bamboo is not a native species.

Key words bioengineering, erosion control, gully, slope stability, vegetation

1. Introduction

Eco-engineering is described as the long term, ecological and economic strategy to manage sites with regard to natural or man-made hazards (Stokes et al., 2004). Whereas civil engineering methods for protecting against erosion and shallow landslides focus on technical constructions and are often restricted to point-by-point or linear effects, eco-engineered approaches are less developed, but can be more enduring and resilient, particularly when coupled with long-term socioeconomic shifts (Böll et al., 2009). Eco-engineering also offers protection in the short term by means of the initial rigidity provided by the utilised inert materials and the pioneer plant species given their quick response to erosion and rapid growth.

The resilience capacity of an eco-engineering strategy can be considered as the return time to bring a disturbed system into a stable equilibrium (Gunderson, 2000) both in terms of engineering and ecological stability. From the engineering point of view which is the focus of this study, the resilience would mediate between the different stable states favouring the transition processes under the effects of disturbance agents (e.g. erosion, landslides, flooding, etc.). Any work strategy promoting ecosystem rehabilitation should also focus on increasing the ecological resilience and, hence, the protection function capacities of local ecosystems.

The eco-engineering approach can be depicted as a three staged strategy where in the first stage, by means of an initial rigidity, the time required for the system to return to its previous equilibrium after the disturbance is decreased. The explicit strategy consists in generating stable conditions where the disturbing effects are mitigated and hence the conditions for triggering local ecosystem recovery mechanisms are generated. During the second stage, the stress transfer phenomenon between the inert elements and the evolving plant community takes place. The transition between the local stable states (local stability domains) is accelerated during this stage. In the third stage, the eco-engineered system has an increased adaptive capacity and can absorb larger disturbances in the local ecosystems before changing its stable state (Gunderson et al., 1999). Generally, by the eco-engineering intervention, the necessary conditions for introducing and establishing local ecosystems are created and, therefore, the global resilience of the intervention area is increased. The inert elements providing the useful initial rigidity are decayed and are no longer providing any structural support.

Engineering structures are necessary to prevent the spread of natural or man-made land degradation processes. By incorporating the vegetation establishment and succession processes into the design stage, the need for intervention is reduced and a long term solution is provided. Throughout the eco-engineering work service life, the key variables that configure the system stability domains change at higher rates and therefore the ecosystem recovery processes are accelerated.

Many governments, managers, engineers and stakeholders are now looking for solutions to rehabilitate degraded ecosystems, whilst increasing their protective function with regard to substrate mass movement. A major drive over the last 5 years has promoted the use of nature-based solutions for disaster risk reduction (Sudmeier-Rieux, 2009), especially with regard to mountain slope and coastal protection. Mountain biomes are particularly vulnerable to shallow landslides and erosion, due largely to an over exploitation of resources, grazing, poorly adapted farming practices and construction such as road building. Although it has been suggested that the frequency of intense storm events may increase as a result of climate change (Stokes et al., 2009), Parker et al (2016) recently demonstrated that landslide frequency in many humid landscapes may be insensitive to projected changes in the frequency of intense rainfall events, and that the time taken to accumulate colluvium is a better indicator of landslide triggering rate. This insensitivity of the landscape to increasing precipitation frequency and intensity is because the return period of landslide-triggering storms is higher than time required for colluvium to accumulate above the critical depth. Therefore, practitioners and researchers should focus on the development of sustainable anthropogenic practices, which are more manageable in the context of current knowledge and practical policy-making decisions, than the uncertain impacts of global warming (Stokes et al., 2009). In this paper, we advocate the use of bamboo as a useful material in bioengineering structures, and we show that bamboo has certain benefits compared to timber forest products. While timber forests require 30-50 years to establish growth (Mulligan and Ramage, 2013), bamboo structural material can be harvested every 3 to 5 years (Gatóo et al., 2014). This rapid turnover is especially significant in tropical areas such as Nepal, India or China where bamboo culms represent a readily available and affordable construction material.

The aim of this paper is to demonstrate a development of innovative bamboo-based eco-engineering design for slope stability by both taking advantage of successful eco-engineering experiences and incorporating the evolving and dynamic nature of the ecoengineering work at the design stage. The designed eco-engineering measure will also be analysed in terms of the improved resilience of the system achieved as a consequence of the eco-engineering approach and philosophy. To accomplish this, our objectives are to analyse an operational eco-engineering work (mixed check dams on Tenerife, Spain) in terms of design and construction, and apply the approach to an instability prone slope in Nepal where bamboo is abundant. With this, we will analyse the benefits and shortcomings of the applied approach detected during the post-construction site survey and incorporate the stress transfer processes between the inert elements and the evolving utilised bamboo vegetation.

2. Materials and Methods

2.1 Background of the mixed check dam ecoengineering work

2.1.1 Analysis of the forest fire effects in the Teide Forestry Crown
The Teide Forestry Crown is located on the Tenerife Island (Canary Islands, Spain) (Fig. 1). The study area occupies the central and north areas of the island where a wide variety of meso- and micro-climates and vegetation can be found (del Arco et al., 2006) growing on mainly steep hilly slopes (40-50%). The natural vegetation consists mainly of pine forest (*Pinus canariensis*) in partial combination with rainforest species (e.g. *Myrica faya* and *Erica arborea*).

Figure 1 Teide Forestry Crown boundary (adapted from https://upload.wikimedia.org/wikipedia/commons/thumb/4/4e/Tenerife_%28Canary_Islands%29 _-_OSM_Mapnik.svg/2000px-Tenerife_%28Canary_Islands%29_-_OSM_Mapnik.svg.png)

The mean annual precipitation is between 600 and 1000 mm and it has a torrential nature characterised by highly intense rainfall events due to intense thunderstorms. The area is prone to wildfires with an average of 70 wildfires per year and affecting an average area of 2560 ha per year in the period 1968-2013 (Instituto Canario de Estadística, 2015).The soils in the area comprise mostly Andisols (Ustands and Udands) due to the island's volcanic nature. The pine forest soils show a greater tendency for runoff generation compared to the surrounding rainforest soils (Neris et al., 2013). The combination of soils and climate characteristics leads to erosive processes which are the main disturbing agent in the study area.

The elimination of the forest floor as a result of a land use change or a wild fire can aggravate extensive erosive phenomena. This was the case of the 2009 wild fire when 4000 ha of pine forest burned and a series of rainstorms (550 mm in 12 days) triggered several debris flows (Neris et al., 2016). The loss of organic matter content due to the forest fire made the Andisols easily erodible (Hernández-Moreno et al., 2007) – a process exacerbated by the rise in runoff and decrease in aggregate stability causing surface sealing as a consequence of forest fires or land use changes (Poulenard et al. , 2001). In the post-fire period, erosion occurred (Poulenard et al., 2001; Morales et al., 2013; Neris et al., 2013) mainly due to:

(i) the increase of runoff;

(ii) the decrease in soil cover and the protective effect of vegetation and organic layers (forest floor); and

(iii) the reduction in aggregate stability (Shakesby and Doerr, 2006).

The erosion was most pronounced within the slope gullies where water run-off concentration dramatically increased both the soil vulnerability and the soil loss rate. A mixed check dams technique (Tardío-Cerrillo and Caballero-Serrano, 2009; Figures 2 and 3) was used in these gullies during the emergency post-fire interventions as a bioengineering measure for slope protection against erosion, soil conservation, and slope stabilisation. Check dams are temporary or permanent cross barriers generally used in concentrated flow areas such as gullies or swales to prevent erosion and promote sedimentation by slowing flow velocities and/or to filtering concentrated flows. They can be constructed from a variety of materials depending on their design service life length. For temporary structures, the usual materials utilised are stones, earth and logs (Figure 2). In order to transfer the know-how from this case study to comparable sites and circumstances, the work undertaken in Spain has to be analysed from different perspectives.

2.1.2. Mixed check dams in Tenerife: Description and work strategy

Due to the magnitude of the wildfire and the resulting risks, the structure was designed to be low-cost, easily and rapidly employable in order to reduce hydrological risks. Similarly to other channel treatments (Norris et al., 2008), its main objective was to reduce water velocity and enhance infiltration and sediment deposition. Designed as a temporary structure, the mixed check dam combined different mitigation techniques such as contour logs, contour trenches and rock dams (Norris et al., 2008). This structure included vegetal debris used as vertical stakes (mainly burned logs of *Erica sp.* and *Myrica faya*), horizontal logs (mainly from burned *Pinus canariensis*), and biodegradable rope to tie the stakes and logs together as a trench and to anchor the whole structure to adjacent trees (Figure 3). The trench was reinforced on the outside by the rock slope to gain stability (less than 50% slope angle), filled on the inside with vegetal debris obtained from silvicultural works, and topped again with rocks (Figures 2 and 3).
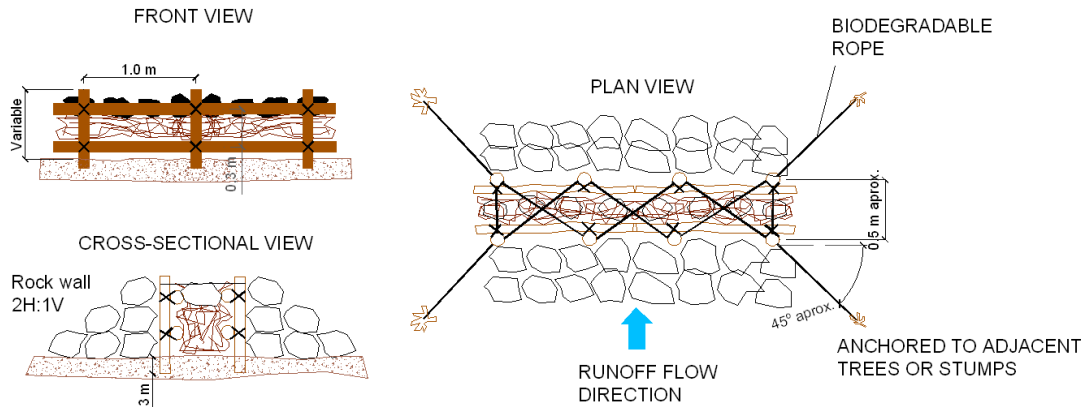
Figure 2 Mixed check dam definition

The dimensions of the mixed check dam varied depending on the channel width, although always ranging between 1 and 2 m in height and between 8 and 10 m in width (Figure 3B). This structure was used as a principal treatment in ephemeral or small-order channels and as a secondary treatment complementing rock dams and gabions in larger channels. Due to the biodegradable nature of most of the components used, these structures were also designed to facilitate colonization by plants (Tardío-Cerrillo & Caballero-Serrano 2009; Tardio-Cerrillo and Garcia-Rodriguez, 2016) (Figure 3A). The features of this innovative structure included:

(i)   reduction in the channel slope and, thus, water speed and detachment capacity;

(ii) promotion of infiltration and sedimentation by increasing the sediment storage capacity (mainly large material as vegetal debris or rocks);

(iii) decrease in resource and time demand by using on-site material for its construction;

(iv) enhancement of the colonization of vegetation due to the biodegradable nature of most of its components;

(v) high adaptability of the design and the components to the environment conditions;

Figure 3 a) Series of mixed check dam colonised by the indigenous vegetation b) Elements of a mixed check dam

2.2. The design of the mixed check dams

2.2.1 Design of structural elements

Both the vertical and the horizontal elements (Figure 4) were modelled as a simply supported beam. The limit state condition in the internal stability check allowed the minimum diameter calculation for both type of elements (Tardio-Cerrillo and Caballero-Serrano, 2009). The horizontal elements were designed as beams subjected to a uniformly distributed load, while the vertical elements were designed as beams subjected to pressures following a triangular distribution shape (Tardio-Cerrillo and Caballero-Serrano, 2009).
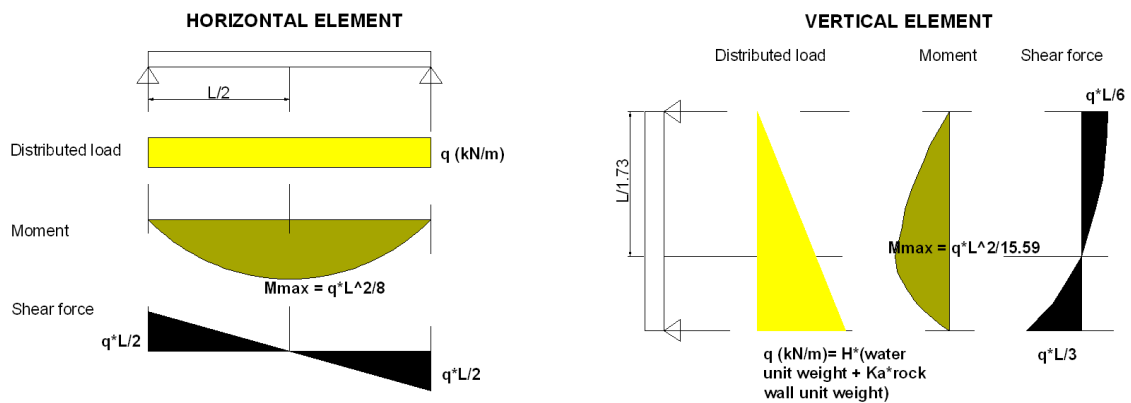

Figure 4 Stress diagrams for the vertical and horizontal elements in a mixed check dam

With the bending stiffness and the design bending strength in the different loading scenarios, the minimum diameter for both the vertical and horizontal elements were calculated according to Equations 1, 2 and 3. The load and material partial safety factors were determined directly from Eurocode 5 (EN 1995-1-1:2004/A1:2008).

$$\sigma_{max} = M_{max} / W \qquad\qquad \text{Eq.1}$$

$$W = \pi \cdot d^3 / 32 \qquad\qquad \text{Eq.2}$$

and

$$X_d = K_{mod} K_k / \gamma_m \qquad\qquad \text{Eq.3}$$

Where:

σ_{max}=maximum normal stress [kPa], M_{max}=maximum bending moment [kNm], d = diameter of the wooden element (m), W= bending stiffness for a circular cross section case [m^3], X_d=wooden element design strength [kPa], K_{mod} =modification factor (with this factor the moisture content effects and the load duration effects are included in the calculation), K_k=wooden element characteristic strength [kPa], γ_m=material partial safety factor (EN 1995-1-1:2004/A1:2008 Eurocode 5). Based on these factors, the minimum dimensions of the structural

elements of the mixed check dam were obtained (Table 1; Tardío-Cerrillo and Caballero-Serrano, 2009; supplementary material).

Table 1 Minimum diameter for both the horizontal and vertical wooden elements of a mixed check dam.

Height of the check dam (m)	Minimum diameter for the vertical elements (m)	Minimum diameter for the horizontal elements (m)
1.0	0.08	0.06
1.5	0.12	0.08
2.0	0.16	0.08

2.2.2. Stress transfer between the initial rigidity and the evolving plants:

The analysed structures can be classified as soft engineering structures (Gray and Sotir, 1996) 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 species used and the biological activity of local degrading mechanisms but also on air temperature, humidity and soil moisture variability (Lacasse and Vanier, 1999). In the eco-engineering 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 (Tardio and Mickovski, 2016):

(i) Determination of the mechanical properties of the wooden elements;
(ii) Determination of the stress diagrams of the different structural elements;
(iii) Determination of the decay rate of the wooden element and its design service life;
(iv) Determination of the plant root system growth and the mechanical properties of the roots;
(v) 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 (Tardío and Mickovski, 2016).

The reinforcement effect due to thin and fine plant roots (excluding the major structural tree roots) can be expressed in engineering terms as an "additional cohesion" added to the strength of the non-rooted soil (Wu et al., 1979; Eq.3). 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 (Wu et al., 1979). The "additional cohesion" ($\triangle S$; Eq.3) 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; Waldron (1977) and Wu et al (1979); Eq.3) assuming that all the roots cross the shear plane perpendicularly and break during the shearing process according to Eq. 3 (Wu et al., 1979).

$$\Delta S = 1.2 t_R$$

<div align="right">Eq.3</div>

Where: ΔS= added cohesion or increase in shear strength due to presence of roots in the soil [KN/m^2]; t_R = average tensile strength of roots per unit area of soil [KN/m^2].

2.3. Danac Khola riverbanks, Nepal

To demonstrate the application of the above approach in geo-climatic regions where bamboo is abundant and traditionally used in construction, a case study from Nepal was selected. The Trail Bridge over Danav Khola river was built under the technical support of Trail Bridge Support Unit (TBSU) of HELVETAS (Swiss Intercooperation International Network), Nepal as a means of crossing the river and connecting farmland under rice paddies. However, the trail bridge could only be used for long periods if the riverbanks were protected and stable (FEED, 2013). The Danav Khola bank protection works mainly consisted of bioengineering techniques including building bamboo vanes along the shore of the river and planting vetiver (*Vetiveria zizanioides*) seedlings over the bank slope body. Monitoring of these measures revealed design flaws that were impeding the soil reinforcement effects of the applied techniques. After an unexpected intense monsoonal rain event, the monitoring of the Danac Khola bioengineering works showed that:

(i) Most of the bamboo vanes with sand bags placed at the toe of the bank resisted the flood water drag forces.

(ii) The vetiver saplings were mostly washed away by both the flood water and the surface flow coming from the top of the bank.

Figure X. Bamboo vanes and vetiver plantation a) before and b) after the flood event

Therefore, unexpected monsoonal rains as a result of climate change were reported to have generated critical scenarios when bioengineering works could be vulnerable, especially during the establishment stage. Climate change phenomena such as changes in the duration and precipitation patterns of the monsoons can be mitigated by applying the eco-engineering approach (Tardio and Mickovski, 2016) where an initial rigidity of inert and dormant materials

(e.g. bamboo culms) can provide the necessary time for the vegetation establishment, growth and development of its stabilising potential.

2.3.1. Design of bamboo cross-barriers

Soil bioengineering has been used widely in Nepal in the past, but the methods currently used have been brought into Nepal over the last 30 years (Schaffner, 1987; Dhital et al., 2012). A traditional technique of close bamboo check dam design in Nepal is shown in Figure 5.
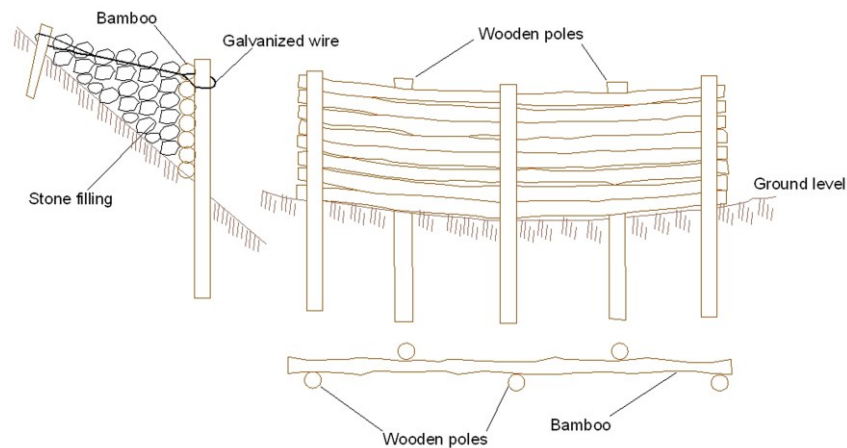

Figure 5 Previous bamboo check dams (according to Sthapit and Tennyson n.d., 2014)

Local reports in Nepal indicate that close check dams do not have a good performance in trapping sediments unlike gridded check dams (Sthapit and Tennyson, 2014) and their design could benefit from an alternative design stemming from the experience with similar structures elsewhere, such as the mixed check dams in Tenerife. Particularly, the main drawback detected in the traditional design was an ineffective debris flow trapping performance. Gridded solutions for bamboo erosion control techniques have been reported as a design improvement of the technique sediment trapping capacity (Sthapit and Tennyson, 2014).

In this work a new strategy is proposed following both the monitoring stage conclusions and the mixed check dam experiences and strategy. As the main problems detected are concentrated on the bank slope, a scheme of bamboo palisades could be installed over the slope following a staggered pattern. In this way, vetiver plants will be protected by the bamboo culms from both the flood water drag forces and the runoff erosion effects. The drainage system for rice paddies located at the top of the banks could be constructed using live fascines (Norris et al., 2008) not only as drainage elements but also as protecting elements of the bank soil along the concentrated runoff water path. However, the drainage system design is out of the scope of this study and will not be discussed further.

Given the semi-empirical nature of bioengineering structures, it is crucial that the know-how of successful engineering interventions is efficiently transferred to different areas. Following the mixed check dam design rationale and applying it to the protection of riverbanks, Figure 6 shows the proposed design comprising two palisades made of horizontal bamboo culms and vertical wooden poles. For this latter element, local woody species could be utilised in line with the sustainability principles of eco-engineering (Mickovski, 2014). Equally, bamboo could be used for this element, albeit this would be a departure from the traditional technique and outwith the scope of the present study. Bamboo should be employed to entrap and support the sediment while the vetiver hedgerows will provide the complementary anchoring and reinforcing functions in such a way that with both elements all the functions necessary for system stability will be achieved. The bamboo palisades will protect the vetiver plants allowing them to grow and settle. Once established and with a developed root system, the vetiver plants would be very difficult to dislodge when exposed to a water flow (Truong et al., 1995).
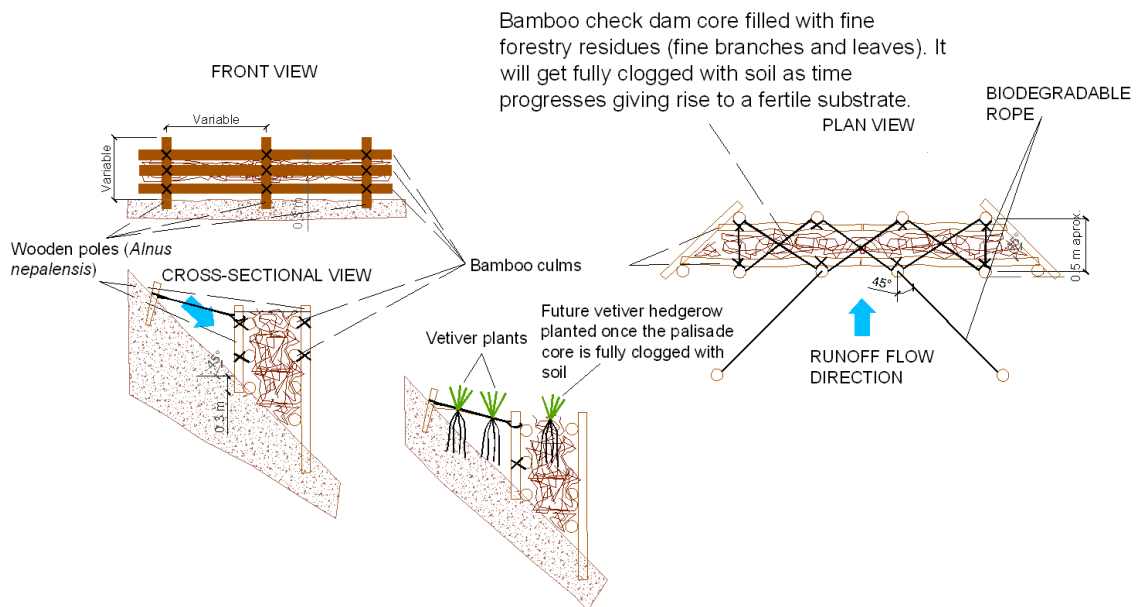

Figure 6 Bamboo check dam general arrangement

Similar to the mixed check dams, the core of the bamboo check dam will be filled with fine forestry or agricultural residues (eg., branches, leaves and grass; Figure 6). All the advantages and successful features of the mixed check dams will thus be incorporated into the proposed bamboo gridded palisade design.

2.3.2. Material properties and design scheme
In Nepal the bamboo elements can be obtained from surrounding bamboo (e.g., *Bambusa nutans*) stands. Bamboo has traditionally been used for soil bioengineering applications, and has often been hailed as a species that is useful for reinforcing soil with regard to erosion and

shallow landslides (Storey, 2002; Chaulya et al., 1999). However, prudence must be shown when choosing bamboo species, because two distinct types of root system morphology can be present. Monopodial species with very shallow root systems (up to 200 mm deep), may not cross a potential shear surface on unstable slopes (Stokes et al., 2007) and can increase the incidence of soil instability (Chen and Huang, 2013). Sympodial bamboo however, even if uprooted, would not pull out neighbouring plants, may cause less damage to the slope surface. Both types of bamboo can be useful in controlling surface erosion, also through modifications in soil chemical properties (Chen et al., 2002; Tian et al., 2003) and soil hydraulic conductivity (Ziegler et al., 2004). In conclusion, managers should probably avoid using bamboo alone when planting on slopes prone to shallow landslides, but could use either monopodial or sympodial species for controlling soil erosion.

The strength and structural capacity of the bamboo elements can be calculated in accordance with existing international design standards (ISO 22156, 2004). The wooden elements can be obtained from locally sourced *Alnus nepalensis* stands. The strength and structural capacity of these elements can calculated according to the existing structural timber design standards (e.g. Eurocode 5; EN 1995, 2004).

The permanent loads on the bamboo palisades will be the saturated soil sediment mound formed behind the bamboo palisades while the temporary loads will be the flood water drag force occurring during critical flood events. To account for these, the load coefficients used throughout the bamboo design scheme can be adopted as 1.50 for temporary loads (e.g. water runoff load) and 1.35 for permanent loads (e.g. sediment mound load). Based on the terrain parameters measured on site (FEED, 2013), the typical inclination of the riverbank will be 45º (100 % slope) and the slope height is 10 meters. The soil will be assumed to be partially saturated during the critical flooding event with an internal angle of friction equal to 22º and cohesion of 5 kPa.

Following the same structural design scheme as the mixed check dams, the strength of the vertical and horizontal elements of the bamboo cross barrier can be calculated using the values shown in Table 2. The load and material partial safety factors were determined from the Eurocode (EN 1995-1-1:2004/A1:2008 Eurocode 5).

Table 2 Parameters and mechanical properties used in the mixed bamboo check dam calculation (EN 1995, 2004). The dam is assumed to be filled with runoff transported sediments. A service class 3 is assumed given the in-ground condition of the structural elements.

K_{mod}	γ_m	Bamboo (*Bambusa nutans*) K_k	Wooden poles (*Alnus nepalensis*) K_k	Soil unit weight (kN/m^3)

		(N/mm^2)	(N/mm^2)	
0.5	1.3	54	35.58	19

For the purpose of this paper, the external stability check mainly comprises the transversal and longitudinal sliding checks. In this latter case, the flood water drag force is compared to the lateral resisting force of the bamboo structure. The longitudinal sliding stability can be assessed as:

$$SF_L = \frac{Lateral\_load\_capacity}{\gamma_w \cdot R_h \cdot J \cdot c_f} \qquad \text{Eq.4}$$

Where:

Lateral load capacity = calculated according to USDA (2007) (kN)

γ_s = unit weight of water (kN/m^3)

R_h = hydraulic radius (m)

J = hydraulic slope (m/m)

c_f = correction factor

The transversal sliding stability can be assessed as:

$$SF_L = \frac{Lateral\_load\_capacity}{Ea_h} \qquad \text{Eq.5}$$

Where:

Lateral load capacity = calculated according to USDA (2007) (kN)

Ea_h = horizontal component of the active earth thrust (kN)

The necessary depth of the vertical elements to withstand both the flood water drag force and the earth thrust can be calculated using the existing design standards (USDA, 2007). The NRCS (Natural Resources Conservation Service) National Engineering Handbook of the USDA (United States Department of Agriculture), particularly its technical supplements, include the design (external and internal stability checks) of wooden palisades and erosion control techniques (USDA, 2007).

2.3.3 Dynamic and temporal considerations at the design stage

Based on the results reported in the literature (e.g. Kusters and Belcher, 2004; Lammeranner et al., 2005) and given that the elements will be in contact with the ground (service class 3), the durability period adopted for this work will be 3 years. Following the resilience and stress transfer design scheme (Tardio and Mickovski, 2016), the following design life milestones can be considered for the structure:

T = 0 years (no plant effects)

This scenario represents the stage throughout the first growth season of the bioengineering work (plant establishment) in which the plant effects are not included yet and the structure resists the loads only with the resistance of the installed structural elements.

T = 1.5 years (vetiver plants have grown roots and shoots and have an effect on the stability of the structure; both bamboo and wooden poles mechanical properties have been adapted because of deterioration processes).

The non-decayed part of both bamboo and wooden pole cross sections are considered to keep their original bending strength properties (Leicester et al., 2003). The decayed cross section is eliminated from the bending stiffness calculation. The mechanical effects of plants now included in the global sediment mound stability check. For this, root depth and root mechanical properties were used. Half of the bamboo culm cross sectional areas are considered to be decayed at this stage.

T = 3.0 years (bamboo structural elements are considered as decayed and do not contribute towards the resistance of the structure. Only plant roots are stabilising the sediment mound). The bamboo service life is completed.

3. Results

3.1 Structural calculations (internal stability check) for T = 0 years

As the cross section of bamboo differs from the full section of ordinary wooden elements (ISO 22156, 2004), for calculation of the minimum required diameter of the horizontal elements a 20 mm thickness (Jackson, 1987) needs to be assumed for the *Bambusa nutans* culms.

Table 3 Minimum diameters for the vertical and horizontal elements calculated using the procedure outlined in section 2.2.1.

Height of the bamboo mixed check dam (m)	Minimum diameter for the vertical elements (*Alnus nepalensis* wooden poles) (m)	Minimum diameter for the horizontal element (bamboo culms) (m)
0.5	0.07	0.06
1.0	0.09	0.08

According to the preceding values it was decided to use a diameter of 0.125 m for both the vertical and horizontal elements. The height of the palisades was 1.0 m on the external face and

the horizontal bending span length was 1.0 m. Vetiver was planted in rows with a spacing of 0.15 m.

3.2 External stability check for T = 0 years

The data used for the external stability check at the end of construction stage (T= 0 years) are shown in Table 4.

Table 4 Values used in the external stability check

ϕ (º)	c (kPa)	R (m)	J (m/m)	Number of vertical poles	γ (kN/m³)	γ_w(kN/m³)
20	5	10	0.01	6	19	10

The values obtained for the external checks for the time milestone of T = 0 years are:

Table 5 External checks at T = 0 years.

Minimum depth of the vertical elements (m)	Transversal sliding safety factor	Longitudinal sliding safety factor
0.8	2.35	3.22

3.3. Stability evolution throughout the structure service life

The bamboo culm service life is assumed to be 3 years (Lammeranner et al., 2005). For T = 1.5 years, the cross sectional area of the bamboo culms are assumed to be half the original value. At T = 3 years, the bamboo culms are considered not to play any role as structural elements and a complete transfer of their stabilising effects to the vetiver plants is assumed. The mean tensile strength of vetiver roots is assumed to be 75 MPa and the root area ratio (RAR) crossing the failure plane at 0.3 m depth is 0.016% for T= 1.5 years (Truong and Loch, 2004) and 0.032 % for T = 3 years (Hengchaovanich and Nilaweera, 1996).

The stability checks at the different time milestones included in this section (Table 6) are the internal stability and the transversal sliding check. The latter is chosen because it usually is the more critical one, and can be very variable due to its sensitivity to the parameters involved (Preti and Cantini, 2002).

Table 6 Internal and external stability checks evaluated throughout the bamboo structure service life.

Time milestone	Internal stability	Transversal sliding

	check	check SF
T = 0 years	Valid	2.35
T = 1.5 years	Valid	3.01
T = 3.0 years	Not applicable	4.18

4. Discussion

4.1. Resilience aspects of mixed check dams

In terms of resilience concepts, the mixed check dam scenario and strategy can be depicted as follows: the key biophysical processes include the climate change effects such as extreme rainfall episodes and temperatures leading to fires and/or erosion and slope instability processes. Stable states are represented by the pyrophyte vegetation associated to the pine forest community in Spain or native vegetation in Nepal. Within the gullies or river channels, the transition between the post disturbance situation and the stable ecological community is mediated by a series of the mixed check dams series. Once the vegetation cover is established and the roots emerge and grow at depth in the soil, the slopes will be protected (Stokes et al., 2014). Biodiversity will then increase and persist until the next disturbance event, reflecting the natural dynamics in the intervention area.

According to the four-phase model for the adaptive cycle (Holling, 1986; Holling, 1992), the way patterns and processes change with time allows ecosystem recovery throughout its disturbance regimes (such as a volcanic system with a certain average of forest fires per year or a fluvial system with a number of flooding events per year). The exploitation phase is characterised by rapid colonization of disturbed areas. This is a very complicated process within the gullies or river channels because of the constant erosion and soil loss. The cross check dams allow the exploitation phase (Carpenter et al., 1993) to take place once the sediment mound is well formed and stable. After a number of deposition events, the check dams will accumulate the transported sediment in the upstream side and, because of the fertile nature of the mixed check dam core (mainly made of soil entrapped by the check dam), the very core of the structure will also be colonised by roots of indigenous plants during the exploitation stage (Tardio-Cerrillo and Carlos-Caballero, 2009). During the conservation stage, material and energy is accumulated and stored in the vegetative system giving rise to a different growth strategy such as the one followed by shrubs and trees. Afterwards, in the creative destruction phase (Scheffer et al., 1993) the disturbance agents (e.g., forest fires or floods) release the accumulated ecological capital. Finally, the system enters in the fourth phase, or reorganization when, as with the check dams, the gully or channel system is able to accumulate more ecological capital and it counts on the presence and effect of the stabilising plant communities to increase resilience.

An unpublisbed recent field survey in Tenerife (Lovreglio et al., 2016) confirms the preceding evolution and resilience improvement. As shown in Table 7, the seedling (*Pinus canariensis* regeneration) were found to be more abundant within the influence of the mixed check dams compared to other traditional erosion control techniques (gabion walls and wattle fences) Besides, it was also found (Lovreglio et al., 2016) that the post-fire biodiversity was greater within the mixed check dams influence as well. Therefore, the forest ecosystem restoration has been accelerated with the use of eco-engineering work approaches.

Table 7 *Pinus canariensis* seedlings (regeneration) absolute density values (nº of plants per hectare) for different erosion control techniques used in Tenerife (Lovreglio et al., 2016; unpublished field work data). Control area = area without erosion control interventions.

Gabions	Mixed check dams	Wattle fences	Control area
1016	3922	2686	2154

4.2 The benefits of the proposed bamboo palisades

Bamboos play a dominant role as woody raw material for a variety of products in the tropical regions (Tewari, 1993). Its versatile nature and innumerable uses have earned bamboo the name ´green gold of the forest´ since it is less expensive than other construction materials (Tewari, 1993). Furthermore, bamboo is an integral part of the culture in several Asian countries and at least one third of human kind uses bamboo in one way or another (Williams and Rao, 1994). Sympodial ´cumpling´ bamboo species are some of the most substantial vegetation structures available to reinforce slopes in Nepal (Howell, 1999; Dhital et al., 2012). Some of the characteristic of bamboo resemble those of wood but its main drawback is that it is not durable with regard to wood pathogens (Gnanaharan et al., 1993). This feature can be perfectly accommodated in the ecoengineering 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.

The possibility of introducing bamboo stands in the area surrounding the bioengineering structure could be useful for supplying source material to both replace damaged elements in the structure, help prevent erosion and extend the proposed intervention to other stretches of the river bank. In this case, the ideal harvest time would be between 2.5 to 4 years after the bamboo plantation since this is the moment at which maturation is reported to occur in the bamboo culms (Espiloy, 1994). Indeed, the use of living bamboo in the proposed gridded palisade design could also include new reinforcing elements in the overall technique performance. In this case, live bamboo pegs (posts) could replace the *Alnus nepalensis* vertical

poles. The live bamboo poles could be a source of both foliage and root soil reinforcement. This option was successfully utilised in the Himalayan Hindu Kush region (DWIDP/JICA, 2004).

The initial rigidity of the palisades will allow for the triggering of new natural processes such as an enhanced resilience, an enhanced ecological functioning and vegetation succession processes. The use of the palisades over the bank body would also reduce the shear stress effects stemming from the flood water flow. The palisades effect on the distribution of flow velocities is expected to be similar to the effect of woody vegetative cover (BMLFW, 1994). The core of the gridded bamboo palisade would entrap the runoff debris which, as a fertile substrate, will allow for both new vetiver hedgerow expansion and spontaneous colonisation by the local species. This feature of the proposed bamboo palisade technique will be a direct translation of a successful feature of the Tenerife mixed check dam case. Once the system is stable and vegetation has increased riverbank strength and resilience other autochthonous plant species will have a stable substrate to colonise. We are not suggesting the use of bamboo as elements in Europe, but rather promoting its use in Asia, where it is endemic. We show that lessons can be learned from bioengineering techniques in Europe, and that the same principles can be applied in both continents. By adapting successful eco-engineering experiences to different geo-climatic zones and local materials (e.g. in UK, *Salix caprea* living wooden poles could be used in combination with local hardwoods elements) new knowledge and strategies will be generated.

Using natural elements and vegetation in engineering structures will not only reduce the carbon footprint and price of the structure, but will promote plant diversity, leading to an indirect increase subsequent ecological processes such as soil microbial and insect diversity. A major challenge remains in that bioengineering techniques need to be accepted by the civil engineering community, who remain wary, because of the lack of norms, insurance agreements and multidisciplinary knowledge required to construct a sound and durable structure. Nevertheless, training and outreach could overcome a certain number of these challenges Currently, European frameworks are calling for a reduction in the use of traditional 'gray' engineered structures and research into the development of long-term, sustainable 'green' infrastructures is being promoted at the government level, not only in Europe, but in many countries worldwide. Through the collaboration between policy makers, managers, engineers and ecologists, future bio- and eco-engineering designs should encompass nature-based solutions for engineering problems.

The ongoing Danav Khola monitoring works will be also used to check the ecoengineering work evolution giving the opportunity to improve the initial design, monitor plants evolution and correct, if necessary, some features of the initial work approach and scheme. This point highlights the importance and need for a monitoring stage in this type of works for successful transfer of know-how.

5. Conclusions

- Successful bioengineering structures were analysed from an engineering and resilience point of view and the underlying strategy was used to offer new solutions in different geo-climatic regions.
- A new bamboo gridded palisade technique using bamboo is presented.
- Problems detected during the monitoring of bioengineering structures developed in Nepal allowed us to identify weakness in the design scheme and to ameliorate the intervention strategy.
- The dynamic nature of bioengineering structures must be incorporated at the design stage in order to realistically simulate and estimate the evolution of the work. The stress transfer phenomena involved are highly novel aspects in the design of the proposed method. The presented calculations reflect the live, temporal dimension in the behaviour of the structure which is an essential particularity of a bioengineering work approach.
- The design of the bamboo gridded palisade provides a solution to the slope vulnerabilities detected in the intervention area. The design and approach are moulded by the ecoengineering work philosophy.
- A traditional civil engineering problem solving approach enhanced with multi-disciplinary knowledge is promoted to enhance the acceptance of eco-engineering design in conventional civil engineering designs. We aim at incorporating eco-engineering as a sustainable and resilient approach in the traditional engineering toolbox.

Acknowledgements

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Figure captions (images as individual files separate to your MS Word text file).

Figure 1 Teide Forestry Crown boundary (adapted from https://upload.wikimedia.org/wikipedia/commons/thumb/4/4e/Tenerife_%28Canary_Islands%29_-_OSM_Mapnik.svg/2000px-Tenerife_%28Canary_Islands%29_-_OSM_Mapnik.svg.png)

Figure 2 Mixed check dam definition

Figure 3 a) Series of mixed check dam colonised by the indigenous vegetation b) Elements of a mixed check dam

Figure 4 Stress diagrams for the vertical and horizontal elements in the mixed check dam case

Figure 5 Previous bamboo check dams (according to Sthapit and Tennyson n.d., 2014)

Figure 6 Bamboo check dam general arrangement

Table captions (tables as individual files in MS Word, separate to your MS Word text file).

Table 1 Minimum diameter for both the horizontal and vertical wooden elements of a mixed check dam.

Table 2 Parameters and mechanical properties used in the mixed bamboo check dam calculation (EN 1995, 2004). The dam is assumed to be filled with runoff transported sediments. A service class 3 is assumed given the in-ground condition of the structural elements.

Table 3 Minimum diameters for the vertical and horizontal elements calculated using the procedure outlined in section 2.2.1.

Table 4 Values used in the external stability check

Table 5 External checks at T = 0 years.

Table 6 Internal and external stability checks evaluated throughout the bamboo structure service life.

Table 7 *Pinus canariensis* seedlings (regeneration) absolute density values (nº of plants per hectare) for different erosion control techniques used in Tenerife (Lovreglio et al., 2016; unpublished field work data). Control area = area without erosion control interventions.