Influence of Plant Roots On Slope Stabilization: A Geotechnical Investigation

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Abstract

Direct shear tests conducted on soil samples reveal that soils with plant roots show an increase in cohesive factor but increase in frictional angle is insignificant. Displacement and shear strength graphs, however, indicate that soil with plant roots can withstand more shear stresses. Among the three plant species selected for the present study, *Chimonobambusa sp.* has the highest shear strength increment, $\Delta C = 5.0 \text{ KN/m}^2$ followed by *Cymbopogon sp.*, and *Pseudosasa japonica* with 4.5 KN/m^2 and 1.0 KN/m^2 shear strength increments respectively. An increase in shear strength is also observed in the reinforced soils with increase in number of roots of these plant species. *Cymbopogon sp.* has higher root density near the surface but decreases with increasing depth and absent at 320mm depth, *Pseudosasa japonica* has the lowest root density but penetrates deeper up to 530mm while *Chimonobambusa sp.* penetrates deepest at 700mm with lateral branches extending up to 650mm. *Cymbopogon sp.*, and *Pseudosasa japonica* may be useful as a bioengineering tool to mitigate soil erosion while *Chimonobambusa sp.* to mitigate both erosion and shallow landslides.

Introduction

Soil bioengineering is the use of living plants or cut plant materials, either alone or in combination with inert structures, to control soil erosion and the mass movement of slopes (Howell 2001). The use of bioengineering approaches by civil engineers while dealing with unstable slopes has become increasingly popular over the last 20 years (Bischetti et al. 2005; Coppin and Richards 1990; Gray and Sotir 1996; Greenway 1987; Norris 2005; Roering et al. 2003; Scheichtl 1980). Vegetation has been recognized as a helpful factor for increasing the shear resistance of soil on an unstable slope (Anderson and Richards 1987; Coppin and Richards 1990; Operstein and Frydman 2000). Live plants and other natural materials have been used for centuries to control erosion problems on slopes and river banks in different parts of the world (Schluter 1986). Trees and woody shrubs in particular have been studied regarding their reinforcing properties i.e. root systems of these plants convey stability to slopes, subjected to mitigate erosion or slippage problems (Schmidt and Karda 2001; Wu 2007). Shrub and grass-root with the heart-root system commonly provide a more significant increase in soil cohesion than tap-root system (Baets et al. 2009), the former contributes more root covers for the broader area on the topsoil reducing shallow landslides (van Beak et al. 2005). The utilization of vegetation as a bioengineering method to enhance the stability of slopes and minimize surface erosion is well known (Cislaghi et al. 2017; Ghestem et al. 2011; Meijer et al. 2018; Naghdi et al. 2013; Shao et al. 2017; Sonnenberg et al. 2012). While roots of herbaceous vegetation rarely cross potential shear planes, however, they increase soil cohesion in the top soil and create a surface-mat effect (Michael et al. 2020). The roots are anchored to the soil mantle thereby governing the slope stability (Tosi 2007). An increase in root number improves the cohesion (Huat et al. 2005), which reduces the detachment of soil particles, but presence of root has a negligible influence on the root-reinforced friction angle when compared with root-free soil (Gray and Ohashi 1983). Bankhead and Simon (2010) explain how fine-root content (root densities, root lengths, and root volume per unit of soil) and types of vegetation are the main factors determining the reinforcement of topsoil. Although the use of conventional technique in retaining slope stability is the common practice for engineers, engineering in tandem with bio-engineering is proven to be a more cost effective approach in the mitigation of slope failures (Devkota et al. 2006; Petrone and Preti 2010). The significant factors that influence soil are the quantity and directional distribution of roots and their tensile strength, reinforced shear strength, and soil-root interaction. Plant root absorbs and circulates water to the atmosphere rather than letting all infiltrates deep into the soil. Different kind of plants exhibit dissimilar root properties and the ways they perform the function. These properties are observed through the root structures, and classified into three major systems: sinkers, heart root, and taproot (Stokes and Mattheck 1996). With the presence of roots, the evapotranspiration process occurs and regulates the soil water content that improves the matric suction,

thus contributing an increase in safety factor, especially on slope area (Bankhead and Simon 2010). Both the mechanical reinforcement provided by plant roots and the hydrological effect of enhanced matric suction from evapotranspiration influence the effect of vegetation on slope stabilization (Ng 2017; Pollen-Bankhead and Simon 2010; Veylon et al. 2015). Genet et al. 2010 and Schwarz et al. 2010 argued that vegetation affects the slope by increasing factor of safety (FoS).

Indo-Myanmar Range (IMR) in general, Manipur in particular, has a sub-tropical climate and an intensive seasonal rainfall. The rock types of the IMR including Manipur are mainly sedimentary shales and sandstones. These rocks are intensely deformed; fractured and jointed giving rise to thick mantle of waste (soil columns) helped by the favourable climatic condition. Such soils are characterised by highly erodible silt size particles followed by sand and clay respectively. Besides, human intervention is the significant cause of soil erosion and landslides in Manipur, particularly along the highways. Anthropogenic factors such as slope cutting for transportation routes and construction materials, jhum cultivations, deforestation and forest fire have increased day by day; consequently increasing bared slopes. Heavy and intensive rainfall during the rainy season is usually either greater than or nearer to threshold values (minimum rainfall intensity by which a slope failure can be triggered). Such incessant rainfall on these bare surfaces of hill-slopes can easily detach erodible slope forming materials and initiate shallow landslides in the form of debris flow and slide. These, in turn, may cause inconveniences in transportation and other developmental works, and affect the socio-economy of the state. Therefore, a multi-disciplinary approach is needed to minimize disturbances and damages due to slope failures along the highways of the state. Bioengineering as a mitigating measure for soil erosion and landslides has not been taken up so far, particularly in the context of Manipur State. Moreover, many effective and costly practical approaches i.e. conventional and engineering mitigation measures cannot prevent all the barren slope surfaces. It is, therefore essential to initiate some reliable and less expensive but environmentally healthy alternative mitigating measures. Bamboo is an environmental friendly resource that acts as a net carbon sink and neutralises acidic soils. Bamboo is used for various ornamental, aesthetic purposes and also has various medicinal values (Bhol and Nayak 2009; Isagi et al. 1993). The anti-erosion properties are keys to the bamboo reputation as a helpful soil conservation tool (Tripathi 2008). Roots of *Chimonobambusa sp.* and *Pseudosasa japonica* (two of the selected plant species) can bind the soils; and therefore, soil erosion due to heavy rain and wind can be minimized. A matured lemongrass root system is known to be strong and deep (Lekha 2004; Poudel et al. 2000). Leaves of the plant have been used in making beverage, oils and have diverse medicinal values. The grass has excellent benefits to humankind as it revitalizes the body and mind and acts as a muscle and skin toner (Vaibhav et al. 2013). The selected plant species are perennial and can survive any natural environmental condition. Considering all these aspects, the present paper aims to examine the geotechnical characteristics and morphological features of three plant species viz., *Chimonobambusa sp.* (Tenwa A), *Pseudosasa japonica* (Tenwa B), and *Cymbopogon sp.* (Lemongrass).

Materials And Methods

2.1 Site Characterization and Plant Species

The areas chosen for collecting plant roots lie in the north-central part of Manipur, Northeast India (Fig. 1). In the study area, rainy season is quite long, starting from the month of April and extending upto October. June, July and August months receive maximum amount of rainfall. Annual rainfall varies from place to place depending upon the location and altitude of the place. The state receives an average annual rainfall of about 2000-2300mm. These amount of rainfall can deform slope forming materials especially soils either in the form of detachment and plastic deformation. It is also known that there were some days whose rainfall intensity is greater than 34mm/day before the

slope failures (Kotlen and Senam landslides); liable to erosion and detachment of soil masses (Table: 1). Such heavy and continuous rainfall during monsoon can dispatch moderately to highly erodible soil masses undoubtedly. Wu et al. (2018) found that soil erosion becomes more sensitive to increasing rainfall intensity and slope gradient on bare loess slopes and the main erosion factor alternates between the two primary factors, hydraulic characteristics and subsequent transport. Hydraulic characteristics are mainly the fundamental factors that affect splash erosion processes because rainfall splashes are the predominant driving forces of soil detachment and subsequent transport (Fu et al. 2016, Ribolzi et al. 2011, Zhang and Wang 2017). It can induce landslides and poses enormous threats; and has caused severe damages over the past years as well as in the present scenario. Manipur, in general, especially the study areas in particular, is characterized by mixed soil i.e. clay, silt, and sand-gravel. Among these particles, silts are major constituents; consequently erodibility of soils is very high. Typical plant species, mode of collection of reinforced soils for direct shear tests as well as morphological measurements of the selected three plant species are presented in Table: 2 and Fig. 2.

Table: 1 Rainfall data and intensity for a few days before the Senam and Kotlen landslides

Date	Rainfall (mm/day)	Rainfall Intensity (mm/hour)	Date	Rainfall (mm/day)	Rainfall Intensity (mm/hour)
26-06-17	27.3	1.13	20-07-19	57.2	2.38
27-06-17	13.2	0.55	21-07-19	41.0	1.70
28-06-17	0.00	0.00	22-07-19	8.60	0.35
29-06-17	42.2	1.75	23-07-19	0.00	0.00
30-06-17	6.20	0.25	24-07-19	18.2	0.75
01-07-17	84.1	3.50	25-07-19	27.3	1.13
02-07-17	16.6	0.69	26-07-19	3.00	0.12
03-07-17	0.00	0.00	27-07-19	64.3	2.67
04-07-17	20.0	0.83	28-07-19	0.00	0.00
05-07-17	30.0	1.25	29-07-19	8.10	0.33
06-07-17	6.10	0.25	30-07-19	6.10	0.25
07-07-17	36.6	1.52	31-07-19	23.2	0.96
08-07-17	44.4	1.85	01-08-19	3.00	0.12
09-07-17	44.0	1.83	02-08-19	17.4	0.72
			03-08-19	70.2	2.92
Senam area $\sum 370.7$			Kotlen area $\sum 347.6$		
Threshold value i.e.		Observed value i.e.	Threshold value i.e.		Observed
$I_T = 14.82D^{-0.39} = 1.53$		$I_O = 370.7/336 = 1.103$	$I_T = 14.82D^{-0.39} = 1.49$		$I_O = 347.6/360 = 0.96$

(*D = 14x24 = 336 hours for Senam and 15x24 = 360 hours for Kotlen)

Table: 2 Measurements of root diameter and length of the collected plants, *Chimonobambusa sp.*, *Pseudosasa japonica* and *Cymbopogon sp.*

Sl. No.	Diameter (mm)			No. of Nodes	Length (cm)	No. of Branches
	Base	Middle	Tail			
<i>Chimonobambusa sp.</i>						
1	5/4.01	4.4/4.1	4/3.8	20	43.0	17 (LMax = 18.2cm)
2	4.80	4.80	4.00	16	12.2	14 (LMax = 18.2cm)
3	6.00	6.50	5.10	41	42.0	38
4	6.80	5.40	5.00	12	35.0	15
5	6.85	5.40	5.00	47	70.0	18
<i>Pseudosasa japonica</i>						
1	1.20	1.10	0.60	-	53.0	-
2	1.00	0.70	0.50	-	45.0	-
3	0.90	0.80	0.40	-	50.0	-
4	1.00	0.90	0.40	-	39.0	-
<i>Cymbopogon sp.</i>						
1	0.50	0.40	0.30	-	35.0	-
2	0.50	0.30	0.20	-	30.0	-
3	0.40	0.30	0.20	-	31.0	-

2.2.1 *Chimonobambusa sp.*: *Chimonobambusa sp.* is a variety of small bamboo, with a height of about 1.1m, maximum diameter of the stalks and roots are about 6.9 to 7.2mm and 6.8mm respectively; and have a heart root system. There are three distinct varieties in root system of the *Chimonobambusa sp.* One of them has nodes with branches (Fig. 2c) and penetrates downwards up to 700mm depth with lateral branches extending about 650mm. Second type is characterized by small roots system without nodes. The third one is those small roots branching from the two root systems. Root density is more significant in the upper part i.e. near the surface and decreases in the lower part. In situ samples of root reinforced soils as well as root free-soils were collected from the coordinates 25°30'31.97"N and 94°07'30.36"E of Mao area.

2.1.2 *Pseudosasa japonica*: *Pseudosasa japonica* is also a variety of bamboo, a perennial woody plant. The height of *Pseudosasa japonica* is about 1.0m, the diameter of the stalk ranges from 4 to 5mm. There are no tap roots, but lateral and other downward dipping root systems, and absence of prominent nodes in the roots is observed. The diameter of horizontal root systems is larger than that of vertical/deeper root systems. One of the downward dipping roots can penetrate up to 350mm, but lateral roots spread only 100mm approximately. Soil samples with and without roots for direct shear tests were collected from the coordinates 25°09'13.5"N and 93°58'35.9"E of Kangpokpi area.

2.1.3 *Cymbopogon sp.*: Lemongrass (*Cymbopogon sp.*) is a tropical perennial grass, and its name is derived from the typical lemony odour of the essential oil present in the shoot. Lemongrass flourishes in a wide variety of soil ranging from rich loam to poor laterite, but grows well on poor soils along hill slopes (Ranade 2004). It is found that the incorporation of lemongrass roots in the soil matrix improves the stability of the soil (Gobinath et al. 2020). Diameter of the collected roots of *Cymbopogon sp.* ranges from 0.5 to 0.2mm, and the most extended length is about 350mm.

Soil samples with and without roots for direct shear tests were collected from the coordinates 24°53'57.94"N and 94°03'35.74"E of Sekta area.

2.2 Direct shear test

Direct shear tests were conducted using the typical strain-controlled direct shear apparatus for soil. The standard testing sample is 6x6x2.5cm³ in dimension. The soil specimens comprising plant roots were carefully sampled in situ from the natural field setting to avoid disturbances. Similarly, the soil samples without plant roots were also collected from the respective sites. A minimum of four (4) in situ samples with plant roots and without plant roots were collected using an ordinary direct shear sampler from the natural hill slopes. Direct shear tests were conducted at different vertical loads as well as at the same vertical loads with a constant speed of 0.25mm/min, for a maximum horizontal displacement of 16mm. In the present work, samples with very few roots were treated as those samples without plant roots. Number of roots present in the sample was observed and root density is measured using a simple method i.e. the number of roots present in the 6x6cm² samples for the direct shear test. Results of direct shear tests with and without plant roots are presented in the form of Tables (Tables: 3, 4, 5, 6, 7, and 8) and Figures (Figs. 3, 4, 5, 6, 7, and 8).

Table: 3 Results of direct shear test on soil samples with and without roots of *Chimonobambusa sp.* at different loads

Sample	Moisture content (w) %	No. of Root	Area (cm ²)	Root/Area	Normal stresses, σ_n (KN/m ²)	Shear stresses, τ (KN/m ²)	Stress ratios τ/σ_n
without roots at different applied loads							
MWPR-A	56.81	30	36	0.83	19.62	22.22	1.13
MWPR-B	64.70	19	36	0.52	14.71	15.27	1.03
MWPR-C	68.57	47	36	1.30	29.43	28.88	0.98
MWPR-D	68.70	27	36	0.75	39.24	33.61	0.85
with roots at different applied loads							
MPR-A	59.14	36	36	1.00	29.43	33.05	1.12
MPR-B	43.45	43	36	1.19	39.24	38.33	0.97
MPR-C	47.01	57	36	1.58	24.52	34.72	1.41
MPR-D	55.00	63	36	1.75	19.62	27.22	1.38

Table: 4 Results of direct shear test on soil samples with roots of *Chimonobambusa sp.* at the same load

Sample	Applied load (KN/m ²)	Shear Stresses (KN/m ²)	Stress ratios τ/σ_n	No. of roots	Area cm ²	Root density
Sample A	39.24	27.77	0.707	30	36	0.83
Sample B	39.24	21.66	0.552	30	36	0.83
Sample C	39.24	38.33	0.976	57	36	1.58
Sample D	39.24	26.94	0.686	27	36	0.75

Table: 5 Results of direct shear test on soil samples with and without roots of *Pseudosasa japonica* at different loads

Sample	Moisture content (w) %	No. of Root	Area (cm ²)	Root/Area	Normal stresses, σ_n (KN/m ²)	Shear stresses, τ (KN/m ²)	Stress ratios τ/σ_n
without roots at different applied loads							
KWPR-A	27.22	-	36	-	19.62	09.44	0.48
KWPR-B	33.62	-	36	-	29.49	11.66	0.39
KWPR-C	21.92	-	36	-	34.33	13.88	0.40
KWPR-D	33.96	-	36	-	39.24	16.66	0.42
with roots at different applied loads							
KPR-A	22.67	79	36	2.19	19.62	10.00	0.50
KPR-B	19.13	46	36	1.27	29.49	13.05	0.44
KPR-C	18.45	45	36	1.25	34.33	15.00	0.43
KPR-D	17.62	38	36	1.05	39.24	17.12	0.43

Table: 6 Results of direct shear test on soil samples with roots of *Pseudosasa japonica* at the same load

Sample	Applied load (KN/m ²)	Shear Stresses (KN/m ²)	Stress ratios τ/σ_n	No. of root	Area cm ²	Root density
Sample A	39.24	14.72	0.375127	54	36	1.50
Sample B	39.24	12.50	0.318552	38	36	1.05
Sample C	39.24	11.66	0.297146	35	36	0.97

Table: 7 Results of direct shear test on soil samples with and without roots of *Cymbopogon sp.* at different loads

Sample	Moisture content (w) %	No. of Root	Area (cm ²)	Root/Area	Normal stresses, σ_n (KN/m ²)	Shear stresses, τ (KN/m ²)	Stress ratios τ/σ_n
without roots at different applied loads							
SWPR-A	36.99	-	36	-	9.81	21.11	2.15
SWPR-B	36.99	-	36	-	14.71	26.38	1.79
SWPR-C	30.74	-	36	-	19.62	29.44	1.50
SWPR-D	34.16	-	36	-	24.52	31.66	1.29
with roots at different applied loads							
SPR-A	26.35	50	36	1.38	9.81	27.77	2.83
SPR-B	29.98	65	36	1.80	14.71	32.22	2.18
SPR-C	26.35	78	36	2.16	19.62	36.66	1.86
SPR-D	28.95	46	36	1.27	29.43	39.72	1.34

Table: 8 Results of direct shear test on soil samples with roots of *Cymbopogon sp.* at the same load

Sample	Applied load (KN/m ²)	Shear Stresses (KN/m ²)	Stress ratios τ/σ_n	No. of root	Area cm ²	Root density
Sample A	14.71	29.44	2.001	24	36	0.66
Sample B	14.71	32.22	2.190	150	36	4.16
Sample C	14.71	26.38	1.793	-	36	0.00

Results And Analyses

3.1 *Chimonobambusa sp.*: Stress-displacement graphs of the soil samples with and without plant roots of *Chimonobambusa sp.* are shown in Fig. 3a and 3b respectively. Samples with very few numbers of roots (MWPR) can withstand upto 0.100KN with the displacement of 2 to 4mm, and failure occurs thereafter(Fig. 3a). While samples with plant roots (MPR) can withstand more load up to 0.140KN when displacing 2 to 10mm (Fig. 3b). Therefore, displacement and shear stress graphs indicate that soil with plant roots can withstand more shear stresses.

The cohesive strength (C) of soil samples of Mao area without plant roots is about 11.2KN/m², and that of soil with plant roots of *Chimonobambusa sp.* is 16.2KN/m² while internal friction angle is 29° in both cases (Fig. 4a). Direct shear tests of soils with the plant roots reveal an increase in cohesive factor i.e. shear strength increment, $\Delta C = 16.2 - 11.2 = 5.0\text{KN/m}^2$, while increase in frictional resistance is insignificant (Fig. 4a). Increase in shear strength with increasing number of roots of *Chimonobambusa sp.* is shown in Fig. 4b.

3.2 *Pseudosasa japonica*: Samples with few or no roots (KWPR) can withstand 0.048KN when displacing 4 to 6mm; however, KWPR-D can withstand 0.06KN when displacing 3.7mm (Fig. 5a). While samples with plant roots of *Pseudosasa japonica* (KPR) can withstand 0.065KN when displacing about 6mm (Figs. 5b). The cohesive strength (C) of the soils of Kangpokpi area without plant roots is about 2.5KN/m², and cohesive strength offered by soil with plant roots of *Pseudosasa japonica* is 3.5N/m². Test results show the value of $\Delta C = 1.0\text{KN/m}^2$, while internal friction angle is 19° in both cases (Fig. 6a). The graphical plot of normal stress and shear stress indicates an increase in shear strength with increasing number of roots of *Pseudosasa japonica* (Fig. 6b).

3.3 *Cymbopogon sp.*: Stress-displacement graphs of the soil samples with and without plant roots of Sekta area are shown in Figs. 7a and 7b, respectively. Samples with few or no roots (SWPR) can withstand 0.11KN when displacing 4 to 6mm (Fig. 7a). While sample with plant roots (SPR) of *Cymbopogon sp.* can withstand 0.148KN when displacing about 6mm (Fig. 7b). Therefore, displacement and shear strength graphs indicate that soil with plant roots of *Cymbopogon sp.* can withstand more displacement. The cohesive strength of Sekta soil samples without plant roots is about 17.5KN/m², while cohesive strength of soil with plant roots of *Cymbopogon sp.* is 22.5N/m², and $\Delta C = 4.5\text{KN/m}^2$. The internal friction angle is 29° in both cases (Fig. 8a). Fig. 8b shows the increase in shear stresses with the same normal loads in the presence of different root density of *Cymbopogon sp.*

Discussions

Prior to the incidents of Senam landslide (9th July, 2017)) and Kotlen landslide (3rd August, 2019), the observed rainfall intensities (I_0) were obtained by using the relation i.e. amount of rainfall in a particular duration of time (mm/h) and their threshold values were obtained by using the relation $I_T = 14.82D^{-0.39}$, where I_T = threshold of rainfall intensity, D = duration of rainfall in an hour (Caine 1980). Following the above relations, the values of I_0 of Senam and Kotlen areas were 1.103mm/h and 0.96mm/h and the threshold values (I_T) of Kotlen and Senam were 1.53mm/h and 1.49mm/h respectively (Table: 1). Observation reveals that the I_0 values were less than I_T values which were not favourable to trigger landslide (Caine 1980). This lack of fit in rainfall intensities i.e. less than the I_T values for triggering landslide, might be due to the fact that durations of rainfall data collection were greater than ten days (Senam: 14 days and Kotlen: 15 days) during which the slope masses might have been well saturated. Moreover, the rainfall intensities on the days of Senam and Kotlen landslides i.e. 1.83 (44mm/day) and 2.92 (70.2mm/day) respectively, were much above the threshold limits. These conditions may be, therefore, sufficient to cause not only erosion and detachment of soil masses but even slide of the slope masses (Roslan and Farid 2001).

Plants have been used along the slopes to protect soil erosion by their reinforcement capability of the soil that improves the slope stability. From the morphological features (Table: 2), it can be inferred that the selected plant species can exert a beneficial effect on stability of the slopes through the reinforcing action of roots on the surficial layers of less than 1m in depth. Tables: 3, 5 and 7 show that samples with higher root density (number of roots/sample area) can withstand more shear stresses. For instances, sample with root density of 0.52 can withstand upto 15.27KN/m² while sample with root density (1.58) withstands up to 34.72KN/m². Variations of shear stresses at constant vertical load with reference to the numbers of roots present in the tested samples are shown in Tables: 4, 6 and 8 as well as in Figs. 4b, 6b and 8b. From these Tables and Figures, it is observed that there is increase in shear strength with the increase in number of roots (root density) of *Chimonobambusa sp.*, *Pseudosasa japonica*, and *Cymbopogon sp.*

Direct shear test results further indicate that shear strength, especially the cohesion, increases by a factor of 5.0KN/m², 1.1KN/m² and 4.5KN/m² respectively for the three plant species i.e. *Chimonobambusa sp.*, *Pseudosasa*

japonica, and *Cymbopogon sp.* (Figs. 4a, 6a and 8a) implying that they could be useful for slope stabilization. Higher values of stress-ratios i.e. shear stresses to normal stresses (τ/σ_n) are also observed in the samples with higher root density (Tables: 3, 4, 5, 6, 7 and 8). It suggests that soils with plant roots have more shear strength than root-free soils. Difference in the average values of stress ratios (τ/σ_n) of soil with plant roots and root-free soil of *Chimonobambusa sp.*, *Pseudosasa japonica*, and *Cymbopogon sp.* are 0.24, 0.03 and 0.37 respectively (Table: 9). So, *Cymbopogon sp.* gives maximum average value while *Pseudosasa japonica* renders minimum value. From Table: 9, it can be inferred that *Cymbopogon sp.* can withstand more shear stresses as compared to the other two species.

Table: 9 Variations in the average stress ratios (τ/σ_n) of the three plant species at different loads

Plant species	Average values of τ/σ_n at different applied loads		
	Without roots	With roots	Differences
<i>Chimonobambusa sp.</i>	0.98	1.22	0.24
<i>Pseudosasa japonica</i>	0.42	0.45	0.03
<i>Cymbopogon sp.</i>	1.68	2.05	0.37

Increases in cohesion factor (C), as observed above, could be related to the variation in moisture content between root-free soil and root-reinforced soil, tensile strength of the roots and root density. Lower moisture content in root-reinforced soil samples of *Chimonobambusa sp.*, *Pseudosasa japonica* and *Cymbopogon sp.* may be due to suction of more water by plant roots as compared to that of root-free soil (Tables: 3, 5 and 7). Obviously cohesive strength increases in the reinforced soil of *Chimonobambusa sp.*, *Pseudosasa japonica* and *Cymbopogon sp.* Plant roots can bear the potential of compensating the negative impact of high soil water content on slope stability, or contribute an adequate resistance against surface damages (Stokes et al. 2009). Soils have an ample amount of shear strength but negligible tensile strength. For soils reinforced by plant roots, during shearing the tensile stresses can be transferred to roots because of the friction and/or interlocking between the soil particles and roots (Meijer et al. 2018; Zhang et al. 2010). It is also known that there is a positive relationship between shear strength increment (ΔC) and root tensile strength (Waldron 1977 and Wu et al. 1979). This means roots give a certain tensile strength to the soil. In other word, roots always have tensile strength; consequently the selected plant species will give an additional cohesive strength to the soils. Presence of roots has large spaces in the soil especially at the topsoil, hence increases the density of soils. In this way, more spaces are covered by the roots and it improves the cohesion by increasing the bonding with the soil particles.

Re-evaluation of the factor of safety (FoS) of one of the landslide areas i.e. Makhan landslide, by employing shear strength increments (ΔC) of the three plants species is given in Table: 10. Slope angle (α), height (H), and internal friction angle (ϕ) of the Makhan slide area are constant, while value of unit weight ($\gamma = 20496.6 \text{ N/m}^3$) is assumed to be unchanged. By taking the increased cohesion value (5.0 kN/m^2) of the *Chimonobambusa sp.* root-reinforced soil of Potato Farm, FoS of Makhan landslide increases from 0.695 to 0.717. In the same way, the re-evaluated values of FoS for *Pseudosasa japonica* and *Cymbopogon sp.* are 0.706 and 0.712 respectively (Table: 10). Although the increase in FoS is marginal as shown in Table: 10, the increase can be of immense use in critical conditions of slope failure. So, *Chimonobambusa sp.* would be more effective than *Pseudosasa japonica* and *Cymbopogon sp.* as the former has higher value of shear strength increment.

Table: 10 Evaluation of FoS employing the shear strength increments of the three plant species

Particulars	A (°)	H (m)	C (N/m ²)	ϕ (°)	γ (N/m ³)	Tan ϕ	g.H.Tan ϕ	C/ γ .H.Tan ϕ	Tan ϕ /F	FoS
Makhan landslide*	41	95	29000	25	20496.6	0.46	907985	0.0319	0.670	0.695
<i>Chimonobambusa sp.</i>	41	95	34000	25	20496.6	0.46	907985	0.0374	0.650	0.717
<i>Pseudosasa japonica</i>	41	95	30000	25	20496.6	0.46	907985	0.0330	0.660	0.706
<i>Cymbopogon sp.</i>	41	95	33500	25	20496.6	0.46	907985	0.0368	0.655	0.712

* a landslide area

Conclusions

The present study suggests that *Cymbopogon sp.* and *Pseudosasa japonica*, as bioengineering tool, could be effective to control and mitigate soil erosion while *Chimonobambusa sp.* both for soil erosion as well as shallow landslides. This initiative can result in rich, live systems that remain in self-balance without the artificial input of energy, and provide many advantages over conventional techniques of mitigating soil erosion and slope failures. So, the following conclusions can be drawn from the present investigation.

1. Shear strength especially in terms of cohesion factor increases in root-reinforced soils of *Chimonobambusa sp.*, *Pseudosasa japonica*, and *Cymbopogon sp.* by 5.0KN/m², 1.1KN/m² and 4.5KN/m² respectively as compared to root-free soils.
2. *Cymbopogon sp.* and *Pseudosasa japonica* can be used as a bioengineering tool for the mitigation of soil erosion while *Chimonobambusa sp.* can be used for both soil erosion and shallow landslides.
3. Due to light biomass and root system, the selected plant species: *Chimonobambusa sp.*, *Pseudosasa japonica*, and *Cymbopogon sp.* are suitable to be planted at the top as well as middle of the slope to control erosion initiated by direct raindrop effects and detachment of slope materials.

Declarations

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Figures

Figure 1

Geological map of Manipur showing locations of the three plant species (modified from Soibam and Khuman 2008).

Figure 2

Photographs showing plant species, morphometric measurements, and shear test sample: a) *Chimonobambusa* sp. and mode of digging for morphometric measurements; b) nodes in the roots; c) measurement of root length; d) shape of roots; e) *Pseudosasa japonica*; f) Sample after failure; g) *Cymbopogon* sp.; and h) Sample for measuring number of roots present.

Figure 3
 Stress-displacement graphs of Potato Farm soil, Mao: a) without roots, b) with roots, of *Chimonobambusa* sp.

Figure 4
 Graphs of normal stress vs. shear stress of Potato Farm soil, Mao associated with *Chimonobambusa* sp.: a) with and without roots at different loads; b) with roots at the same normal load. A, B, C and D are the samples where the numbers within parenthesis indicate shear stresses and numbers of roots respectively.

Figure 5
Stress-displacement graphs of soil of Kangpokpi area: a) without roots; b) with roots, of *Pseudosasa japonica*.

Figure 6
Graphs of normal stress vs. shear stress of soil of Kangpokpi area associated with *Pseudosasa japonica*: a) with and without roots at different loads; b) with roots at the same normal load. A, B and C are the samples where numbers within parenthesis indicate shear stresses and numbers of roots respectively.

Figure 7

Stress-displacement graphs of soil of Sekta area: a) without roots; b) with roots, of *Cymbopogon* sp.

Figure 8

Graphs of normal stress vs. shear stress of soil of Sekta area associated with *Cymbopogon* sp.: a) with and without roots at different loads; b) with roots at the same normal load. A, B and C are the samples where numbers within parenthesis indicate shear stresses and numbers of roots respectively.