Bamboo Crib Wall: A Sustainable Soil Bioengineering Method to Stabilize Slopes in Nepal

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ABSTRACT

Stabilizing natural as well as man-made slopes in various parts of Nepal is a challenging job. Generally, conventional retaining structures (masonry, concrete or gabion walls) are constructed to stabilize such slopes. The construction and maintenance costs of such walls are increasing every year. A soil bioengineering approach to stabilize slopes using bamboos and plants is explained. The objective of this research work is also to examine the effectiveness of bamboo crib walls to retain the slopes. The performance of the bamboo crib walls were monitored for five years and the results are discussed. The paper highlights the design and construction procedure, strength and durability of bamboo crib walls reinforced with vegetation. A comparison of costs between conventional gabion retaining wall and vegetated bamboo crib wall has also been made for economic justification. The result shows that the introduction of plants inside the bamboo crib wall will not only increase the life of such wall but also increases the stability of whole slope in long-run. Experimental results and qualitative assessment of bamboo crib walls show that the technique of making vegetative crib wall using bamboo could be a sustainable alternative to conventional retaining walls and has potential to add socio-economic value to the communities.

JEL Classification: O31, O33

Keywords: Bamboo, Crib Wall, Soil Bio-engineering, Vegetation, Slope Stability

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1. Introduction

Stabilizing the natural as well as man-made slopes in various parts of Nepal is a challenging job. Due to heavy monsoon rain, rugged topography and young mountains, frequent slope failures and soil erosion are very common in Nepal. In most of cases the natural slopes are disturbed by human to construct a road through it. Nepal has been investing its huge amount of resources to stabilize such roadside slopes. Generally, conventional retaining structures (masonry, concrete or gabion walls) are constructed to retain, stabilize or reinstate such slopes. The cost of such walls is increasing every year due to increased cost of construction materials. Furthermore, the repair and maintenance of retaining structures damage caused by monsoon rain are becoming even more expensive and difficult.

The conventional retaining structure made of gabion, concrete or stone masonry, once collapsed, should be removed from the slope as soon as possible. If it is not removed, the collapsed retaining structure would add surcharge load on the slope which would further increase instability. Furthermore, these conventional retaining structures are relatively rigid constructions and therefore are not suitable for slopes with large displacements or on creeping landslides. Additionally, these “hard” solutions often cause irreparable scars in the landscape in countries like Nepal, which are highly dependent on their natural environment for their prosperity. This is particularly relevant to Nepal in terms of eco-tourism.

Although plants have been used for engineering purpose for hundreds of years, the rapid development of modern technology has gradually made these old techniques obsolete at present time. In recent years, with the increasing awareness of the people on the ecological environment, there is a growing tendency to use vegetation and vegetative techniques for various engineering purpose. The concept of "soil bioengineering" was initially originated from Europe, although plants and plants related materials were used in other continents for hundreds of years for erosion control and earth retaining structures. Soil bioengineering uses plants to solve engineering problems of slope stabilization and erosion control. Soil bioengineering can be regarded as an appropriate and sustainable technology to stabilize the road side slopes and erosion control for developing countries since it is a combination of sciences and basic economic principles. Soil bioengineering approach takes into account the living dynamism of plants of the field. It is a justifiable engineering solution to slope stability. Geomorphology, biology, microbiology, environmental sciences, forestry and landscape architecture, all have a part to play in the diagnosis and treatment of slope failures. Soil bioengineer generally chooses a combination of species, planting techniques and associated structures to manipulate the processes occurring on site towards greater stability.

Pioneering works in soil bioengineering were done in Austria, Germany, Switzerland, UK and the United States. Since last few decades, it has been expanded to other developing countries like Nepal. Although some farmers in Nepal have been using plants and plant materials to retain soil mass on slopes or in river bank erosion control in different ways in the past, an organisational level implementation of soil bioengineering works was started in Nepal in 1975 by the department of soil conservation and watershed management (DSCWM). The first bioengineering technique implemented by DSCWM was bamboo-cum-loose-stone check dam. Some bamboos check dams were constructed to begin control of rill and small gully erosion on the Labok landslide in Biring watershed, Ilam district (Sthapit & Tennyson, 1991). The DSCWM had then continued practicing some bioengineering techniques such as grass plantation, tree plantation, turfing, bamboo check dams, etc. over the years. However, the systematic practice of different soil bioengineering techniques in Nepal was started in 1984 under the Eastern Region Road Maintenance project which was funded by Department for International Development (DFID), UK (Howell, 1999).

Thereafter, over the last three decades, various organizations have been practicing the soil bioengineering techniques in Nepal successfully. For example, the Local Road Improvement Programme (LRIP) in Palpa district adopted the environment-friendly improvement and construction of 96 kilometres of road in 1986 using different bioengineering measures for slope stabilization (Shrestha, 2009). Similarly, the construction of German Development Cooperation (GTZ) supported local road project (65 km) in Dhading district. In 1987, government also adopted environment-friendly road construction techniques using bioengineering (Shrestha, 2009). Over the years several other agencies such as Japanese International Cooperation Agency (JICA) and International Centre for Integrated Mountain Development (ICIMOD) supported projects and Department of Road (DOR) have applied bioengineering measures in various projects successfully. Dharan-Dhankuta road, Dharan-Hile road, Banepa-Bardibas road, Naubise-Mugling road and Muglin-Narayanghat road are some of the examples where bioengineering techniques have been applied successfully. Till now the use of soil bioengineering in Nepal is limited to control the surface erosion and to prevent shallow-seated slope failures. Soil bioengineering as a major function of retaining soil mass in the form of retaining walls has not been practiced so far, although some farmers have been using this technique to retain soil slopes in traditional way (making wattle fence) for long time.

Nepal is very rich in natural resources. There are varieties of species of plants in Nepal, which can be used in soil bioengineering purpose in different ways. Retaining structures made from wood and stones already have a long history. The roman emperor Gaius Julius Caesar describes in his work “De bello Gallico” written between 58 and 52 B.C. a so-called “Gallic wall”, which is quite similar to a wooden crib wall (Kerschbaumsteiner, 1997). In Austria crib walls have been used as fast and cheap stabilizing methods during the flood catastrophes in 1965 and 1966 (Schiechtl & Stern, 1992). In Nepal the technique of making wooden or bamboo-crib has not been used so far, although few concrete crib walls have been constructed along the Tribhuvan Highway. This might be because of the unavailability of the timbers in the quality and quantity required for the construction.

Different species of bamboos are widely distributed throughout Nepal and are extensively used for various purposes. The use of bamboos to stabilize slopes and its use in erosion control has a very long history in Nepal (Tardio et al., 2018). Farmers in Nepal are using bamboos to control erosions at riverbanks and canals, making dykes and steps in farm fields in conventional style. Thus, the use of bamboo to perform its engineering functions as a retaining structure is only limited to the construction of wattle fences of small dimensions. Although the bamboos are used extensively in bioengineering for erosion control in Nepal, its use as a live retaining wall /structure is very limited. So an idea was developed to use bamboo, a cheap and easily available material, instead of using wood or wooden logs for the construction of vegetative crib wall.

This paper describes the results of experimental research work using soil bioengineering approach based on an old technique of making crib construction to stabilize slopes using bamboos and vegetative cuttings. This paper is based on an experimental work in which ten numbers of bamboo crib walls reinforced with vegetation's cuttings are constructed in three separate landslide areas in Nepal. The purpose of these structures is to retain the soil mass and to recover the land as terraced field for farming purpose. The aim of this research work was to observe the suitability of this type of structure to stabilize the slope and to assess the general performance along with the durability of such walls. Since this type of structure using bamboo is constructed for the first time in Nepal, there are no historical records to assess the overall performance and durability of such walls.

Further objective of this research work is to examine how the bamboo crib walls can be effectively constructed and how it will take loads from the slope at the initial stage of construction and how the load will be transferred to the plants (inserted into crib walls) in long-run and stabilize the slope. The design and construction procedure, strength and durability of bamboo crib walls reinforced with vegetation are also described in this paper. The general performance of bamboo crib walls was observed at field by monitoring the construction of vegetative bamboo crib wall for five years. In addition a comparison of costs between conventional gabion retaining wall and vegetated bamboo crib wall has also been made for economic justification.

2. Methodology

2.1 Site description

The project area is located in the south corner of the Kathmandu valley. It is about 15 km away from the city center located at Godawari-4, Badikhel. There are basically two different sites and three different landslides within the project area. The location map of the project area is given in Figure 1.

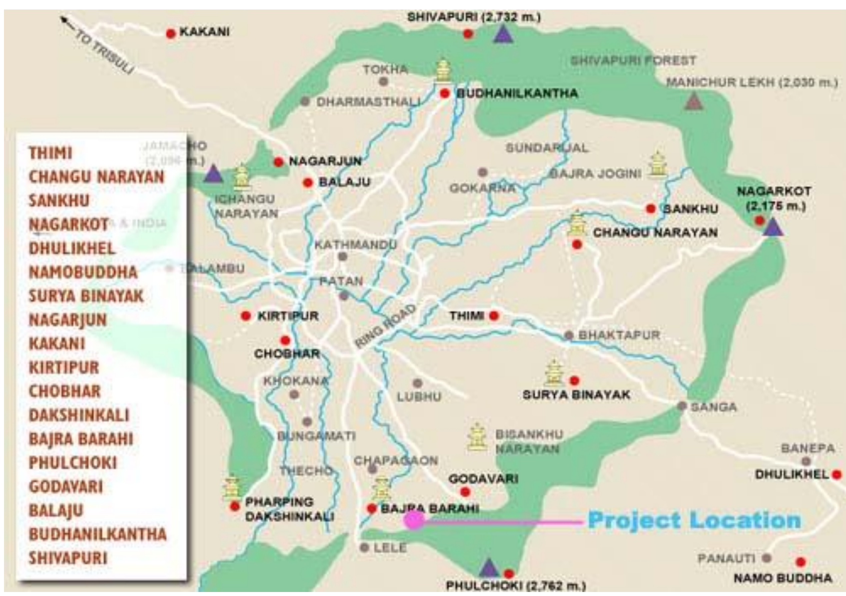

Figure 1. Location of project area on Kathmandu valley map.

Site A:

The slope is facing west and having an average slope angle of 30°- 50°. The slope starts from Kodku river upwards and end to the top of the mountain (Phulchoki/Mahabharat range, with an elevation of about 2762 m). In the present project, only about 140 m long slope starting from the river bed level (with an elevation of 1410 m) up to an elevation of 1490 m has been considered. The most of the part of the slope is barren land. The slope under present project consists of three main parts. The lower part of the slope is covered with some small weeds and few Utis (*Alnus nepalensis*) trees. There is one small irrigation canal flowing across the slope in the middle. On the top part of the slope there are some Chilaune (*Schima wallichii*) tress and bamboo bushes. The uppermost part of the slope is a community forest area mainly consisting of Gobre Salla (*Pinus wallichiana*) and Rani Salla (*Pinus roxburghii*).

The top part of the slope under consideration was a maize and millet field till 1992. Due to decreasing productivity of the field, it became uneconomical to cultivate this field and the farmer stopped to cultivate and they planted some Utis/Alnus (*Alnus nepalensis*), Lapsi (*Choerospondias axillaris*) and Chilaune (*Schima wallichii*) trees and bamboos. The photograph of project site A is shown in Figure 2.

There are two distinct landslides which occurred on August 2002 in two different parts of the slopes. The upper part of slide has an average width of about 12 m and about 35 m in length and there is no failure surface in the slope between these two slides. The upper part of the slide contains red clay mixed with silt. The lower part of the slide is about 50 m long and 30 m wide, where the main failure occurred. The downhill part towards the toe of the slope consists of conglomerate type of soil, mixed with gravel and fine sand. The lower part contains loose gravel mixed with sand and silt with some big stones.

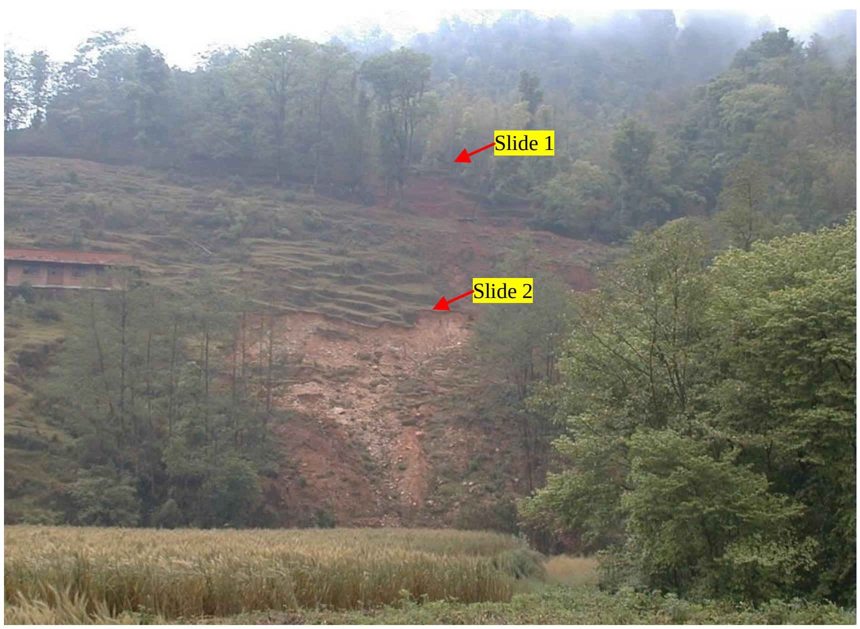

Figure 2. View of landslides at project site A in Badikhel/Lalitpur, Nepal (April 2003).

Site B:

The location of this site is about 500 m upstream of the same river, Kodku. This site has also similar topography as that of site A. The project site has west-facing having an average slope of 30°-45°. The slope starts from a river upwards and end at the top of the mountain. The elevation of the bottom of the slope at the river bank is about 1425 m. In the present project, only about 50 m long slope starting from the river bed level (1425 m) up to an elevation of 1455 m has been considered. The slope was covered with some small weeds and few Utis (*Alnus nepalensis*) and Chilaune (*Schima wallichii*) trees before the slide occurred. There is one small irrigation canal across the slope near the top of the slide. On the top part of the slope there are some Chilaune (*Schima wallichii*) trees and Alnus (*Alnus nepalensis*) trees. The uppermost part of the slope is a forest area mainly consisting of Gobre Salla (*Pinus wallichiana*) and Rani Salla (*Pinus roxburghii*). The photograph of the project site is shown in Figure 3.

Figure 3. View of project site B (landslide before and after construction of bamboo crib wall), Badikhel/Lalitpur, Nepal (May, 2004).

Due to heavy monsoon rain on July 2003, a landslide occurred in the project area. The slide started at the top near a small irrigation canal which is a border of forest and the cultivated land, about 50 meters away from the toe of the hill. The slide swept away small bushes and few trees. Due to steep slope of about 45°, all the materials were rolled down the hill and fell into the river at the toe of the slope. The difference of elevation of the toe of hill and top scar is about 30 m. The slide has an average width of about 15 m and about 35 m in length and there is no failure surface up to 15 m above the toe of slope. The upper part of the slide contains brown clay mixed with silt. The downhill part towards the toe of the slope consists of conglomerate type of soil, mixed with gravel and fine sand. The lower part contains loose gravel mixed with sand, silt and some big stones also.

2.2 Definition of crib wall

A crib retaining wall is a structure built up of individual elements to form a series of box-like cells into which infill is placed; the infill acts as an integral part of the structure. A crib cell is a box-like structure formed from headers and stretchers (see Figures 4 and 5) into which infill is placed (Acharya et al., 2015). Crib elements may be of concrete or wood. In the present project, bamboos are used as crib element and live cuttings are used in between two crib cells. These walls are therefore called live crib walls or live-reinforced crib walls or vegetative crib walls. In general, crib walls can be described as a specialized form of gravity-retaining structure using on-site fill material, held within a constructed framework, in order to provide most of the necessary mass to resist overturning by the weight of the slope (Morgan & Rickson, 1995). Crib retaining walls are usually constructed to stabilize the base of a slope that has failed. Thus, crib walls are supposed to work as a retaining structure for protection of slope or embankments.

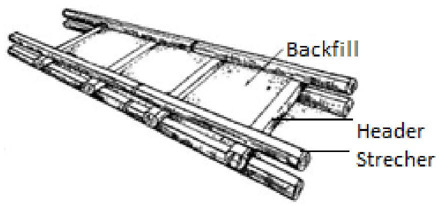

Figure 4. Typical crib construction**.**

Figure 5. An example of wooden crib wall.

2.3 Materials and construction technique

Basically there are four different ways of crib construction (see Figure 6). Depending upon the material used and type of crib elements, crib walls up to a height of 25 meters are possible (Brandl, 1987). In the present project, schema type 2 is used in making bamboo cribs because this type of construction is suitable for low height walls. Ten bamboo crib walls (about 150 running meters) of heights between 1.5 m to 2.0 m were constructed in a period of May 2003 to June 2004 on three research sites in a hill slope in Lalitpur, Nepal. This work was the part of experiment of the author to observe the performance of vegetative bamboo crib walls during the PhD study.

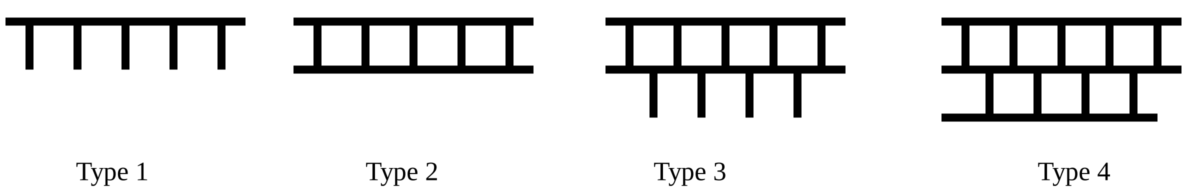

Figure 6. Different ways of crib construction (plan view).

Bamboos used for the construction of the crib walls were cut in the nearby area. There are two varieties of bamboos used in the construction, Tama Bans (*Dendrocalamus hamiltonii*) and Taru Bans (*Bambus anutans*). The bamboo was freshly cut and transported to the site. The stems were about 8-10 meters long and had an average diameter of around 8 cm. The diameter of round timbers used for construction of wooden crib walls usually is between 20–25 cm. The bamboo used had a mean diameter of around 8 cm. With this dimension it needs many layers to gain wall height. Due to this fact and also to enhance stability it was decided to use bamboo bundle in either for the header or stretcher element made up of three bamboos fixed together by wire (see Figure 7 middle picture). First of all, bamboos were cut in required lengths and placed together on the site to form a type 2-crib cell (see Figure 6). Then the infill was placed above it and it was compacted with a rammer. Then the cuttings were laid horizontally with a spacing of 15-20 cm, filled with soil material and water was sprinkled on the surface and again compacted with rammer. Then the next layer was placed in the similar way till the required wall height was reached. In this work, mainly the branches/rooted plants of Phaledo (*Erythrina arborescens*/Roxb.), Kalki (*Callistemon citrinus*/Crimson bottlebrush), Lakuri (*Fraxinus floribunda* /Himalayan Ash), Chutro (*Berberis aristata*/Indian Barbery), Amliso (*Thysanolaena latifolia*/ Broom grass), Khareto (*Phyllanthus parvifolius*), Kanda Phul (*Lantana camara*), etc. were used.

Figure 7 demonstrates the building procedure of the vegetated bamboo crib wall. This structure, once filled, acts as a retaining wall. The cut branches (local species mentioned above) collected from a local area, provide immediate mechanical support and subsequently begin rooting in the soil, further stabilizing the slope. In addition, the portions of the branches, which are exposed to light, will produce leaves, and provide an aesthetically pleasing vegetative cover on the slope without the added cost of gardening. The bamboo provides immediate protection and stability for the structure, but their importance is gradually lessened as they decompose, and the live cuttings grow and proliferate. The resulting root mass binds the fill and the parent soils into a single coherent mass, which will finally stabilize the slope.

Figure 7. Bamboo crib wall construction stages.

2.4 Other material used in crib construction

The conventional retaining walls may be a costlier solution for slope protection works in developing and least developed countries. Under such circumstances vegetative log crib walls could be “an appropriate technique” and “a low-cost and sustainable alternative” to conventional retaining walls in landslide prone areas where future ground movements are expected (Acharya, 2018). Crib walls can be made from timber logs, pre-cast concrete or metal members. Pre-cast concrete crib walls are popular in developed countries. The choice of material depends on the affordability and availability of material and technology. However, considering the cost of materials, the use of pre-cast concrete or steel member in crib wall construction would be unaffordable or uneconomical solutions for least developed countries like Nepal. An alternative to concrete or steel members in crib wall construction is the use of plant material, i.e., bamboo or wood.

2.5 Justification of using bamboos

Considering the wide availability and diversified utility of bamboo as one of the construction material in Nepal, the researcher as suggested by Professor Dr. Florin Florineth (University of Natural Resources and Life Sciences, Vienna, Austria) tried to use bamboos in earth retaining structure (crib walls) to stabilize landslides. The idea to use bamboo instead of wood evolved from the typical situation in Nepal, where deforestation is one of the major problems and the round timber, which is generally used in crib wall construction, is not available in the quality and quantity required and is costlier than bamboo. On the other hand, bamboo is easily available in Nepal and its use in construction has already a long tradition in Asian countries. Moreover, in recent years, the bamboo plantation in road side soil bioengineering works has been practiced successfully in various areas of Nepal and the use of vegetative structures in roadsides slopes stabilization has been increased due to introduction of soil bioengineering practices in road construction and maintenance (Dhital et al., 2013).

Bamboos can become a suitable substitute for timber because it possesses comparable physical and mechanical properties and is commonly available. It is a fast growing and abundant. There are about 1200 species of bamboos in the world. Bamboo has phenomenal growth rate potential, with some species growing at a rate of 15 to 18 cm daily, with maximum height in just four to six months. There are about 23 genera (24% of the world) and 81 species of bamboo (5.2% of the world) found in 73 of the 75 districts of Nepal (Pokhrel, 2008). Out of these, about 30 species are suitable for soil bioengineering.

Some bamboo species can grow to over 30 meters high and have a diameter of 40 to 60 cm (Ahmad, 2000). Dhanu bans (*Bambusa balcooa*) found in Nepal is common upto 1600m, can grow upto a height of 25 m and with a diameter of 15 cm (Tewari, 1993). Similarly, Taru Bans (*Bambusa nutan*) and Tama Bans (*Dendrocalamus hamiltonii)* commonly available in Nepal can grow up to 15 m high.

Bamboo is versatile plant with a short growth cycle. It grows to its full height in 3 months. It can be harvested in 3-5 years versus 10-50 years for most softwoods and hardwoods (Desalegn & Tadesse, 2013). It is one of the strongest building materials with a tensile strength that rivals steel and weight-to-strength ratio surpassing that of graphite.

The strength parameters of different materials from various literatures are presented in Table 1. The table shows a comparison of mechanical properties of bamboo with other wood species and steel. As an alternative construction material and as a cheaper substitute for timber, concrete or steel, bamboos were used in this research project. If bamboos can serve the engineering purpose, it will be more cost effective and sustainable to use bamboos than using timber logs, concrete or steel elements in the construction of crib walls.

3. Analysis of bamboo crib wall and its performance

3.1 Strength and durability

Since the crib walls are specialized form of gravity-retaining structure, two types of stability analysis (i.e., external and internal stability) are required to ensure the safety of the structure. For the external stability analysis of such type of walls the calculation is done as for other gravity retaining walls by assuming it a monolithic construction, considering the composite body a whole, known as Monolithic theory (Brandl, 1984).

Table 1

A Comparison of Strengths of Different Wood Species with Bamboo and Steel

Materials	E-Module (N/mm²)	Compressive strength (N/mm²)	Tensile strength (N/mm²)	Bending strength (N/mm²)	Shear Strength (N/mm²)
Bamboo *(Bambus)*	20000	62-93	148- 384	76-276	19.8
Birch (*Betula)*	16500	43	137	125	12.0
Common hornbeam(*Carpinus)*	16200	66	135	13	8.5
Larch (*Larix)*	13800	47	107	99	9.0
Common Ash (*Fraxinus*)	13400	44	165	12	12.8
Oak (*Quercus)*	13000	65	90	100	11.0
Teak *(Tectona)*	13000	68	119	105	9.0
Common Alder (*Alnus*)	11700	55	94	85	4.5
Spruce (*PiceaAbies*)	11000	50	90	78	6.7
Poplar (*Populus*)	8800	35	77	65	6.5
Steel St 37, DIN 18800	210000	218	218	218	126

But for internal stability analysis the strength of crib elements, fill material and vegetative cuttings should be considered in the analysis. It is required to consider the two extreme conditions while designing a vegetative bamboo crib wall:

a. Just after the construction (the role of vegetation will be negligible compared to crib elements.)

b. After the decay of crib elements (the slope will be naturally stabilized, plant roots support the slope with increasing the shear strength of fill material.)

In the first condition, as per Schuppener (2001), the resistance of the vegetative crib wall is given by,

Total Resistance (R) = Resistance by crib wall + resistance by vegetative cuttings (1)

The resistance by cuttings (R_p) is given by,

$$R_P = \pi * D * L * \tau_f * \cos(\alpha+\theta) \quad (2)$$

Where, L, D = length and diameter of cuttings

τ_f = average bond strength between cutting and fill material,

θ = possible failure slope angle, and α = inclination of cuttings

During construction, if we use cuttings having diameters more than 25mm and length more than 1 m, resistance by cuttings can be included in the calculation; otherwise, the effects of cuttings can be neglected as it will be negligible compared to the resistance by crib elements. In this project, we did not consider the role of cuttings at initial stage. The crib walls were designed according to the standard design procedure of concrete/timber crib walls without considering the role of cuttings (Brandl, 1984).

For the second situation, it is assumed that vegetation on the slope will revitalize and the failed slope will naturally stabilize. Since it is difficult to quantify an exact role of plants, an analysis of this situation is not considered here. In this case, we only assume that the slope will be stabilized by natural process.

For design of crib wall and crib construction, following safety checks should be performed (Brandl, 1987):

- Safety against slip failure of whole mass
- Safety against slide (sliding of crib elements)
- Safety against overturning of earth-side crib elements
- Safety against overloading and shearing of joints

For dimensioning such type of crib walls, following parameters are required:

- The strength of crib elements in bending and tension
- The friction coefficients between fill and crib and vegetation cuttings
- The cohesion and shear strength of fill material
- The strength of joints of crib elements
- The tensile, shear and bending strength of vegetative cuttings used in crib walls

The durability of crib walls mainly depends upon the type of the wood used in the construction as wood from some tree species is very durable compared to others. A great number of timber crib walls were built in the Rocky Mountains, USA. Some of them with well-drained backfill are 70 to 80 years old and still serviceable (Gray & Sotir, 1996). Kerschbaumsteiner (1997) has examined different crib walls constructed in various places in Austria. He found that most of crib walls which were constructed before 1980 are still in serviceable condition.

Considering the performance of wooden log crib walls, the durability of such walls can be assumed long-lasting. There are evidences of wooden crib wall construction in Garden Bach at Doelach, Austria, that the wooden logs used in crib construction are found in very good condition even after 25 years (Figure 8). Even after 50 years of the construction, the wooden crib walls are intact near Galina, Vorarlberg, in Austria (Florineth, 2004). As there is no past records and evidence on bamboo crib wall, author tested few bamboo logs found in a riverbed (completely buried) in Lalitpur, Nepal, which had been used for river protection works and were found sufficiently strong even after 30 years.

Figure 8. The condition of wooden crib wall (constructed almost vertical) after 20 years of the construction, in Königstätten, Lower Austria (July, 2007).

3.2 Post construction performance

Under this experimental research work, ten numbers of vegetated bamboo crib walls of heights between 1.5 to 2 m were constructed on three different landslides (refer Figures 9, 10 and 11). In addition, other bioengineering measures such as brush layering and grass plantation were also carried out on the slope. Then the performance of crib walls were monitored for five years. During the first and second year, minor repair and maintenance of vegetation were also carried out. The performance of crib walls including bioengineering works was evaluated based on the growth of vegetation, vegetation coverage on slope, decrease in soil erosion and loss of soil and damages to the structure and bioengineering measures.

The bamboo crib structure on all three landslides functioned well and appeared stable just after two monsoon periods. There were some minor rills formed by runoff on the slope during first and second years after the construction which were fully covered by vegetation after third year. All vegetative walls are still intact and the vegetative cuttings were grown very well. No major soil erosion was occurred on the slopes and the soil loss was negligible after three years.

Figure 9. Bamboo crib wall on experimental site 1 in Badikhel/Lalipur, Nepal, on May 2003 (left) and on August 2003 (right), (Tardio et al., 2018).

Figure 10. Bamboo crib wall on experimental site 2 in Badikhel/Lalipur, Nepal, on December 2003(left) and October 2005 (right)

In a similar research work carried out in Thankot, it is observed that the survival rate of cuttings after 6 months was 72% and that of rooted plants was 86% (Lammeranner et al., 2005).

3.3 Public opinion survey

In addition to the qualitative evaluations and assessments of the sites, a survey was also carried out to gather the public opinion/assessment about the vegetative bamboo crib walls. The purpose of this survey was to know the public view and acceptance to this technology. There were fifty people involved in this survey. Since this kind of structure using bamboo and live branches was new for these people, they were curious about this technique and they had actively participated in this survey.

Figure 11. Bamboo crib wall on experimental site 3 in Badikhel/Lalipur, Nepal, on May 2004 (left) and October 2005 (right).

The following questions were asked to know and evaluate the performance and effectiveness of the vegetated bamboo crib wall:

1. Are you happy with the techniques of slope stabilization using bamboos?
2. Does such technique will further help deforestations?
3. Will this technique fit in the landscape properly?
4. Will these structures be strong enough to take the loads from the slope for long time?

5. How durable will be such technique?

The response to this public opinion survey has been presented in result and discussion section below.

3.4 Cost comparison

A cost analysis (as per material price in 2020) for a 30.5 m long and 1.5 m high bamboo crib wall is presented in Table 2. This cost is calculated based on the actual requirement for the purchase of materials and payment to the labors for the construction of a vegetated bamboos crib wall. This cost does not include the price for cuttings or rooted plants, because all the plants and cuttings were collected free of charge from nearby community forest. Approximate cost estimates of similar wall made of stone masonry, concrete or gabion to perform same function are given in Table 3.

Table 2

Cost Analysis (as of price in 2020) for the Construction of a Vegetated Bamboo Crib Wall

Materials for L= 30.5 m, B=1.2 m, and H=1.5 m, vegetated bamboo crib wall	Unit	Quantity	Rate in NRs	Total amount in NRs
Bamboos	m	675	50	33750.00
Binding wire	Kg	4	90	360.00
Total labor used for construction including cutting collection	Nos.	24	750	18000.00
Total cost				52110.00
Cost per m^3				949.20

Table 3

Costs Comparison for the Construction of a Retaining Wall to Perform Same Function Using Different Material

Wall Type	Minimum width of wall required/used in practice in meters	Unit	Quantity	Rate in NRs	Total amount in NRs	Cost per meter in NRs
Vegetated bamboo crib wall, 30.5 m long	1.2 m	m^3	54.90	949.20	52110.00	1708.52
Stone masonry (L=30.5, B= (0.5+0.9)/2, H=1.5)	0.5m at top 0.6 H at bottom	m^3	32.02	9500.00	304190.00	9500.00
Gabion wall (30.5 m)	1 m	m^3	45.75	5500.00	251625.00	8250.00
Cost saving per meter (compared to gabion wall)						6541.48

Table 3 shows that the unit cost of bamboo crib wall is much less than that of other types of retaining walls. Therefore, the vegetated bamboo crib walls could be a cost effective solution for retaining walls for a height up to 3 meters. The rates for materials and labors are based on district rates of Lalitpur revised for the year 2020.

4. Results and discussion

4.1 Post-performance evaluation

Results of this experimental works on bamboo crib walls from the year 2003 are more encouraging. As of the writing of this paper, it has been already 17 years and all three landslides areas are fully reinstated and covered with vegetation. There is also a very positive response from local villagers on this type of construction. There were also other experiments (centrifuge model test (Acharya et al., 2015) and analysis on bamboo crib walls (Acharya, 2018) carried out by the author. The research result shows that this type of construction can be applied successfully where a low height (up to 3 meters) retaining walls are required. In a similar research work carried out in Thankot, the development of the vegetated bamboo crib walls was found very satisfactory in terms of the performance of the cuttings and rooted plants inlayed into the bamboo constructions (Lammeranner et al., 2005).

After close monitoring of ten numbers of vegetative bamboo crib wall for five years, the researcher observed that the damages on the slope caused by landslide were repaired by natural process of regeneration of vegetation. All bamboo crib walls were intact and no movement of slope was observed. The growth of vegetation was satisfactory and the ground coverage of vegetation was above 90%. Thus, it can be concluded that after five years of construction of vegetative crib walls the load of such walls will be taken by plants (vegetation grown on the reinstated slope) or the slope will be self-stabilized by recovering its natural strength before failure. Being a highly flexible construction with natural reinforcements of living plants, this type of construction will remain intact with slope, even after the structural failure and it will be able to resist further slope failure. These all shows that this type of crib construction are comparably strong and durable.

4.2 Public opinion survey results

The response from the questionnaire survey conducted for public opinion is presented in the Table 4.

Since there is a positive response from more than 70% of the respondents, the techniques of making vegetative bamboo crib would be easily accepted by local people if we make aware of this technique at community level. This result shows that there is a very high socio-economic and environmental value of such type of construction.

Since the local people do not have the experience on the use of bamboos in making such walls and they do not have any idea about the durability of bamboos. One thing is clear that these types of walls fit in the landscape very nicely (Figure 11). These walls are low cost techniques and environmental friendly structures and will therefore be easily accepted by the community having subsistence economy.

4.3 Cost effectiveness, socio-economic benefits and sustainability

The vegetative crib construction uses the renewable and low cost construction materials and offers a very flexible construction which can be used anywhere. It does not require qualified

Table 4

The Public Responses on the Construction of Vegetative Crib Wall

Questions	Response %		Specific remarks/comments
	Yes	No	
a. Are you happy with the techniques of slope stabilization using bamboos?	70	30	Bamboos are weak/not suitable for retaining wall construction (30%)
b. How durable will be such technique?			This will not be a sustainable solution (30%)
< 2 year	40		
3-5 years	40		
> 5 years	20		
c. Does such technique will further help deforestations?	25	75	
d. Will this technique fit in the landscape properly?	80	20	
e. Will these structures be strong enough to take the loads from the slope for long time?	???	35	Most of responders do not know

workers and it is a labor-based technology. Therefore, in developing countries where cheap labors are available and where there is increasing unemployment there is a very good opportunity to use such techniques. In developed countries where there is a danger of environment degradation, this technique could be an alternative to the practitioners.

In general, compared to conventional approach of civil engineering the soil bioengineering has the following benefits:

- Costs are lower, especially in the long term. Aside from maintenance cost, only labor forces will be required for maintenance, and where labor is cheap, the maintenance cost will also be low.
- The strength usually increases with time. The mechanical effects on slope stability develop as the plant community matures. Inert structures become weaker as they weather and unlike living plants they cannot adapt to changes in the microenvironment.
- Compatibility with the environment in terms of conserving biodiversity, ecological integrity and scenic beauty is a natural consequence of soil bioengineering.
- Acceptability to local people is no longer a problem as the bioengineering approach can be more participatory involving co-operation, design contribution and paid labor of road neighbors.
- Use of locally available materials will motivate local people to explore their own sources of income.

Considering the reality of a developing country like Nepal, sustainable solutions to the problems related to infrastructure development are very important for the economic development and poverty reduction. Physical development without hampering the physical environment will enhance the quality of life in long-term. People today are more environment and safety conscious than before and they like to use environment-friendly and sustainable construction techniques. If necessary, they are ready to pay an extra cost for it. Therefore, if the durability of vegetative crib walls is ensured and the professionals are assured about the safety, economy and durability of such structures, this technique will certainly replace the conventional civil engineering construction technique to the extent of its limitations.

4.4 Discussion

Any “new” technique is required to be tested first for its performance and only then it can be applied in practice. The main weakness of the present technique is that there are not proper methods for its dimensioning. People who want to have a required level of safety and serviceability will not be able to adopt this technique, because of unavailability of national/international norms recognized by the respective national and international authorities. There are different guidelines and manuals prepared for site specific conditions which need to be generalized on the basis of worldwide experiences on the use of this technique. However, recently there is a publication on "Analytical Approach to Design Vegetative Crib Walls" which provides some design guidelines for designing vegetative crib walls (Acharya, 2018).

5. Conclusion and recommendations

The performance of walls in this experimental work demonstrates that this technique is a favorable economic alternative in slope management. As this technique is more flexible, it can be easily combined with other geotechnical and civil engineering measures and applied also in large-scale slope failures problems. When technically feasible (if there is a possibility to grow plants), this type of soil bioengineering techniques can be adopted to produce equal or better economic and environmental results than the traditional geotechnical solutions. The introduction of plants inside the bamboo crib wall will not only increases the life of such wall but also increases the stability of whole slope in long-run. Results show that the old technique of making crib wall using the locally available material (bamboo) in stabilizing slopes might be a viable alternative to conventional gabion walls. The post-performance of these walls demonstrated that this technique could also be an alternative for other geo-technical slope stabilization methods. Furthermore, this technique allows for more long-term environmental benefits, such as air and water quality improvements and it can also be a sustainable solution to geotechnical problems.

Education and dissemination are important components of any new technology. Therefore, this technique also required to be tested in several conditions and the results should be disseminated. A research team comprising of geotechnical and soil bioengineering experts should continuously involve in further research for dimensioning this type of structures.

Finally, it needs to be emphasized that techniques are never to be blindly replicated without taking into account of the basic engineering principles. The most important issue in use of soil bioengineering techniques is the site investigation or the site assessment to determine the causes of failure. The next important issue is the design of an appropriate system using suitable techniques for mitigation and remediation measures. The vegetative crib techniques should be designed to function as part of the complete soil bioengineering system. Proper site assessment and appropriate design of the soil bioengineering system are the key factors for the successful implementation of vegetative crib techniques.

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