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STATE OF THE ART/PRACTICE PAPER

Rainfall-Induced Slope Failures and Use of Bamboo as a Remedial Measure: A Review

J. S. Gidon[1] · S. Sahoo[1]

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Abstract Problems due to slope instability during rainfall season can cause major landslides occurrences. Different rainfall intensities and duration affect the slope in different manners. To counter this problem, numerous studies have been carried and many innovative techniques have come up on how to stabilize the soil so as to ensure stability. The different techniques involve chemical stabilization, retaining walls, vegetation, different methods of reinforcements, etc. Most of these methods are proving to be fatal to the environment; hence, sustainable methods of reinforcements are the latest area of interests. Bamboo has been widely used as a reinforcement material for soil stabilization. This paper presents the current state of art on the application of bamboos in the stabilization of landslide caused due to rainfall. Bamboo can be used in many forms and has proven to be effective in almost all its forms. Various ways that a bamboo can be used as reinforcements are studied in detail.

Keywords Bamboo · Landslides · Rainfall · Reinforcements · Stabilization

✉ J. S. Gidon
sharailingidon@gmail.com

S. Sahoo
smrutirekha.sahoo@nitm.ac.in

[1] NIT Meghalaya, Laitumkhrah, Bijni Complex, Shillong, Meghalaya 793003, India

Introduction

Landslides occurrences are one of the major problems faced by many countries in the world. There are many factors contributing to the cause of landslides. They occur due to natural factors like rainfall, earthquake, volcanoes, etc., or human activities like deforestation, land encroachment, construction work, farming, poor drainage, etc. In addition, other factors like steep slopes, fragmented rocks can form a slope geometry favoring landslides. This paper mainly focused on rainfall as a main contributing factor to landslides [1–5]. Heavy rainfall on an unsaturated soil triggers an occurrence of landslides due to the increase in pore water pressure. The stability of the soil is directly affected by the change in the matrix suction of the unsaturated soil. When rainwater seeps, the wetting front of the unsaturated soil is increased, leading to the decrease in matrix suction and a consequent reduction in the soil shear strength [6, 7]. The intensity of rainfall has an immense effect on the critical slip surface of a slope.

To tackle this problem, many techniques are developed over the years. These techniques can be categorized into chemical stabilization [8–11] and mechanical stabilization. The materials used for this purpose vary widely from RCC, stones, geotextiles, geomembranes, etc. These materials are in the form of RCC walls, gabion walls, crib walls, soil nails, retaining walls, micropiles, stone columns, etc. However, the use of these materials can bring about environmental issues like air, land and water pollution, emission of carbon dioxide causing global warming, depletion of resources and increase in the amount of non-degradable substances in the geo-environment. Due to this, sustainable and eco-friendly innovations have been developed to lessen the harmful effects they have. One of the most recent innovations is the use of bamboo in various forms as a slope stabilizing material [12–14]. In the recent years, many researches have been carried out on how bamboo can be used in various fields of civil engineering, and one of them is the use of bamboo as a reinforcement material and retaining the stability of a soil slope. Most distinguished properties of bamboo are its renewability, sustainability, evenly distributed stresses, low density, light weight, high wettability and high wear resistance. Bamboo can efficiently be used as a reinforcement material, and it can sustain for a long time if properly treated or seasoned properly [12, 14]. This paper presents the current state of art on the application of bamboos in the stabilization of landslide caused due to rainfall.

Rainfall-Induced Slope Failures

Slope instability due to excess rainfall is a problem faced by many countries such as Philippines, Singapore, India, and Norway [15–17] during heavy monsoon period. To understand the mechanism of slope failure due to rainfall, various analyses have been carried out numerically, analytically and experimentally [18, 19]. Failures are directly related to the soil characteristics, slope angles, surrounding vegetation, rainfall duration and intensities. Rainfall pattern can occur in many ways; it can be high-intensity rainfall for a short time which can cause sudden slope failure due to the intensity and excess weight of the overburden soil. Low-intensity rainfall occurring for a long period of time can have the same effect due to the gradual change in pore water pressure of soil and seepage [6, 20]. As the matric suction or negative pore water decreases, the effective stress in the soil will be decreased and thus reduces the soil shear strength, eventually resulting in slope failure [21]. To thoroughly understand the mechanism of slope failure due to rainfall, in-depth studies have been carried out in the form of experimental and numerical analyses.

Experimental Investigation on Slope Stability

Experimental studies involve laboratory and field testing. A three-dimensional seepage flow model to analyze the slope stability and a standard water-phase flow model for seepage analysis were carried out with the experimental setup shown in Fig. 1 [18]. It was observed that the effect of air on seepage was found to be less significant on slope stability [18]. An experimental flume setup explained the phenomenon of retrogressive landslides. It was observed that after the infiltration of 80 mm/h rainfall, sequential slope failures were observed and these failures started at the toes of the slope and slowly moved toward the crest (Fig. 2) [22]. Proper slopes instrumentation can provide a better understanding on how the slopes will response to rainfall infiltration and evapotranspiration processes and their effects for a long period of time [23]. The behavior of partially saturated landslides was investigated using field investigations, laboratory investigations and numerical analysis in Seoul, Korea [24]. The initiation of landslide was caused due to a rainfall intensity of 112.5 mm/h followed by an antecedent rainfall of 306.5 mm/h lasting for around 16 h. The observed value of negative pore pressure at the ground was approximately 75 to 85 kPa and 20 kPa during dry and wet seasons, respectively [24]. The higher the slope angle, the erosion effect was greater and the loss of soil was more [25]. A schematic diagram of slope rainfall failure test device (SRFTD) is given in Fig. 3. Friction angle plays a significant role on the value of factor of safety (FOS). The stability of slope is increased when the friction angle is increased [26].

Numerical Analysis on Slope Stability

Numerical studies include the analysis of slope models using finite element-based software. Numerical analysis using the finite element method (FEM) has proven to be reliable. Strength reduction analysis in FEM is a very common and reliable approach [27–29]. One of its importance is that the slope stability analysis during rainfall or water infiltration can be simplified if the pore water pressure and matrix suction are computed by the transient seepage analysis by using the same finite element mesh [30]. A transient seepage analysis and slope stability analysis were carried out in order to be able to observe the action of slope during and after rainfall and to study the slope stability, respectively. A numerical evaluation of the actual slopes using real slope geometry, soil properties and GWT (groundwater table) was performed for different parameters [15]. Parametric research has also been carried out, and comparison of outcomes was performed with the findings from the numerical evaluation. The results show that the higher the rainfall intensity and higher the GWT, the lesser the soil shear strength. The analysis using continuous rainfall shows that the minimum factor of safety was minimum at 24 h of rainfall. Due to the presence of fine particles, the crucial slip surface is attained several hours after the rainfall stopped [15]. In order to understand the triggering factors of a progressive landslide, the behavior of stratified hill slope using a numerical simulation of the slope was investigated. The slope under study is slightly stable, and the factors causing slope failure were found out. Finite element-based evaluation of slope stability was effectively used for identification of different strata and water level existing on the distressed site. This evaluation was then validated by field reconnaissance inputs and real-time observations. Due to improper design,

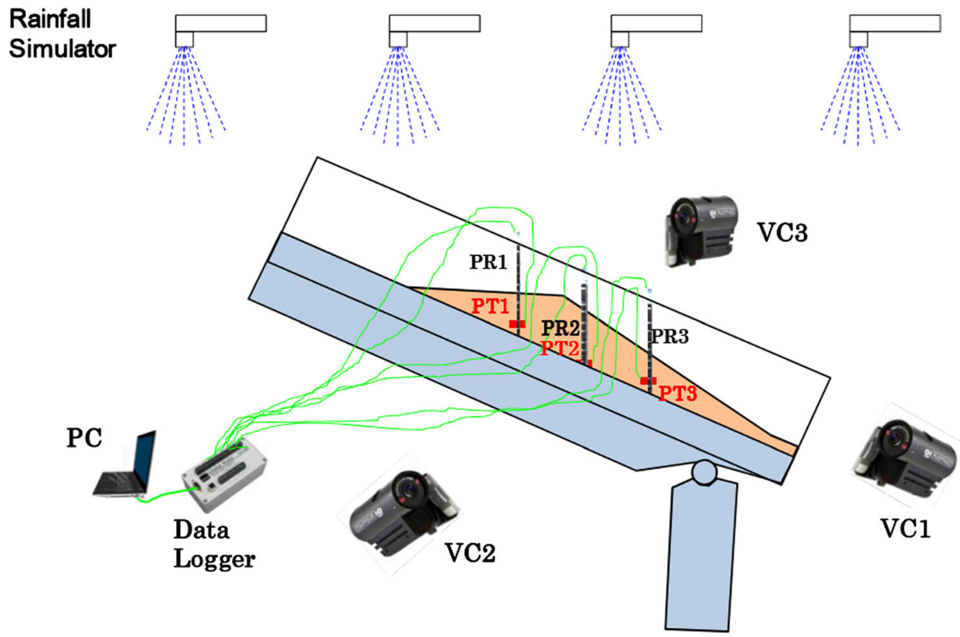

Fig. 1 Experimental setup of a slope subjected to rainfall [18]

Fig. 2 Photographs of retrogressive landslides [22]

planning and construction of the retaining walls, the slope movement was not stopped; instead, it delivered an extra backfill load adding to the slope instability. Flawed drainage plan rendered the toe drainage channel to be dysfunctional at the site [16].

One of the great impacts of climate change is the variation in rainfall patterns. This affects the ground surface flux and ultimately causes a possible slope failure. In case of heavy rainfall, proper drainage is critical. Even after rain stops, the FOS (factor of safety) keeps on decreasing [15, 31]; this is due to the continuation of seepage of water. Uncertainties in soil hydraulic properties and shear strength properties affect the stability and deformation of slopes [32, 33]. Excess pore water pressure was the main cause of instability of slope [34]. The presence of silt and sand in the soil matrix makes the area more vulnerable to rainfall-induced landslides [17].

In the year 2008, a retaining excavation failed due to heavy monsoon occurred in the month of June in Fujian, China. The retaining structures were soil nailing made up of steel pipe. Another wall was analyzed and constructed which is a soil-nailed wall using *moso bamboo* as a restorative measure which lasted during the severe rainfall in July 2008 [35]. The slope was 1:1 along which the excavation was done. The soil was divided into three layers: 1.5-m-thick miscellaneous layer, 0.9-m-thick silty clay layer and 17.6-m-thick sludge layer. PLAXIS 2D which is a finite element-based software was used for modeling and analyzing the slope. The stability analysis of the earth-retaining wall was carried out using the strength reduction method adopting a Mohr–Coulomb model using the soil parameters shown in Table 1. The potential slip surface is shown in Fig. 4b with factor of safety (FOS) of 0.87. With reference to the slip surface obtained, the earth-retaining

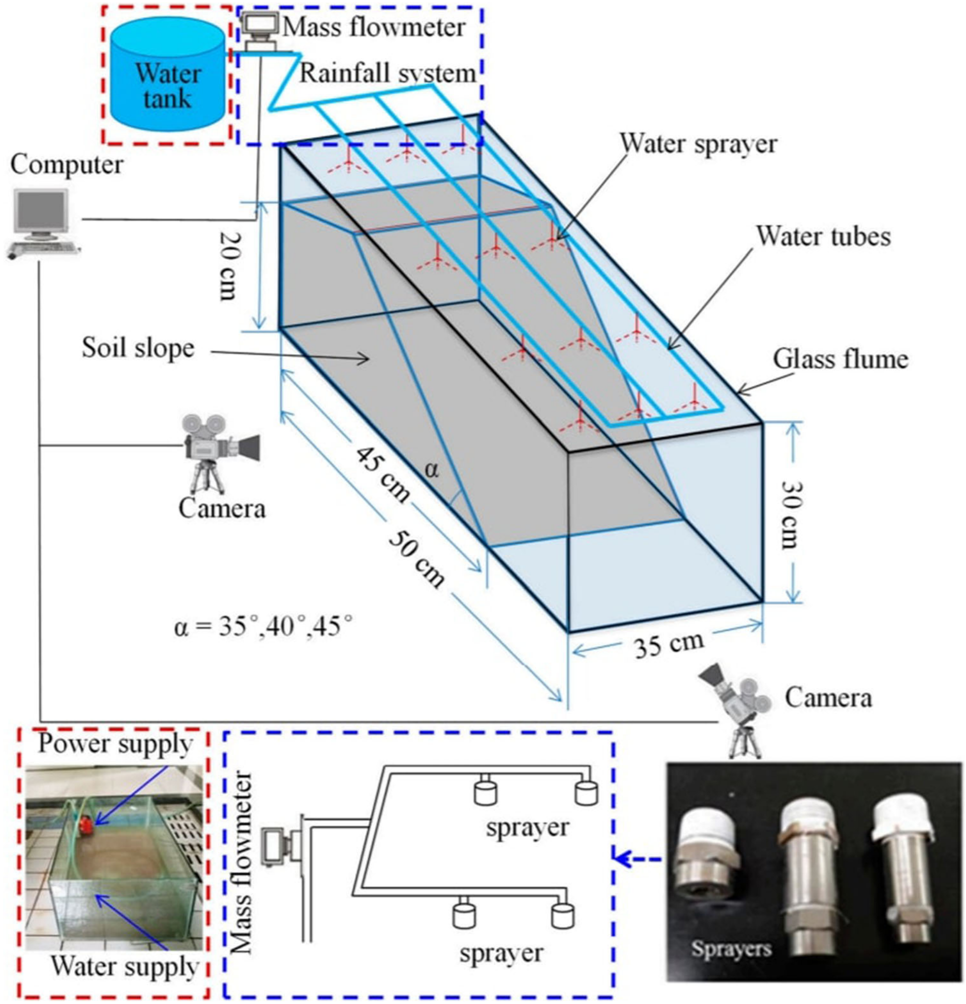

Fig. 3 Schematic diagram of slope rainfall failure test device (SRFTD) [25]

Table 1 Mohr–Coulomb model parameters of soils [35]

Soil type	Thickness (m)	Unit weight (kN/m^3)	Young's Modulus (kPa)	Poisson's ratio	Cohesion (kPa)	Angle of internal friction (°)	Reduction coefficient of interface frictional strength (R_{inter})
Miscellaneous fill	1.4–3.5	18	6000	0.3	7	7.1	0.67
Clay	0.5–3.1	17.5	7000	0.3	24.6	2.3	0.67
Sludge	14.5–21.8	16	500	0.4	9.3	6.7	0.67

wall was reinforced by placing steel pipes of 48-mm diameter in five rows (Fig. 4c) and installing nail spacing of 1.2 m and 0.8 m in transverse and vertical direction, respectively. The steel nails were of 12, 10, 8, 6 and 4 m with an angle of inclination of 10° to the horizontal. The reinforcement properties are given in Table 2, and the analysis gave an improved value of FOS of 1.06 (Fig. 4d). The increase of FOS from 0.87 to 1.06 shows a marginal increase in the ability of steel pipes to stabilize the slope, which can explain the field failure of the steel pipes to act as soil nails during heavy rainfall (aforementioned) [35].

A new wall was constructed, and as a remedy it was reinforced with single row (10 m length) and five rows of moso bamboo piles and soil nails, respectively. The nails installed were of 4, 6, 8, 10 and 12 m lengths in an opposite order to that of the steel pipes at inclinations of 10°, 15°, 20°, 25° and 30°, respectively (Fig. 4e). The properties of the *moso bamboo* used are shown in Table 2. The length of the bamboo used as single row piles is 10 m and at a

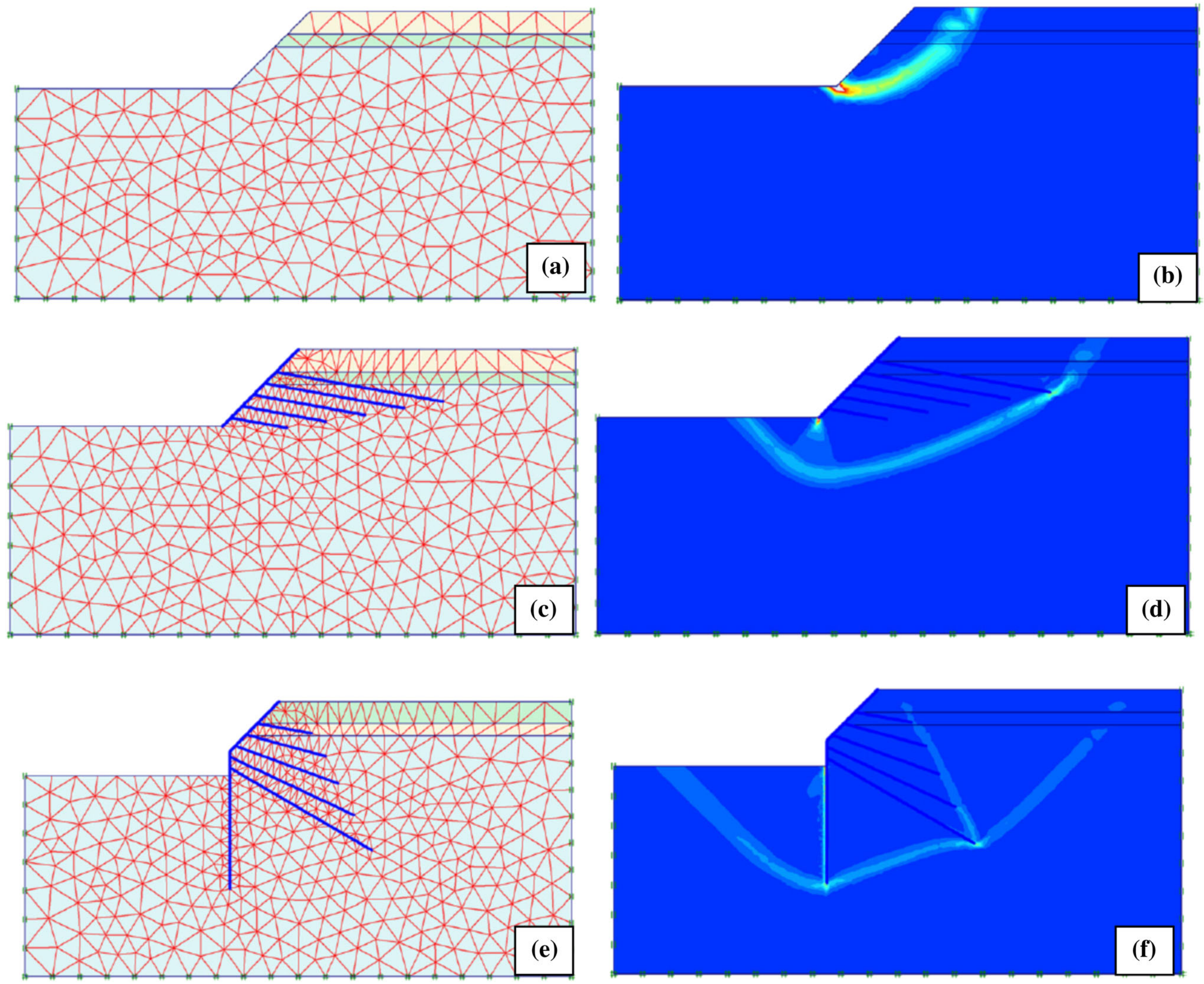

Fig. 4 Comparisons of slope stability analysis at critical state: **a** model without retaining structures, **b** contours of shear strain of model, **c** mode with steel pipe soil nails, **d** contours of shear strain of model, **e** model with *moso bamboo* soil nails and **f** contours of shear strain of model [35]

Table 2 Mechanical parameters of retaining structures [35]

Structural type	Elastic modulus (kPa)	Poisson's ratio	Sectional area (m^2)	Inertia moment (m^4)	Tensile stiffness (kN.m)	Bending stiffness (kNm^2/m)	Weight (kN/m/m)
Steel pipe soil nail	2×10^8	0.2	4.24×10^{-4}	1.08×10^{-7}	8.48×10^4	21.6	0
Moso bamboo soil nail	1×10^7	0.22	2.20×10^{-3}	1×10^{-6}	1.832×10^4	11.42	0
Moso bamboo pile	1×10^7	0.22	2.20×11^{-3}	1.37×11^{-6}	1.832×11^5	68.5	0
Concrete surface course	2.55×10^7	0.22	0.1	1.37×12^{-4}	1.832×12^6	2550	2.5

traverse spacing of 0.2 m. The analysis was carried out in PLAXIS 2D, and the value of FOS was 1.19 for the critical surface shown in Fig. 4f; it can be noted from Fig. 4f that the slip surface has increased in depth in comparison with that of steel pipes reinforcements. This result obtained was further verified when the on-field soil-nailed wall system remained intact during heavy rainfall. The new bamboo wall system actually enhanced the slope performance [35].

Slope Stabilization Techniques

Slope stabilization is achieved by reducing driving forces and increasing the stabilizing forces or both. Driving forces can be lessened by providing proper water drainage or excavation of the unstable part of the soil slope. Stabilizing forces are increased by stabilization of soil by adding admixtures or compaction, constructing retaining structures and ground reinforcements [36]. Soil improvement involves modification of engineering properties in order to strengthen the soil. Commonly used soil stabilizers are lime, cement, fly ash and fibers [10, 37–40]. Different slope-retaining structures used widely are masonry and mass concrete walls, reinforced concrete walls, gabion walls, crib walls (timber or concrete), sheet piles, king post walls, soil-nailed walls and geogrid or metal strip-reinforced soil walls. Slope reinforcements are in many forms using geosynthetics, soil nails, stone columns and reticulated micropiles. The construction of retaining walls, sheet piles, soil nailing, micropiles requires proper designing and skilled labor. Use of chemical additives and excessive use of cement-based structures can be harmful to the geo-environment. Use of cement and steel structures involves high energy consumption, emission of carbon materials: It also contributes to the pollution of the surrounding environment [41]. Abandoned steel pipes, concrete and steel bars are not easily disposable and can potentially disrupt any adjacent construction [35].

Preliminary work was carried out by analyzing a slope reinforced by piles of 1.2 m. Slope stabilization by excavating the sliding mass and providing pile retaining wall in Eskişehir, Turkey prevented soil displacements [42]. Landslides can be controlled by providing surface and subsurface drainage, retaining wall, shotcrete and anchoring of the excavated area by rock bolts [43]. Recycled plastic pins and modified moisture barrier can also be installed for stabilization of slope [44]. To prevent the excessive landslide in Western Alborz in north of Iran, it was proposed that a rigid retaining wall is to be constructed which is supported by shorter piles on the upper part of the mass (tied-back wall) [45]. Reinforcement techniques such as soil nailing [46, 47], shotcrete and rock bolts are harmful to the geo-environment. This leads to the search of other sustainable and reliable options like bamboo. The use of bamboo as an alternative material for slope reinforcement is widely adopted in many countries [35, 48–52]. The potential of bamboo as soil reinforcements can be realized from the facts that it sustainable, reliable, flexible, eco-friendly, economical, etc. It can be widely used in various forms, and it is applicable to many types of soil. Bamboo is a biodegradable material, hence widely used for temporary slope stability. However, proper treatment and preparation of bamboo can make it more durable and it can last for a very long time. Bamboo is naturally available in a fibrous form making it tensile; hence, it can resist more tension [12, 53].

Use of Bamboo for Slope Stabilization Techniques

The use of eco-friendly, energy efficient, locally available slope stabilizing techniques is the need of the hour. This can be partly achieved by extensive use of bamboo as a reinforcing material. In this section, the applicability of bamboo in different soil types, its strength and the different physical forms that it can be used is widely discussed.

Types of Soil

The use of bamboo is sustainable and eco-friendly and can be adopted to many types of soil. A laboratory trail for bamboo as a reinforcement in a lateritic soil was done by Mustapha in 2008. Peat soil having low shear strength, low bearing capacity and high compression has also been improved by using different layers of bamboo reinforcements [54]. Expansive soils like black cotton soil possess a serious threat from geotechnical point of view. Black cotton soil samples collected from Tamil Nadu were reinforced by bamboo fibers leading to the increase in the soil strength [55]. A CBR tests was conducted to study the improvement in the properties of clayey silt soil when mixed with bagasse ash and reinforced with the bamboo grid [56]. Soft clay can be reinforced using bamboo cells and geocells [12]. Soft clay has low shear strength and high compressibility making it vulnerable to settlements, and bamboo has a great potential to be used as reinforcement [52]. Bambusa *tulda bamboo* species can be used in the form of fibers to reinforce poorly graded sand found in Arunachal Pradesh [57]. Bamboo woven in bidirectional (square aperture) and tridirectional (hexagonal aperture) patterns can be used to reinforce river sand [58].

Bamboo Strength and Treatment Techniques

Studies have proved that compressive strength of bamboo is 2–4 times more than the value of many species of timber. It is also worth noticeable that bamboo with high moisture content has a compressive strength lower than bamboo with low moisture content. The average tensile strength of bamboo is found to be 3 times higher than most conventional construction grade timbers [59]. Table 3 shows the different mechanical properties of different bamboo species in green condition and when it is air-dried [60].

Bamboo is applicable in soil bioengineering applications due to its low shrinkage, good physical and mechanical properties and good average density [61]. In case of

Table 3 Physical and mechanical properties of Indian bamboos (in round form) [60]

Species	Properties							
	In green condition				In air-dry condition			
	Density (kg/m^3)	Modulus of rupture (N/mm^2)	Modulus of elasticity (N/mm^2)	Max. compressive strength (N/mm^2)	Density (kg/m^3)	Modulus of rupture (N/mm^2)	Modulus of elasticity (N/mm^2)	Max. compressive strength (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	10.5	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	–	–	–	–

bamboo structured in the form of geocells and geogrids, the tensile strength can mobilize with low strain of less than 3%. However, for geocells and geogrids larger strain is required to mobilize maximum tensile strength (more than 10%). Due to this, bamboo cell and bamboo grids applications are limited to small strain problems [12]. Bamboo has more tensile strength than geocells and geogrids. Bamboo has ultimate strength 10 times more than that of commercially available geocells and geogrids even with the same density [12]. Table 4 shows the different properties of geocell, geogrid and bamboo [12]. Bamboos are easily degradable; hence, it does not last for a long time, due to which the topic of bamboo treatment arises. For bamboo to be used as reinforcement for rainfall-induced slope failure, it is of utmost importance that it is treated properly. Many techniques are available for bamboo preparation [12, 53, 62–67]. Bamboos treated at 180 °C for 1–2 h and then cooled in sunflower oil at 20 °C give the maximum performance level [62].

Under moist condition, natural bamboo can be durable up to 5 years [59]. The preservation techniques that are used basically depend upon the dry or the wet condition of the bamboo. For fresh bamboo treatment, methods include sap displacement method, soaking process and diffusion process. In case of dry bamboos, soaking, pressure impregnation and hot and cold process are some of the treatment process used [63]. Many geotechnical researchers are seeking the use of bamboo as a sustainable method

Table 4 Properties of geocell, geogrid and bamboo [12]

Sl. No.	Properties	Geocell	Geogrid	Bamboo
1	Ultimate tensile strength (kN/m^2)	20	20	253
2	Density (g/cm^3)	0.95	–	0.97
3	Species	–	–	*Bamboosa bambos*

of reinforcements [12, 64]. Bamboo possesses a high prone to attack by biological organisms. The degradation with time is a high concern to geotechnical engineers when they want to use bamboo as reinforcement. This biodegradation can occur in the form of insect attacks, moisture, fungi attacks, etc. Preparation of bamboo before using it as a reinforcement of any kind is vital in order to make it long lasting, have high strength and high structural performance. The proper treatment of bamboo is very effective against the fungi attacks, termite attacks and other insects' attacks. Bamboo reinforcements can be treated with boric acid and borax solutions [68]. It can be treated by drying in air, greenhouse, oven-dried or fire [69]. Soaking technique can be adopted for treating the bamboos due to its simplicity and efficiency. The soaking method involves air-drying the bamboo grids first and immersing them in a preservative solution for a fixed duration of time [12]. Chemical solutions such as boron-containing compounds, CCA (copper–chrome–arsenate) and copper–chrome–boron are used as preservatives. For preservation of dry bamboo, CCA is commonly used which is a composition of copper, chromium and arsenic. Copper and termites effectively act against fungi and insects, respectively. The bamboos to be used are first immersed in CCA for 7 days and then dried in the sun before use [53].

The reaction of *moso bamboo* was studied when it is treated with Tung oil at 100 °C, 140 °C, 180 °C and 200 °C for 3 h, respectively [65]. The properties of the *moso bamboo* were modified after treating in heated Tung oil, and the physico-mechanical properties of *moso bamboo* were investigated. The changes in density, chemical compositions and cellulose crystalline should eventually cause a change in the mechanical properties of the bamboo. The mechanical properties of the bamboo, such as ultimate stress, modulus of elasticity (MOE) and modulus of rupture (MOR), remained the same even after treatment. At a temperature of less than 140 °C, no notable changes occurred in the ultimate strain, but over a temperature of 180 °C it decreased [65]. It was found that after treatment, the mechanical properties were higher than the untreated bamboos, and the bamboo was stronger and stiffer but more brittle. Tung oil heat treatment has proven to be an economic and environmentally friendly way of treating bamboos [65]. Bamboo samples can also be air-dried and prepared according to the procedure highlighted in part 1 of BS 1377 (1992) [66]. Different techniques were adopted to treat bamboo as presented in Table 5. Treatment in different types of oils and heated at various temperatures and air-dried in oven are presented in the table (Table 5). The results show that bamboos treated at 180 °C for 1–2 h and then cooled in sunflower oil at 20 °C give the maximum performance level [62].

The durability of the bamboo can also be improved by using bitumen coating. The bitumen-coated bamboos are used as reinforcement and tested in laboratory in the form of grids of 1-cm diameter. A test tank of 28 cm × 28 cm × 30 cm in volume was made of iron plates of 6-mm thick, and an iron plate of 10 cm × 10 cm × 0.6 cm was used as a footing. A pre-calibrated proving ring having maximum capacity of 2 kN was used as a measuring. Dial gauge fixed at the top of the foundation was used to measure the settlements taking place at the top of the foundation. Three reinforcements were used (i) geogrid, (ii) bamboo grid coated with bitumen and (iii) bamboo reinforcement coated with bitumen. About 20–30% reduction in settlement was observed when the soil was reinforced with bamboo. It was also observed that bamboo reinforcements serve as a better reinforcement compare to geogrids [67].

Bamboo as Soil Reinforcements

Bamboo possesses a flexible nature which enables it to be made or weaved in many forms. Bamboo has been used in the form of fibers or chips, grids, mats, strips, bamboo cells, crib walls, fencing or walls and also in the form of plates and sticks. These different physical forms of bamboo will be discussed in this section.

Bamboo Fibers or Chips

Toyoura sand of 15% water content was used with a combination of Portland cement to make test specimens. This mixture was combined with bamboo chips as shown in Fig. 5. Before using, the bamboos were boiled and dried for 1 h. The results showed that curing days of 28 days gave the maximum improvement in the soil compressive strength and the more the quantity of cement the better is the performance [70]. Compaction tests conducted proved that the inclusion of bamboo fiber improved the performance of black cotton soil. The most efficient percentage of mix of the bamboo fiber was found out to be 1% by weight. The increase in strength was maximum when bamboo fiber percentage was 1% [55]. Bamboo when used as reinforcements in the form of fibers of length 20 mm and 30 mm shows that longer fibers give better performance than shorter fibers [57]. Bamboo chips of sizes 6 mm and 10 mm were used. Different bamboo sizes have their own advantages: Bamboo chips of 10 mm improve the strength of the specimen even in small amount and 6 mm bamboo chips improved cement and water reaction due to its small size. The presence of cement improves the results much better in comparison with bamboo chips; hence, bamboo chips cannot be used as cement substitute.

Table 5 Bamboo treatment techniques [62]

Set	Subset	Treatment method	Treatment duration (h)	Cooling medium	Cooling duration (h)
1	1a	Flax oil, 100 °C	1	Flax oil, 20 °C	24
	1b		2		
	1c		3		
2	2a		1		1
	2b		2		
	2c		3		
3	3a		1		12
	3b		2		
	3c		3		
4	4		2		72
5	5a	180 °C in oven	1		24
	5b		2		
	5c		3		
6	6a	100 °C in oven	1		24
	6b		2		
	6c		3		
7	7a	Sunflower oil, 100 °C	1	Sunflower oil, 20 °C	24
	7b		2		
	7c		3		
8	8a	180 °C in oven	2		24
	8b		2		
9	9a	100 °C in oven	1		24
	9b		2		
	9c		3		
10	10a	Sunflower oil, 180 °C	1		24
	10b		2		
	10c		3		

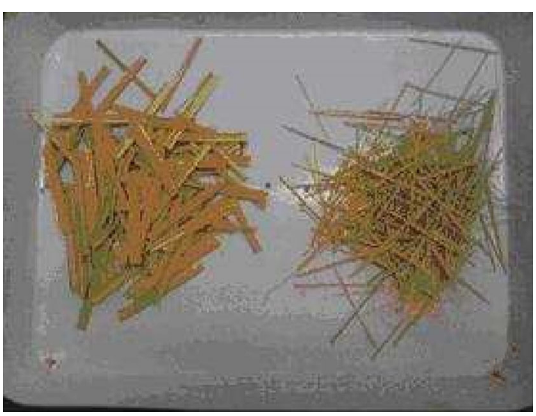

Fig. 5 Bamboo chips [70]

However, an additional strength was observed for cemented sand after the addition of bamboo chips [71].

Bamboo as Soil Nails or Pile

To understand the different properties of bamboo materials, laboratory tests and numerical analysis were performed to analyze the settlement of bamboo pile. When a load of 5 kN was applied, both numerical analysis and experimental results show that the settlements were least when bamboo pile was 30 cm long [48]. Laboratory test was performed to check the bearing capacity and the maximum load that the slope can withstand with and without reinforcement [49]. The soil used is finely graded sand, and bamboo piles of different sizes at different spacings were used as reinforcements for the slope. It was observed that the maximum increase in bearing capacity was observed when pile diameter was 45 cm. The most acceptable spacing was 7.5 cm, at which the bearing capacity increase reached the maximum point [49, 50]. *Moso bamboo*s were used as soil nail reinforcements to stabilize a wall situated in Fujian, China [35]. The bamboos used serve as a good replacement of steel bars and steel pipes as soil nails due to its environment-friendly nature. The inclusion of bamboo piles increased the stability of the excavated area by deepening the slip surface of the slope. A numerical analysis validated the reliability of bamboo as pile system [35]. Slope stability analysis was carried out on a slope located in Indonesia. The analysis was carried out for slope with and without reinforcements. The observed value of safety factor of the slope without using any reinforcement under natural condition was 1.32. The soil was further analyzed using bamboo pile reinforcements, and the value of factor of safety increased to 1.77–1.87 [51].

Bamboo Grids or Mats

Bamboo grids increase the bearing capacity of peat soil supporting a shallow foundation. When the grids are placed at the base of the foundation, the bearing capacity was increased by 140%, 224% and 279% for one layer, two layers and three layers of bamboo reinforcements [54]. A comparative study between high-strength geotextile (HSG), bamboo-geotextile composite (BGC) and an unreinforced (UR) embankment constructed on soft clay soil was performed. The settlement of BGC embankment shows that, compared to UR embankment and also HSG embankment, the BGC has enhanced the soft soil much better. The bamboo square pattern takes the load from the backfill material for the BGC system and therefore reduced the settlement much better than others. Bamboo's hollow section enables the trapped air inside the bamboo and gave the effect of buoyancy, thus distributing small load of embankment to the soft clay layer [72].

Local bamboos were used in the form of bidirectional (square aperture) and tridirectional (hexagonal aperture) grid patterns (1-mm thick and 3-mm wide) (Fig. 6) [58]. The effect of the bamboo grid on the bearing capacity of soil vanishes when the reinforcements were placed at a distance more than 0.5 times the footing width. The optimum increase in the bearing capacity of soil was observed to increase by a factor of 2.5 to 3.0. The reduction in the settlement of soil was 47% for bidirectional bamboo grid reinforced sand and 53% for tridirectional bamboo grid [58]. Bamboo reinforcements in the grid form of 1 mm thickness and 10 mm width were used, and direct shear tests on fly ash and on fly ash with bamboo geogrid were done [68] to understand the interaction mechanism between fly ash and fly ash and in between fly ash and bamboo geogrid (Fig. 7). When bamboo grid was used, the interface friction angle for molding water content of 10% and 20% molding was 25° and 19.2°, respectively, and the interface efficiency (Ci) for both cases was 0.71 and 0.66, respectively. These values show that there is a good bonding between fly ash and bamboo geogrid. However, 10% water content shows that fly ash can be more efficiently use as a backfill material in retaining wall application and bamboo geogrid as reinforcement [68].

To understand the behavior of bamboo–geogrid reinforced fly ash walls when subjected to uniformly distributed loading (UDL) conditions, a series of model experiments were carried out in a laboratory. Variability in the length, vertical spacing and coverage ratios of bamboo–geogrid reinforcement were applied to understand their influence on the backfill settlement, surcharge failure and horizontal displacement of the facing. For the model study, bamboo geogrid was used as reinforcement in the form of mattresses and strips (Fig. 8) prepared in the laboratory [73]. Five different bamboo species from five different places and reddish fine lateritic soil were located from Nigeria (Lapai Local Government Area of Niger State). Reinforcements were placed in five layers (Fig. 9). Maximum ultimate bearing capacity was observed at two layers of reinforcement. The fourth and fifth bamboo layers did not show any significant effect; this is due to the fact that the pressure bulb does not cross the last two layers [74]. Two experimental flumes were set up in a laboratory and designed to test two situations, i.e., interrill experiments

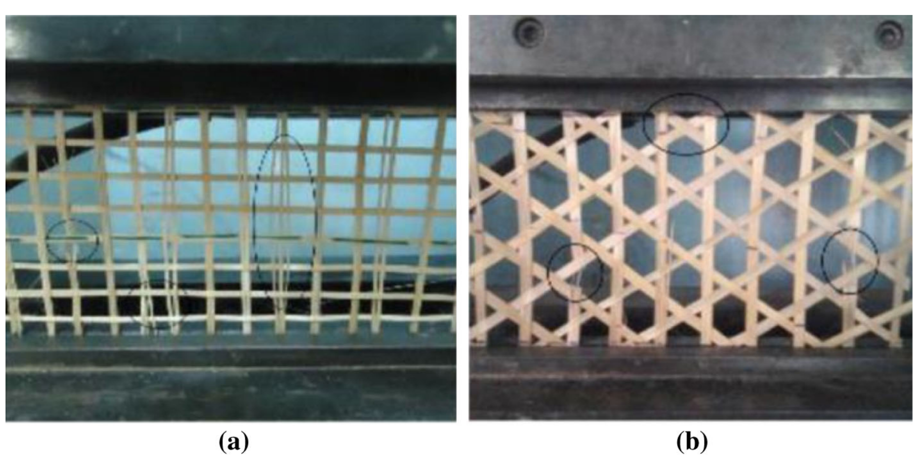

Fig. 6 **a** Bidirectional bamboo grid and **b** tridirectional bamboo grid [58]

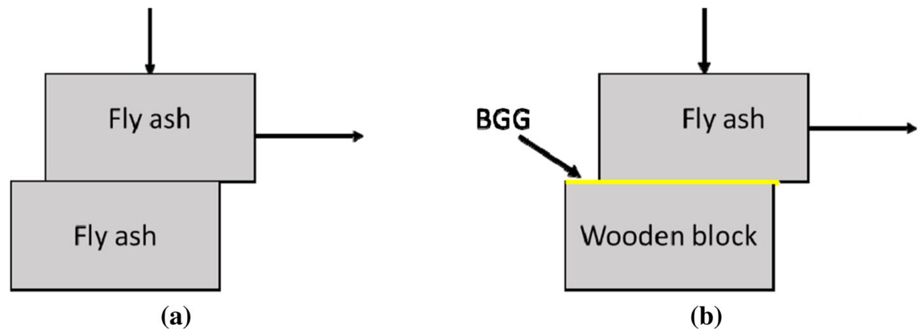

Fig. 7 Direct shear tests for **a** fly ash to fly ash and **b** fly ash to bamboo geogrid (BGG) [68]

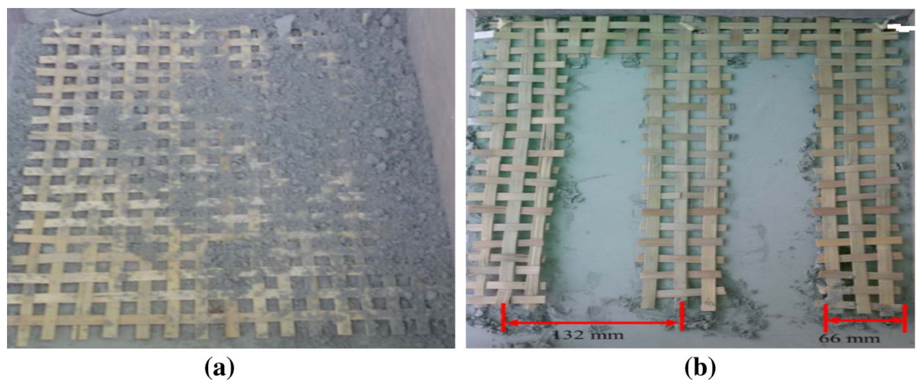

Fig. 8 Placement of reinforcement in the model tank: **a** bamboo–geogrid mattress, **b** bamboo–geogrid strips [73]

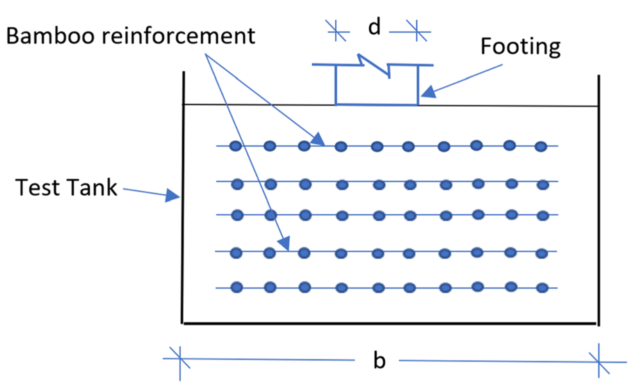

Fig. 9 Arrangement of layers of bamboo reinforcements [74]

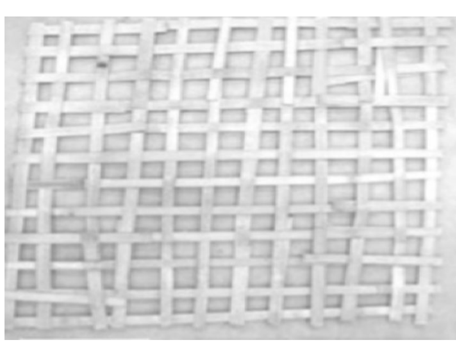

Fig. 10 Bamboo grid [75]

and concentrated flow experiments. Biological geotextiles were used in these tests in which bamboo was used in the form of grids (Fig. 10). The results showed that there is a reduction in the depth of surface runoff and the soil loss rate when the biological geotextiles were used and a reduction in mean of 46 percent and 79 percent was observed in comparison with the values for soil without geotextiles, respectively [75].

The interaction between the soil and reinforcements was studied by conducting shear test and pullout test, and it was found out that the resistance of the bamboo grids (Fig. 11) in clayey and weathered clay was more than that of the Tensar SS2 geogrid [76]. A foundation mat below a breakwater prevented settlements in a muddy area located in the west coast of Peninsular Malaysia. Figure 12 shows that the culms were trimmed to 3 m length and tied together with the help of ropes. Observations show that primary consolidation was completed 16 months after the completion of construction and no differential settlements were observed throughout the observations, which show the integrity of the foundation mats [77].

A ‘geobamtile’ system and its method of construction are presented in Fig. 13. Geobamtile system is a form of raft or mat foundation which is formed by tying together matured bamboo culms with galvanized iron each of 5 m length to form a grid network. The gestation period is reduced with the application of geobamtile system over soft ground and proved to perform better than the commonly adopted methods like piled embankment, lightweight polystyrene blocks, etc., which are expensive and

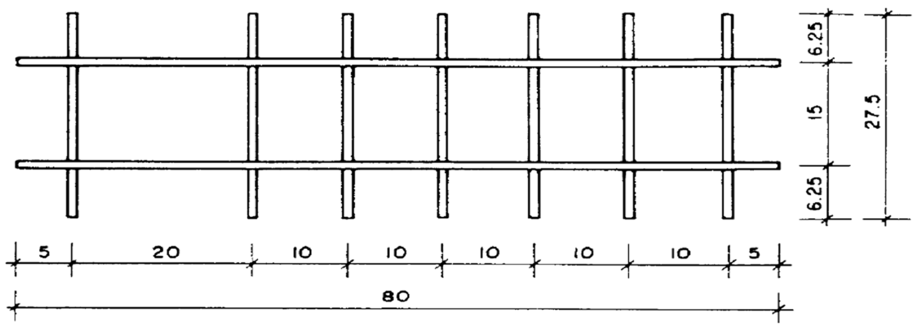

Fig. 11 Bamboo grids used in pullout test (Units are in centimeters) [76]

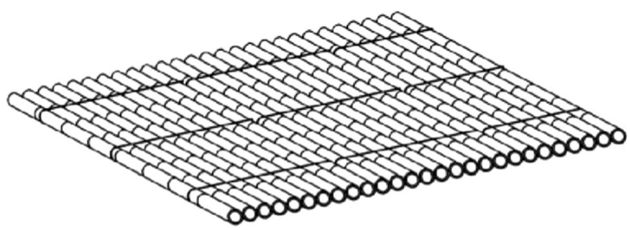

Fig. 12 Bamboo foundation mat [77]

Fig. 13 Geobamtile system [78]

time-consuming [78]. Application of woven and nonwoven geotextiles to stabilize a fill deposition over a soft soil has proved to be effective [66]. Bamboo fascine mattresses are used to act as an easy working platform while laying the geotextile. The geotextile must directly roll over the bamboo fascine. The factor of safety increases against bearing capacity failure [79].

Bamboo Cells

A laboratory experiment for doing a comparison study between different types of reinforcements was performed by doing plate load test on a clay deposit when it is unreinforced and reinforced with commercially available geosynthetics and natural reinforcement material. Natural reinforcements include the use of bamboo in the form of three-dimensional (3D) cells which are similar to geocells (bamboo cells) and two-dimensional (2D) grids which are similar to geogrids (bamboo grids). The bamboos were first cut into 20-mm-wide strips to a specific length and are woven together to form a grid using galvanized wires. These bamboo grids are tied together to form bamboo cells (Fig. 14a). The use of geocell and geogrid as combined reinforcements increased the clay bed bearing capacity by six times. The use of bamboo grid and bamboo cell increased the ultimate bearing capacity of the clay by 1.3 times more than that reinforced with the commercially available geocells and geogrid. It was also observed that the footing settlement was substantially decreased. Tensile strength and surface roughness of bamboo were found to be 9 times and 3 times more than the values of geocells materials, respectively [12, 53]. Bamboo cells have tensile strength 9 times higher than geogrids and geocells. It was observed that the settlement was decreased with the inclusion of the reinforcements. A clay bed reinforced by combination of bamboo grid and bamboo cell has the ultimate bearing capacity 1.2–1.5 times higher than that reinforced by geogrid and geocells [12].

Bamboo Walls

World Bank of India in collaboration with the state PWD of Mizoram used bamboo as a bioengineering material to stabilize many unstable slopes in the state of Mizoram, India. Bamboo terracing, bamboo crib walls and bamboo knitting and bamboo matting were developed to suit the requirements of each slope [52]. Along the shore of Danav Khola riverbanks, Nepal bamboo vanes were built and vetiver (*Vetiveria zizanioides*) seedlings were planted over the slope. After monitoring, it was observed that when monsoonal rain came, bamboo vanes with sand bags provided resistance to the forces at the toe of the bank due to floodwater and the vetiver saplings were almost washed away by the floodwater. In this case the main problem existed at the bank slope of the river, a staggered pattern of bamboo palisades could be installed over the slope. In this way, bamboo culms will serve as a protection to the vetiver plants from both the floodwater drag forces and the runoff erosion effects [61]. Figure 15 shows the proposed design

Fig. 14 Photographs: (a) bamboo cell and (b) geocells [12]

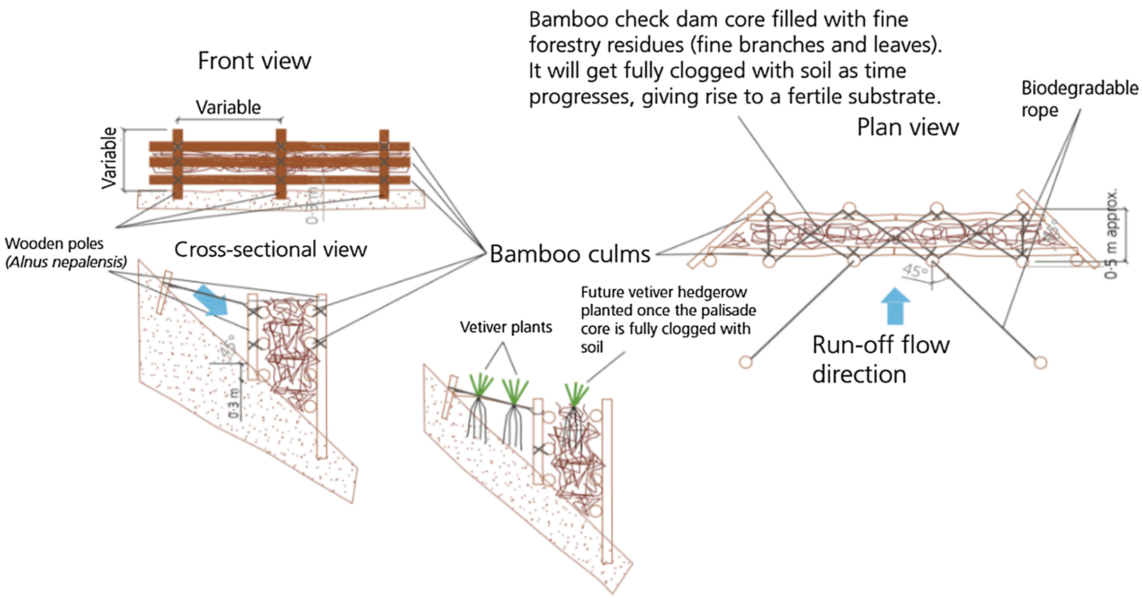

Fig. 15 Bamboo check dam general arrangement [13]

comprising of two palisades made of horizontal bamboo culms and vertical wooden poles [13]. This proved to be a resilient and sustainable soil reinforcement system. As the vegetation grows, the effectiveness of vegetated crib walls also increases overtime. The structural function of the whole system was improved, once the plants become established. The wooden-supported structural integrity was then gradually replaced by the growing vegetation [80]. To increase the slope instability, the crib walls are usually installed at an inclination of 10°–15° toward the slope [13]. Bamboo fencing was adopted as one of the bioengineering techniques in Hindu Kush Himalayas. The fencing was used to prevent soil erosion (Fig. 16), to hinder gully extension and to control flood waves along a river bank. For the main posts, live bamboo pegs are usually used, making the whole structure to be rooted. The slope sediments are trapped with the help of the bamboo fencing, and the surface runoff is also reduced due to the improved vegetation nearby [81].

Bamboo in Other Forms

Bamboo in the form of circular plates has been tested as reinforcement to a lateritic soil. The bamboo plates were tested to find the unconfined compressive strength of the soil. Tests were conducted for plates of zero layer, one layer, two layers and three layers. When no bamboo was placed, the unconfined compressive strength was 226 kN/m^2 and it increased to 621 kN/m^2 when there are three layers of bamboo plates [82]. Using CBR test, different layer systems of bamboo sticks as reinforcement at varying depth (i.e., 0.75 inch, 1.5 inch, 2.25 inch) were taken for different footing dimensions (i.e., 3 × 3 inch, 3.5 × 3.5 inch, 4 × 4 inch). The orientation of the multilayer system was parallel–perpendicular–parallel. Soil reinforced with single-layer reinforcement shows an increase in the load bearing capacity up to 1.77 times, and for multiple-layer-reinforced soil the increased was 2.02 times higher than that of an unreinforced soil [83].

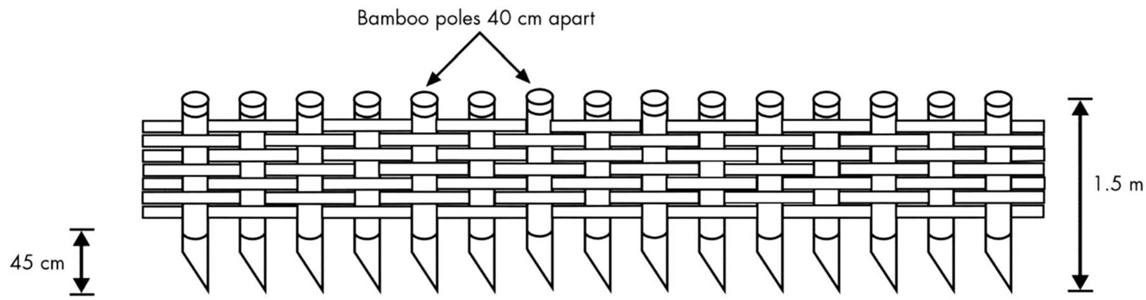

Fig. 16 Sketch of bamboo fencing [81]

Vertical geogrids and bamboo sticks are used as reinforcing elements for a foundation. A model strip footing with length, width and height measurements of 610 mm, 102 mm and 460 mm, respectively, rested on a reinforced sand subgrade. It is recommended that reinforcements should be placed at a distance of 0.5B (B = width of the footing) from the center of the footing. The bamboo sticks should be provided at both sides of the footing and driven vertically [84]. A direct shear test was conducted following ASTM D3080 on a soil reinforced with *Apus bamboo* roots. Some modifications on the size of the direct shear box (11 cm × 11 cm × 11 cm) were done in order to accommodate large samples. A pullout test was conducted using a screw jack. The upper box was moved horizontally using the screw jack and at a displacement rate of 0.8 mm/min. The soil-root volume ratio shows that the peak shear strength was increased up to 55% [85].

A numerical simulation was performed on an existing area situated in Taiwan which is a forest consisting of *Makino bamboo*. The slope under study has landslide problem despite the presence of bamboo plantings. An investigation was carried out to check the characteristic shear strength of soil-root system of the slope. The resulting simulation shows that there is a very less contribution of the *Makino bamboo* to the slope stability. The main factors responsible for the instability of the slope are the wind loading on the bamboo culms and the rainwater infiltration during monsoon period [86]. Mohr–Coulomb failure mode was used in the numerical analysis of the slope, and the root system was simulated modeling a linear elastic material. The result shows that there is an increment in the strength of the soil rooted by *Makino bamboo*. However, the results also show that influence of the soil-root system was not effective when the soil slope is steep (50°–70°) and when the depth of the bamboo roots were shallow (0.8–1.0 m) and the height of the bamboo was large (> 10 m). Hence, it can be speculated that the effectiveness of the *Makino bamboo* roots was limited medium slope (25°–40°). The contribution was also limited due to high rainfall intensities during monsoon period and when there is a high wind load [87].

Case Study: A Project in Mizoram

Landslide occurrences are very frequent in various states of India. Northeast India is surrounded by Himalayan Mountain Belt in the north, Shillong Massif Plateau in the south and Indo-Myanmar Range in the east [88]. Sikkim is one of the states located in the Himalayan region which is susceptible to geo-hazards such as landslides due to earthquake and rainfall [89, 90]. North Sikkim average annual rainfall is 3333.7 mm (2010–2016). The rainfall pattern of Sikkim, especially in the eastern Himalayan side, plays a significant role in initiating and activating of landslides. Empirical methods were used to assess the rainfall threshold causing landslide in Sikkim. In the year 2016, during heavy monsoon period, National Highway No-44 (NH-44) was blocked due to landslides causing huge boulders to cover the road causing road blockade [91].

A state project was carried on by World Bank in the state of Mizoram which is located in Northeastern part of India to stabilize hillsides which are prone to landslide. Mizoram is a state of high altitude where slope stability is a serious problem when constructing hill roads. The geology of the area consists of soft rock and immature formation; this type of formation together with the region receiving high precipitation, it is critical for slope stabilization at the top and bottom of the road. An investigation done identified 100 locations prone to landslides along a stretch of 164 km. Mizoram's residents used the soil slopes for agricultural purpose; hence, on top of stabilizing the failed slopes it was also important to come up with a solution which will help in retaining the fertility of the hill slopes and also protecting the biodiversity of the surrounding environment. World Bank team conducted a project which makes use of bamboo to stabilize the hill slopes by combining the techniques used by local residents with new technical ideas from Rural Access Project (RAP) in Bhutan [52].

Bamboo structures were built in different ways to tackle different slope failures. These structures were in the form of bamboo crib walls, bamboo knitting and bamboo terracing. Figure 17 shows a slope stabilized with bamboo

Fig. 17 **a** Bamboo wall for slope stabilization and **b** the bamboo works remained stable even during fierce monsoon rains in 2007 (Mizoram) [52]

walls which are built stepwise across the length and breadth of the slope. The whole bamboo culms were used to strengthen the soil, and they were placed vertically and horizontally to form bamboo fences. Bamboo was also knitted and used as shown in Fig. 18. In this case, bamboos were placed on top of the slope to form a grid pattern. The knitted bamboo provided a short-term stabilization to the slope. To further strengthen the slope locally, grown flora was planted on top of the knitted bamboo. This process allows the plants to grow while the bamboo structure retained the soil during rainfall [52].

Summary of Important Findings

Bamboo is mostly available in the tropical, subtropical and temperate regions of the world [92] and therefore can be extensively used. During growing season, bamboo has a very high growth rate of 30 to 100 cm per day. It requires around 3–5 years to grow into matured culms and to be ready for harvesting [93–95]. Bamboos are naturally straight and hollow, have light mass and have high strength culms which make them acceptable for structural applications. It has many acceptable properties such as high strength, flexibility and easy availability in some areas and faster growth. The tensile strength and compressive strength of bamboo are much higher (i.e., three times and two to four times, respectively) more than some of the commonly used timber species used as reinforcements [59]. They can be used as a replacement for timber due to its good physical and mechanical properties [13]. Bamboo can be effectively used as reinforcement to different types of soil, i.e., lateritic soil [82], peat soil [54], black cotton soil [55], clayey silt [56], soft clay [72], poorly graded sand [57] and river sand [58].

Fig. 18 Construction of bamboo knitting structures and plantation of local species of flora in progress [52]

Bamboo can be used as a reinforcement to prevent rainfall-induced landslides. Rainfall can make the bamboo more susceptible to decay; hence, proper treatment and preparation are necessary before utilizing it. In case of real-time field application, a large-scale treatment process is required. The use of oils [62, 65] can be a very effective and efficient way of treatment as it is environment-friendly and sustainable treatment process. The use of chemicals [53, 68] and drying process [69] can be toxic, expensive and non-eco-friendly treatment process and can result in loss of great amount of energy. Hence, more research is required to be carried out to find more economical, environment-friendly and sustainable treatment processes and other alternatives for treatment of bamboo. Oil treatment is cost-effective, eco-friendly and sustainable; hence, it is considered to be one of the good options to use for bamboo treatment [65].

Due to its flexibility, bamboo has been used as reinforcements in different forms by different researchers all around the world. The random inclusion of bamboo chips in soil increased the shear stress by 4% [57], and the most efficient mix with black cotton soil was found as 1% by weight [55]. However, on-site application of bamboo chips and fibers has not been extensively studied. This can be due to its low potential as a slope stabilizing agent. Bamboo has been extensively used in the form of soil piles and soil nails [35, 48–51]. M*oso bamboos* (i.e., a particular Bamboo species) were used as pile reinforcement. This bamboo species has diameter more than that of the commercially available steel bars and pipes and natural effective length of 6 m to 14 m. Due to its reliability, cost-effectiveness and limited negative effects on the surrounding geo-environment in contrast to steel soil nails, it is highly recommendable to be used as a temporary reinforcement material [35]. The soil settlement was also reduced in different proportions when bamboo was used in the form of bidirectional and tridirectional grids, mats and bamboo cells [12, 58, 74, 77]. The use of bamboo in the form of geogrids and bamboo cell increases the overall tensile strength of bamboo [12].

Bamboo in the form of grids and mats is useful when the top soil of the slope needs protection from washing off due to rainfall. In the meantime, this will allow the plants to grow on top of the protected soil slope [52], thereby providing permanent slope stabilization. The ultimate bearing capacity of the clay was 1.2 to 1.5 times higher when bamboo grid and bamboo cell were used compared to commercially available geocells and geogrids. Bamboo cells have tensile strength higher (i.e., 9 times) than geogrids and geocells [12]. Bamboo cell and bamboo grids cam be used as a replacement for on-field application in place of the commercially available geocell and geogrid, hence an environment-friendly approach. For rainfall-induced landslides, the use of bamboo in the form of fencing or walls has proven to be effective [52]. Crib walls made up of bamboo can be used as an alternative to gabion and masonry retaining walls [13]. However, the excess number of bamboos to be used for constructing crib walls can be expensive due to the treatment processes involved. Hence, the use of freshly cut green bamboo is preferable for crib wall construction.

Conclusion

Following conclusions can be made from the review work done.

1. Bamboos have proven to have a great potential to be used as soil reinforcement. The use of naturally available elements such as bamboos in engineering structures will reduce carbon emission and cost of structures [13].
2. From the literatures studied, it is clear that one of the main disadvantages of using bamboo as remedial measure for rainfall-induced slope failures is that it cannot be used as permanent slope reinforcement because it is prone to termites and fungus attacks. It is only applicable for the construction of temporary structures.
3. The bamboo treatment process is of high cost and time-consuming. Even if the bamboo is carefully and properly treated and seasoned, it is not possible for it to achieve sufficient strength to be used as a permanent solution for slope stabilization, especially in rainfall-induced slope failures.
4. Proper study of the slope stability requirement is necessary before recommending bamboo to be used as a solution. It is suggested that numerical and analytical studies are made before considering bamboo as a remedial measure.

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