

Sustainable Slope Stabilization Using Biochar and Vegetation Root Reinforcement

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ABSTRACT

Slope instability is a significant geotechnical and environmental issue that can lead to erosion, landslides and structural collapse, especially in monsoon affected areas. In this study, the influence of biochar amendment and root reinforcement on soil mechanical behaviour and slope stability was investigated by working with the soils sampled from the erosion-susceptible area in Dinajpur Rubber Dam in northern Bangladesh. Acacia auriculiformis biochar and Napier grass root (*Pennisetum purpureum*) were applied to the soil at a rate of 5%, 10% and 15% biochar contents combined with a mix of 0.5%, 1% and 2% root content combinations on dry weight basis. Index properties, compaction characteristics, permeability, field density, and direct shear testing in line with ASTM standards formed part of a full laboratory test programme to quantify the impact of treatment. The test results showed that the addition of biochar lowers maximum dry density and increases optimum moisture content. Root treatment greatly improves the shear characteristics parameters and slope stability, and the best effect is that treated with 5-10% biochar and 1-2% root content. In this condition, the factor of safety (FOS) was increased from 1.349 with untreated soil to be 2.294. Biochar at the high addition rate (15%) induced marginal increase for strength, as a result of low level of interparticle bonding and soil-biochar interactions. The results obtained were confirmed by numerical slope stability analysis carried out using the software GeoStudio SLOPE/W, and a much higher factor of safety value was achieved for treated slopes when compared to unsprayed cases. In summary, the joint use of biochar and vegetative root reinforcement is an effective, sustainable, and environmentally friendly method to enhance land mass stability in the erosion-prone region's collapsing slope.

Keywords: Biochar; grass root; geostudio; permeability test; slope stability

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1. Introduction

Slope instability is a universal geotechnical and geo-environmental problem, which threatens serious risks to all types of infrastructures, human environment and ecological environment on the Earth [1]. For example, shallow landslips, surface erosion and embankment instability continue to have made prominent impact in tropical and subtropical countries due to high intensity rainfall events associated with low humus content soil structure and poor drainage condition increasing the degradation of slope [2-4]. In monsoon prone countries like Bangladesh, bottom-up slope stability is further promoted by seasonal pore water infiltration due to rainfall, changes in groundwater levels and soil developments which join together

causing time-to-time erosion as well as localized slope sliding [5-6].

Common techniques to stabilize a slope, such as soil replacement, retaining structures, cement stabilization and geosynthetic reinforcement are typically expensive in their construction costs and high in embodied carbon [7-8]. Additionally, Demiroz & Saran (2024) employed mineral additives and basalt fiber, whereas Karademir (2024) used lime and polypropylene fiber to enhance the microstructure of clay soils [9-10]. Takcı et al. (2023) used the proportion of bentonite in the soil mixture to analyze slope stability [11]. Additionally, bentonite and polymeric support fluids were used by Akhtar (2023) to stabilize excavations [12]. According to Öztürk (2025), textile waste significantly raised cohesive soil's unconfined compressive strength [13]. Consequently, efforts to build up

sustainable nature-based and low-carbon solutions improving soil mechanical function with minimized environmental footprints have become more promising alternatives [14-15]. Biochar amendment and vegetative root reinforcement are identified as some of the possible solutions for improving the stability of soil and mitigating slope failure. Biochar is carbon-rich, porous material that is obtained from the pyrolysis of biomass in a low-oxygen environment. Its use in soil systems has been well researched within agricultural and environmental engineering due to its ability to enhance soil conditions, water holding capacity, and carbon storage [16-17]. In geotechnical engineering, it has been found that biochar can significantly alter the soil density, permeability, compressibility and shear strength by modifying particle packing pattern, interparticle friction and pore structure [18-19]. Numerous research studies have provided quantitative evidence of the effectiveness of biochar on soil erosion. Soil amended with biochar experiences 16–30% lower dissolution of soil particles (i.e., soil loss) and approximately 25% reduction in surface runoff as compared to its unamended counterpart due to enhanced improvements of the soil structure and infiltration rate [20]. One global meta-analysis reported that biochar amendment caused, on average, a 27.9% reduction in soil erosion across a wide range of different soils and climate conditions [21]. Field experiments conducted in silt loam soils showed that biochar amendments reduced soil erodibility by as high as 59% after three years of applications [22]. At the same time, reductions in soil detachment capacity of 6–80% (based on soil texture and application rate) have been observed with biochar treatments [23]. Nevertheless, the mechanical behaviour of biochar-amended soils is still very sensitive to biochar concentrations, feedstock kinds, particle sizes and soil mineralogy and high amount of added biochar may adversely affect strength owing to poor bonding and greater void ratios [24-25]. Vegetative root reinforcement serves as an alternative method for sustainable slope stabilization and it involves the soil shear strength that plant roots can provide through tensile resistance, anchorage and confinement [26-27]. Roots are discrete structures which act as connecting elements between soil particles, they limit deformation and delay the development of a shear plane particularly within thinner sections of soils prone to erosion and rainfall induced failure [28-29]. Certain grasses, such as Napier grass, has been of significant interest to producers because of its fibrous and dense rooting system, rapid growth and adaptability to the tropical environment [30-31]. Experimental studies have shown that higher root content results in a higher apparent cohesion and better slope stability, but long-term degradation of roots due to decay, spatial variability and moisture sensitivity are still important influences on the long-term behaviour e.g. [32-33].

Even though various studies have been conducted investigating biochar addition into slopes or soils with roots reinforcement, the integrative impacts of both on the soil mechanical performance and slope stability are under researched. The interplay between biochar-mediated changes in soil fabric and root-induced tensile reinforcement is complicated, and is not yet comprehensively evaluated or understood, especially under field-mimetic environments [34-35]. Biochar could enhance root proliferation and moisture retention, which may contribute to bond strength between roots and soil [36-37], while when biochar content is high, its influence on strength reduction can be remedied by roots through

reinforcement mechanisms. Nevertheless, it is important that biochar-root optimum combinations, threshold contents and its impact on slope FOS need to be systematically tested with experiments and numerical simulations. Additionally, most studies performed to date are based on laboratory-scale investigation and have little incorporation of numerical slope stability analysis to verify field scale performance [38-39]. More advanced limit equilibrium and finite element-based tools such as GeoStudio SLOPE/W provide useful platforms to incorporate experimentally derived shear strength parameters in slope stability analysis, for a more comprehensive evaluation of treatment effectiveness under realistic boundary conditions [40-41].

In this perspective, the present study was conducted to assess joint effects of biochar application and root reinforcement in soil mechanics as well as slope stability with respect to erosion hazard emanated from soils sourced from the Dinajpur Rubber Dam area, northern Bangladesh. Biochar produced from the trunk of *Acacia auriculiformis* and roots (*Pennisetum purpureum*) were introduced at different ratios, and their impact was measured through a comprehensive ASTM-standard laboratory experiment, complemented by numerical analyses for slope stability. The study aims to determine the optimal combinations of biochar and roots that can be used for maximum shear strength and slope factor of safety, understand the underlying behaviour of strength improvement with biochar & its degradation at higher application rates, and also propose this eco-friendly technique as a sustainable solution for the stabilization of slopes in monsoon-prone regions.

2. Materials and Methods

This paper aims to investigate the roles of biochar addition and root reinforcement in slope stability using a combined method including laboratory tests, vegetation experiments, and numerical simulation. Biochar of *Acacia aureus* and Napier grass were preferred for the treatment due to their wide availability, environmentally friendly nature, and suitable for soil improvement purpose. The methodological structure was implemented step-by-step for the investigation of soil parameters, root contribution and slope performance in order to guarantee a sound and unambiguous evaluation of the research objectives.

2.1. Location of study area

The study area is near of Dinajpur Rubber Dam, in northern Bangladesh which has a problem with slope erosion and superficial instability. The land is gently sloping to undulating and consists primarily of silty sand soil. Variations in annual rainfall and seasonal changes in the ground water table play a large role in how the slopes perform in this area. Because of its potential for erosion and exposure to the field it was chosen both as a sampling and an off-slope location. The location of the study area is indicated in Figure 1.

2.2. Materials

2.2.1. Preparation of biochar

Biochar is a carbon-rich material produced at low oxygen levels during the pyrolysis of organic biomass (e.g., wood or crop residues). It is primarily used as a soil conditioner to improve the soil's ability to hold water and support the activity of microbes. Biochar can also

be used to stabilize terrain by enhancing the soil structure and erosion resistance. Figure 2 shows the biochar used in this study for soil stabilization.



Figure 1. Location of study area



Figure 2. Biochar of *Acacia auriculiformis*

2.2.2. Root reinforcement using Napier grass

Napier grass, also known as elephant grass, is an efficient species for slope retention due to its deep fibrous root system. The roots grow vertically to a depth of 2–4 m and widely laterally to cover a spread area of 1.5–3 m, thus giving the soil strong anchorage and increasing its cohesion, shear strength, resistance to shallow slope failure processes and surface erosion risk. A compact root mat in the upper 30–60 cm enhances soil cohesion, aggregation and hydrological stability by increasing infiltration rates and reducing overland flow. Fast growing habits, tolerance to poor soils and low maintenance type for tropical and subtropical areas. It is these features which make Napier makes an affordable bio-mechanical alternative to alleviate slope erosion. Munirwan et al. (2025) identified that the roots of elephant grass enhanced the shear strength of soils by an enormous extent which lowered the occurrence of slope instability and shallow landslides [42]. The application of Napier grass as a slope reinforcement material is shown in Figures 3(a-b).

2.3. Designation of test specimens

Soil was taken from three different location and denoted as Location 1, Location 2 and Location 3. Firstly, the test was performed for natural soil or untreated soil and then mixed biochar and root content. Hence, Combinations were created to simplifying the overall operation. To simplify the experimental procedure,

different combinations of biochar and root reinforcement were prepared and categorized as shown in Table 1.



Figure 3. (a) Napier grass applied for slope reinforcement and (b) Napier grass specimen used in this study

Table 1. Sample categorization.

Sample Designation	Soil (%)	Biochar (%)	Root (%)
Mix1	94.5	5	0.5
Mix2	94	5	1
Mix3	93	5	2
Mix4	89.5	10	0.5
Mix5	89	10	1
Mix6	88	10	2
Mix7	84.5	15	0.5
Mix8	84	15	1
Mix9	83	15	2

2.4. Experimental procedure

The experiment intends to test the effects of root reinforcement as well as biochar application on soil shear strength and stability. Soils samples were taken from erodible slope of Dinajpur Rubber Dam project area. The soil samples were air-dried, crushed and sieved through a 2 mm sieve for the laboratory test. Biochar was prepared from *Acacia auriculiformis* biomass via slow pyrolysis at 300 °C for 3 hours under oxygen limitd condition and incorporated into soil at rates of 5%, 10%, and 15% by dry weight; control soils were left untreated. To evaluate vegetation-induced reinforcement, Napier grass was grown on prepared soil beds with or without biochar amendment and also on small-scale slope models. Root system distribution (root depth, lateral spread and root density) was traced during a known duration of growth to assess their role in soil reinforcement and slope stability. Figure 4 illustrates the step-by-step framework of the research methodology and Table 2 shows the tests standards.

Table 2. Test standards.

Tests Name	Standard
Specific gravity	ASTM D 854 [43]
Grain size distribution	ASTM D 422 [44]
Atterberg limit tests	ASTM D 4318 [45]
Modified proctor test	ASTM D 1557 [46]
Permeability Test	BS EN ISO 17892-11 [47]
Field Density Test of Soil	ASTM D1556 [48]
Direct shear test	ASTM D3080 [49]

2.5. Slope stability analysis using GeoStudio

Stability analyses of the slopes were performed using GeoStudio SLOPE/W based on a user manual procedure. A project new one was prepared with proper titles and descriptions, and all computation was carried out using SI units (m, kN) to reconcile the laboratory and field data. The slope geometry was generated using drawing tools to define soil regions and slope boundaries, with adequate

boundary conditions assigned for numerical stability. Soil behavior was represented by input laboratory-derived properties of cohesion, angle of internal friction, unit weight and pore-water pressure. The pore-water states were modeled considering a phreatic line as an approximation of the groundwater table. Limit equilibrium analysis was performed based on the Mohr–Coulomb failure criterion, and potential slip surfaces were identified using an entry–exit search method. The factor-of-safety was calculated by the software itself and optimal critical failure surface was detected, then it was interpreted to assess the slope stability. The geometric model of the slope adopted for numerical analysis is presented in Figure 5.

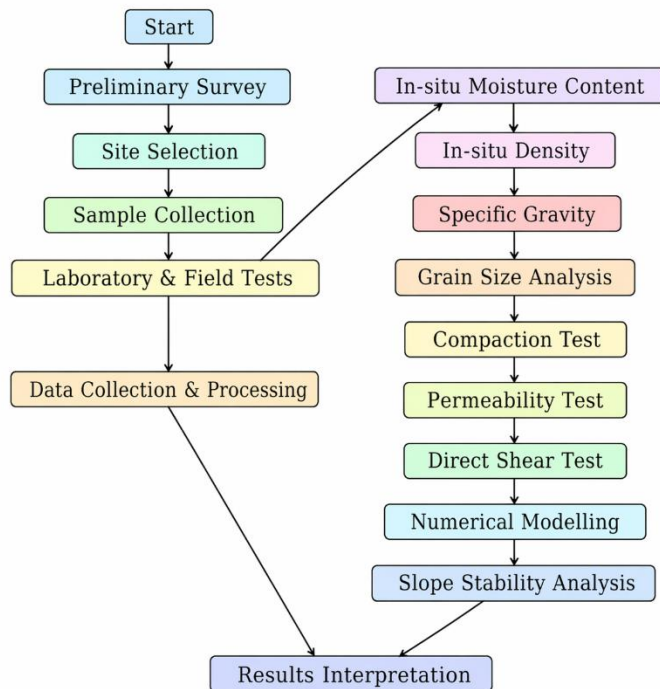


Figure 4. Flowchart of methodology

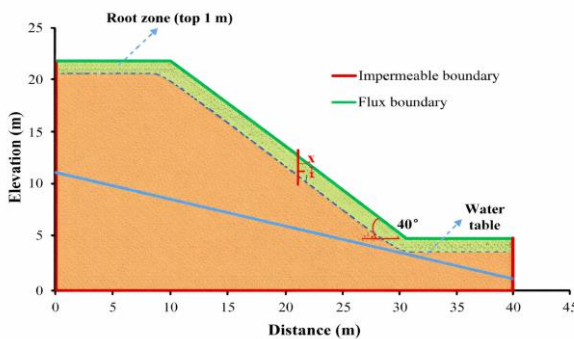


Figure 5. Geometric model of the slope used for numerical analysis

3. Results and Discussion

3.1. Specific gravity

Specific gravity test was done on three soil samples of natural silty sand soil. Location 1, 2, and 3 were found to have average values of specific gravity of 2.70, 2.68 and 2.73, respectively. Such values of specific gravity show that the soils being tested are silty sand soils and inorganic as the soils fall within the normal range of 2.60 to 2.80 which is the normal range of the silty and sandy soils. The small

variability between the samples might be justified by the fact that proportion of small particles and mineral composition of each location is different. The results confirm that the soil is predominantly made of quartz and other light minerals [50], which are characteristic of the silty sand deposits. Thus, the levels of specific gravity obtained demonstrate that the soils tested possess the overall behaviour inorganic silty sand and possess moderate density and proper engineering properties to continue the investigations on the stabilization.

3.2. Grain size distribution

The grain size distribution curve is plotted by combining data from hydrometer and sieve analyses. This test was done by following to standard test method for particle-size analysis of soils [44]. All three soils underwent grain size analysis tests, and the result of each test is shown in Figure 6.

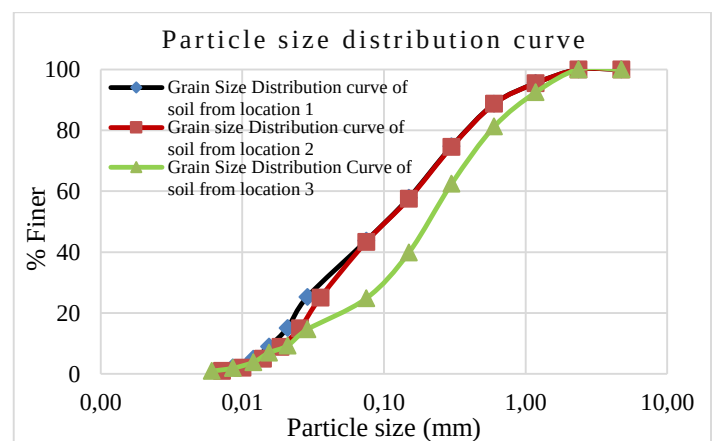


Figure 6. Grain size distribution curve for location 1, 2 and 3

From Figure 6 it is found that 0% gravel, 56.24 % sand and 43.76 percent silt and clay are the percentages of the soil of location 1 sample. Characteristic particle sizes were $D_{60} = 0.169$ mm, $D_{30} = 0.050$ mm and $D_{10} = 0.017$ mm. The calculated C_u and the C_c are 9.84 and 0.91, respectively. In the same manner, the soil sample located in sampling zone 2 is composed of 0% gravel, sand 56.66%, and silt-clay 43.34%. The particle profile parameters were $D_{60} = 0.172$, $D_{30} = 0.050$ and $D_{10} = 0.017$ giving $C_u = 9.94$ and $C_c = 0.905$ and the soil sample 3 contains 0% of gravel, and its composition is 75.19% of sand whereas silt and clay percentage accounts for 24.81%. The particle size parameters were $D_{60} = 0.284$ mm, $D_{30} = 0.090$ mm, and $D_{10} = 0.030$ mm, respectively. The computed coefficients $C_u = 9.39$ and $C_c = 0.96$ suggest well graded sand matrix with appreciable fines content. According to the Unified Soil Classification System (USCS), the soil, as described by Deng et al. (2018), can be classified as Silty Sand [51].

3.3. Atterberg limit

Tests were performed for both the liquid and plastic limits, and plasticity indexes. This test was done by following to standard test methods for liquid limit (LL), plastic limit (PL), and plasticity index (PI) of soils [45]. The results of Atterberg limit tests are summarized in Table 3. In the three samples liquid limit was similar and in the low range (25.77%–27.36%), which does not show variation of soil texture across the fields. It was reported by Qusai et al. (2025) that

sand (or coarse) content incline to result both the LL and PI linearly decreasing, this is confirmed by our findings of a low LL [52]. Further, the plastic limits are low, so it takes a rather low moisture content to force soil into its plastic state and PL - LL (Plasticity index) is also small. Such low-plasticity behaviour is usually observed in soils like silty sand, which are essentially more frictional and less cohesive than clayey soil.

Table 3. Laboratory test results of LL, PL and PI.

Location	LL (%)	PL (%)	PI (%)
1	27.36	25.64	1.72
2	25.77	24.59	1.17
3	25.88	24.84	1.04

3.4. Modified proctor test for natural soil

In the case of the natural silty sand soil, the modified Proctor tests were applied to determine the differences in the dry density and moisture content. The test was conducted in accordance with the oven-drying procedure [46] because it is the most popular and accurate and reliable one. The compaction curves used to compute maximum dry density (MDD) as well as optimum moisture content (OMC) is illustrated in Figures 7 (a-d).

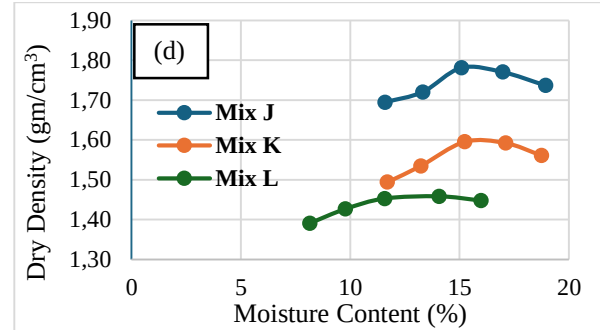
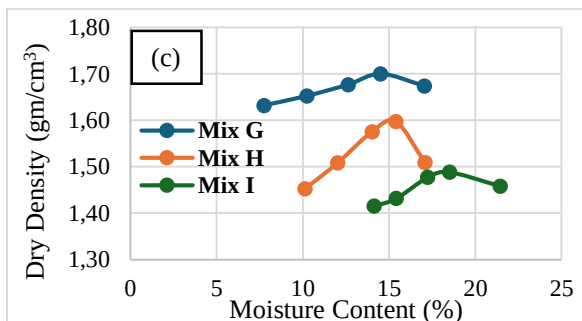
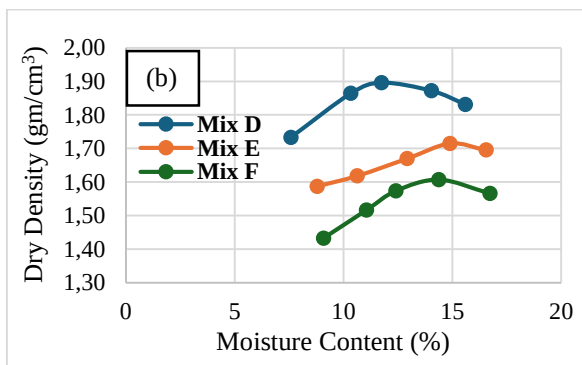
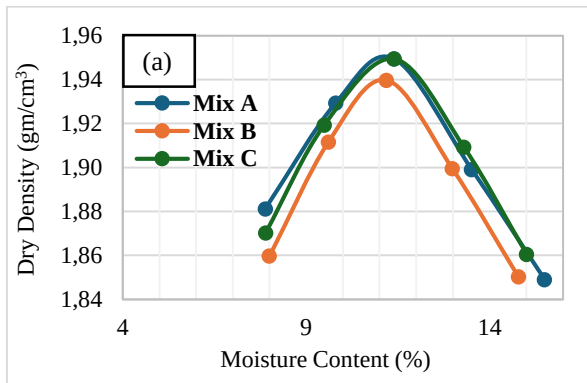


Figure 7. Changes between dry density (gm/cm^3) and moisture content (%) for (a) natural soil Mix A, B, C (b) Soil with 5%, 10% and 15% Biochar-amended for location 1 (c) Soil with 5%, 10% and 15% Biochar-amended for location 2 (d) Soil with 5%, 10% and 15% Biochar-amended for location 3

Modified Proctor test results show regular and consistent trend of reduction in MDD and increase in OMC compared to those of the natural soil for the biochar amendment levels considered and all locations (Table 4). The natural silt sand provided relatively high MDD of 1.94-1.95 g/cm^3 with low OMC of 11.19%-13.30%, indicating dense packing structure of particle and its characteristics as a granular soil is significantly in plastic limits.

Table 4. Summary of modified Proctor test results for natural and biochar-amended soils.

Soil Condition	Location	Mix	OMC (%)	MDD (g/cm^3)
Natural soil	1	A	11.40	1.95
Natural soil	2	B	11.19	1.94
Natural soil	3	C	13.30	1.95
Soil with 5% Biochar-amended	1	D	14.52	1.70
Soil with 10% Biochar-amended	1	E	15.41	1.60
Soil with 15% Biochar-amended	1	F	18.51	1.49
Soil with 5% Biochar-amended	2	G	14.52	1.70
Soil with 10% Biochar-amended	2	H	15.41	1.60
Soil with 15% Biochar-amended	2	I	18.51	1.49
Soil with 5% Biochar-amended	3	J	15.23	1.60
Soil with 10% Biochar-amended	3	K	15.23	1.60
Soil with 15% Biochar-amended	3	L	14.06	1.46

On the contrary, when biochar was applied to soils, there is a reduction in MDD and hence can range to as low as 1.46 g/cm^3 while an increase in OMC was observed reaching up to 18.51%, regardless of sample locations. This is due to the low-specific gravity and implant of biochar structure, which replaces heavy mineral particles with a lighter carbonaceous material yet fewer source in soil density but possessing high concentration and water storing capacity. Therefore, the maximum density can only be attained at a higher moisture level. While addition of biochar may have beneficial effects on soil moisture retention and generate a porous structure in the soil matrix, too high a content of biochar also attenuates compactness of the soil which could have effects other than environmental that relates to engineering properties such as shear strength and slope

stability. Comparable patterns have been observed in other studies, such as Sun's et al. (2023), indicating the continuity of the observed compaction behaviour [53].

3.5. Permeability test

Coefficient of permeability of the silty sand soil and its blends with different proportions of biochar were estimated using falling head permeability tests. Permeability tests on the soil specimens were conducted using the apparatus presented in Figure 8 and the average permeability values that we obtained are reported in Table 5.



Figure 8. Permeability testing of soil specimen

The coefficient of permeability of the mixes is observed to be slightly different. The natural silty sand has an average permeability of value 2.69×10^{-3} cm/sec, thus having a moderate permeability from its general behavior. The permeability is a little higher than in the case without biochar when initially, $k = 2.72 \times 10^{-3}$ cm/sec, then decreases to $k = 2.16 \times 10^{-3}$ cm/sec for the highest biochar concentration. According to this tendency, at low biochar contents the large pores of silty sand matrix remain connected so that water can easily enter the soil. However, when the amount of biochar is increased, not only does the fine particles and the porous concretes in biochar [54], starts to fill into the gaps between those sand grains level, causing sand to become less permeable.

Table 5. Summary of Permeability test.

Mix No.	Average Coefficient of Permeability, K (cm/sec)
A	2.69×10^{-3}
B	2.72×10^{-3}
C	2.16×10^{-3}

3.6. Results of field dry density test

Field dry density of in-situ silty sand was determined using the sand replacement method. Test was performed at three locations to determine the compaction and uniformity of the soil layer (Table 6). The maximum dry densities of soil are within 1.94 and 2.00 g/cm³ and bulk density are within a range of 1.69 to 1.73 g/cm³. The corresponding water content values are ranging from 14.68% to 15.25% indicating similar state of moisture in all test places. The average dry density of the fields soil is ~ 1.71 g/cm³, almost exactly

equal to the laboratory maximum dry density (1.70 1.73 g/cm³) determined by the modified proctor test. The close proximity of these two figures shows that the field compaction was good and that tests were performed within compacted soil near its OPT that is important for fine quality in testing compaction. Such homogeneous, in places, in-situ compacting is necessary for slope stability since if compaction were disturbed by wet conditions an uneven compaction process may result in localized settlement or weak areas, as was mentioned by Guo et al. (2023) and with less strength [55].

3.7. Results of Direct Shear test

For the evaluation of the shear strength characteristics of the natural silty sand, samples collected from Location 1, 2 and 3 were tested through Direct Shear Test. The experiments were performed at three normal levels condition i.e., 37.77 kPa, 113.31 kPa and 188.84 kPa. Correspondingly, the maximum shear stress values for these three cases were 35.74 kPa, 67.77 kPa and 106.76 kPa respectively. The calculated shear stress and the measured values are shown below in Figures 9(a-l).

Shear strength parameters were measured using direct shear tests on the natural and biochar-root-treated mixtures of silty sand sourced from three sites. Cohesion (c) and internal friction angle (ϕ) were calculated based on linear Mohr-Coulomb failure envelopes. The untreated soil had a cohesion and ϕ of 15.94–16.82 kPa and 23.87°–28.43°, respectively, indicating relatively lower shear strength owing to lack of interparticle bonding/ reinforcement. The simultaneous improvement to these two properties by the biochar, which could be increased via root presence, was very attractive. The cohesion increased at 5% biochar and 2% root contents to 24.08, 26.58 and 28.34 kPa, for Sites-1, -2 and -3 respectively, while the angle of shearing resistance (ϕ) increased to 29.49°, 27.87° and 32.43° respectively use the same units like other tables, if possible, with angles pared up mean value is higher therefore better stabilization from there analysis came out as in good way. The optimum effect was achieved at 10% biochar and 2% roots with cohesion values of 33.24, 83.00, and 33.65 kPa and ϕ values of 35.19°, 27.87° and 32.43° in three sites respectively. These findings reveal the marked improvement of interparticle bonding strength and frictional resistance generated by the biochar-root system consortium.

On the other hand, those containing 15% biochar mixtures showed a relatively slight increase ($c = 21.47$ – 28.88 kPa; $\phi = 24.17$ – 29.00 °), which may indicate that excessive biochar addition can decrease effective role of interlocking force between soil particles in spite of root reinforcement effect. In general, biochar-root treatment significantly enhances the shear strength of silty sand. The CA ratio (10% biochar + 2% roots) yields the maximum improvement, which can be used as proper input parameters for numerical slope stability analyses and in agreement with previous studies [56–58]. Figures 10(a-h) illustrate the variation of C and ϕ for different soil mixes.

Table 6. Determination of field density of soil taken from different location.

Location No.	weight of excavated soil from hole (gm)	Weight of sand before test (gm)	Weight of sand after test (gm)	Cone Calibration (gm)	Weight of sand in hole (gm)	Volume of Hole (cm ³)	Bulk Density (gm/cm ³)	water content (%)	Dry Density (gm/cm ³)
1	4505	8485	3310	1550	3625	2294.30	1.96	14.68	1.71
2	5500	9480	3595	1550	4335	2743.67	2.00	15.25	1.73
3	4045	9150	4320	1550	3280	2075.95	1.94	14.94	1.69

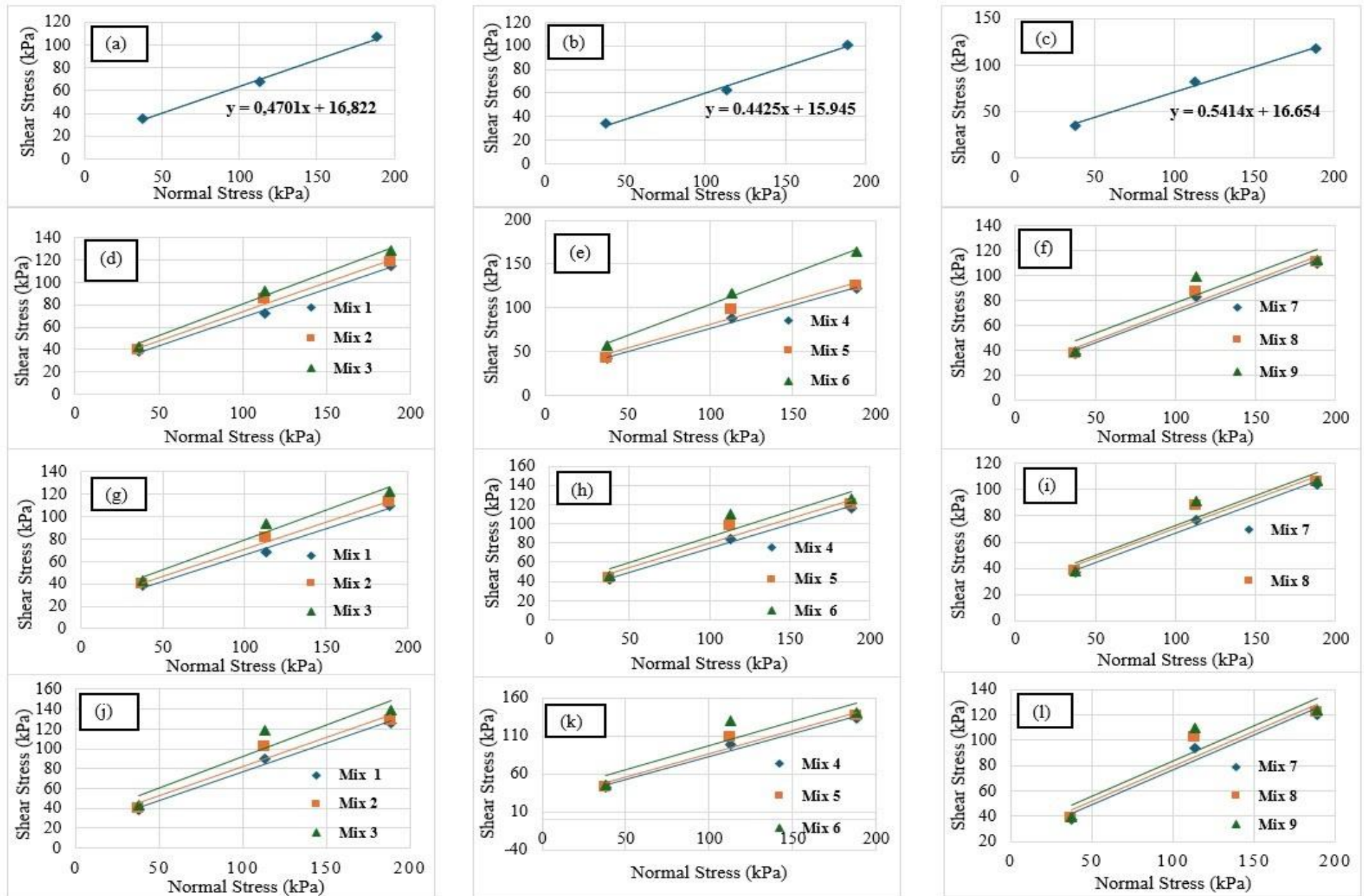


Figure 9. Relationship between maximum shear stress and normal stress for (a) natural soil of location 1, (b) natural soil of location 2, (c) natural soil of location 3 (d) mix1, mix2, mix3 of location 1 (e) mix4, mix5, mix6 of location 1, (f) mix7, mix8, mix9 of location 1, (g) mix1, mix2, mix3 of location 2, (h) mix4, mix5, mix6 of location 2, (i) mix7, mix8, mix9 of location 2, (j) mix1, mix2, mix3 of location 3, (k) mix4, mix5, mix6 of location 3, (l) mix7, mix8, mix9 of location 3

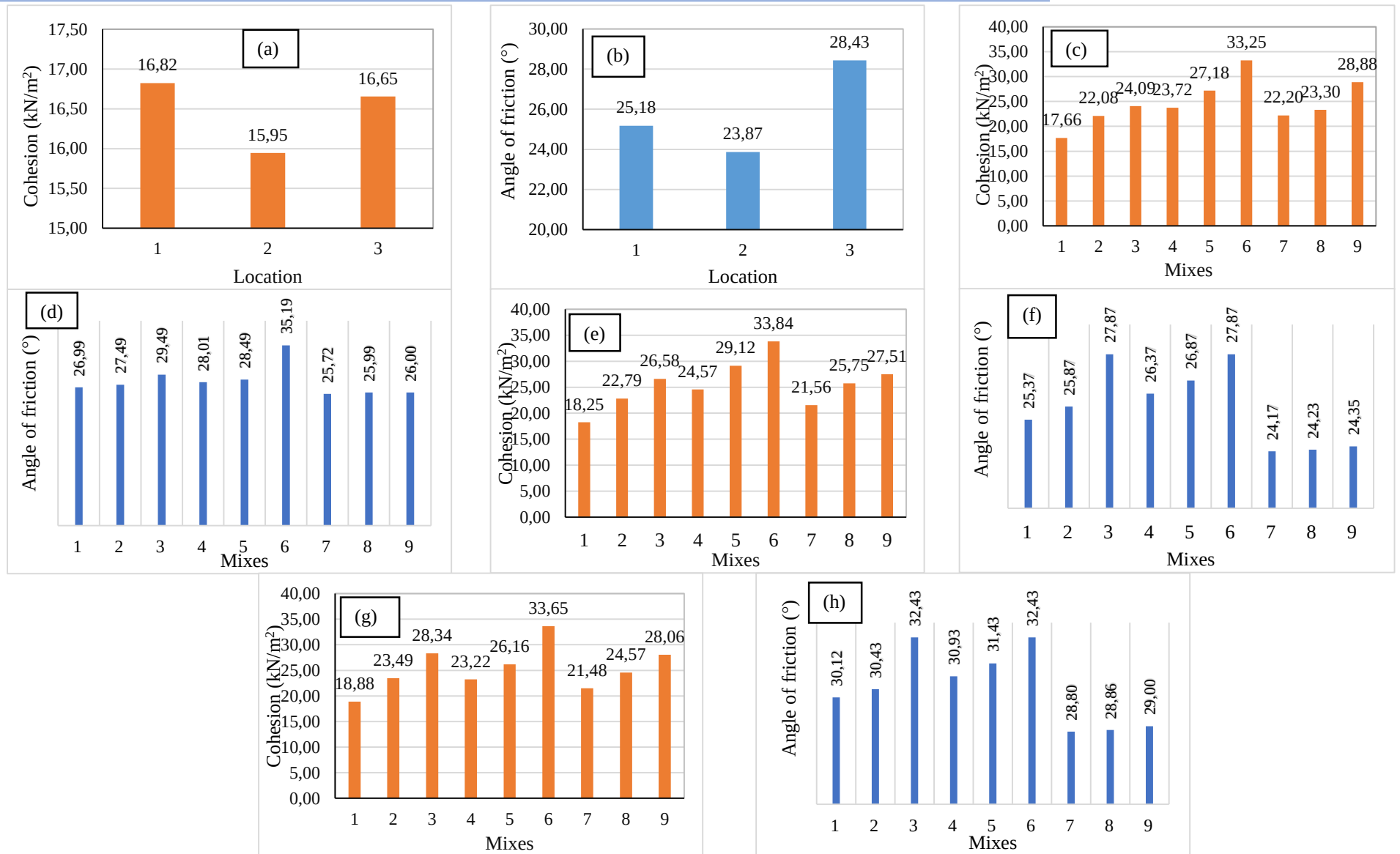


Figure 10. Changes of (a) cohesion of natural soil and (b) angle of internal friction of natural soil (c) cohesion of improved soil mix1 to mix9 for location 1 (d) angle of internal friction of improved soil mix1 to mix9 for location 1 (e) cohesion of improved soil mix1 to mix9 for location 2 (f) angle of internal friction of improved soil mix1 to mix9 for location 2 (g) cohesion of improved soil mix1 to mix9 for location 3 (h) angle of internal friction of improved soil mix1 to mix9 for location 3

3.8. GeoStudio SLOPE/W analysis

The stability of the natural as well as improved soil slopes is assessed using GeoStudio SLOPE/W to assess the efficiency of the adopted method of reinforcement. Slope response was discussed by means of the factor of safety (FOS) and corresponding failure mechanism obtained for the sole purpose in numerical analyses. A comparison was made to understand the effect of improved geotechnical properties on overall slope response. Results show a significant enhancement in FOS amplitude and change of the critical slip surface after biochar–root treatment, indicating that a stable-failure regime is achieved. The FOS distribution for the natural slope is given in Figure 11(a), and Figures 11(b-j) depict the response of the treated slope at Location 1 as a comparison demonstrating that although root reinforcement may not markedly enhance stability, significant improvement might still be achieved by combining biochar with root reinforcing effects.

Similarly, factor of safety changes and critical slip surface evolution after biochar–root treatment at Locations 2 and 3 are presented in Figures 12 (a-j) and 13 (a-j). These results show a general increasing tendency of FOS and a significant displacement of the state surface to shallower and less critical levels, due to greater shear resistance of the modified soil matrix. The changes observed prove the biochar–root system has a systematic enhancement efficiency for various site conditions, and the universality of the reinforcement is shown on different sites.

A sustainable enhancement of slope stability can be achieved at the three sites with biochar–root treatment office without allow to root growth, but the best-rated specimen is differed due to acquisition condition.

At Place 1, the sensitive soil barely passes with a FOS of 1.349. It is observed that the stability increases along with biochar and root content, and Mix 6 (10% biochar + 2% roots) exhibits maximum stability leading to highest cohesion (33.24 kPa), friction angle (35.19°) and FOS (2.294). The combination which gives the best stabilization in this location. The natural soil material at Location 2 has the lowest FOS (1.274). The best performance is with Mix 2 (5% biochar + 1% roots) that obtains the highest FOS peak of 2.008 despite not having the highest cohesion. This suggests that a balanced increase in c and ϕ , rather than maximal parameter values, determines the performance of global slopes at this location.

The untreated slope of Location 3 is relatively stable (FOS = 1.484). Mix 3 (5% biochar + 2% roots) provides the most promising results with the maximum FOS of 2.208 being reached and significant increases in the cohesion and friction angle of 28.34 kPa and 32.43°, respectively.

In general, all sites show considerable improvements in strength from the biochar–root reinforcement. Although in general the positive trend is for moderate percentage of biochar inclusion (5–10%) with higher roots dosages (1–2%), site-specific responses indicate that the optimal mix depends on local soil vehicle and its interaction with reinforcement.

3.9. Limitations of the study

The paper under consideration examines the impact of biochar amendment and root reinforcement on the soil mechanical behavior and slope stability on the samples found in the location of erosive soil in the surroundings of the Dinajpur Rubber Dam. Although the

outcomes suggest a significant enhancement of slope stability, a number of constraints are to be considered in regards to sediment processes and erosion that the reviewer points out.

Laboratory experiments and numerical simulations are used as the main means of the analysis, which might not be entirely applicable to the complex field conditions. Specifically, no direct measurement of the sediment transport and inflow of the transboundary river system was made and therefore the effect of the upstream sediment input to local erosion and deposition could not be measured. As well, extensive field based soil characterization such as laboratory identification of soil texture and accurate estimation of erodibility parameters were also constrained. The study conceptually is related to the process of erosion, but the complete application of the Universal Soil Loss Equation, including site-specific factors (R, K, LS, C and P) was out of scope of this work. Lastly, the evaluation of seasonal variability and long-term performance of biochar and vegetation is limited due to the lack of long-term monitoring. These aspects will be covered in future research by using field-scale measurements, sediment sampling and detailed erosion modelling.

4. Conclusion

In this research, the geotechnical performance and slope stability behaviour of natural silty sand and biochar–root–reinforced soil was investigated using combined experimental test and numerical simulation. Laboratory tests verified that the undisturbed soil is low-plasticity sandy silt with moderate permeability and low shear strength. Adding biochar has been shown to enhance soil parameters which impact erosion and shallow failure. Also, the addition of biochar and root reinforcement had remarkable impact on properties compaction, permeability and shear strength; thus, determining the behaviour of slope stability. It's concluded that there was a significant improvement of the factor of safety for all reinforced soil mixtures compared to untreated for numerical slope stability analyses. The findings show bio-reinforcement improving not only strength properties but also environmental-friendly choice of stabilization compared with the traditional method. The key finding of this study is summarized here:

- ✓ As per laboratory test results, the soils of the three locations have a specific gravity between 2.68 and 2.73, indicating that they have normal sandy to silty soils.
- ✓ The grain size analysis shows, the sand in Locations 1, 2, and 3 has a well-graded sand. The content of sand lies between 56% and 75% which means that it is mainly sandy soil.
- ✓ With a plasticity index of 1.04 to 1.72, the values of the Atterberg limits indicate low plasticity of the soils implying that the soils are non-expanding and can be used in stabilization activities.
- ✓ The results of the Modified Proctor Test that indicates good compaction properties of natural soils are MDD values equal to 1.94 g/cm³ to 1.95 g/cm³ and OMC values equal to 11.2% to 11.4%.
- ✓ Addition of biochar leads to a decrease in MDD and an increase in OMC, which means that the low density and high porosity of biochar increase the water retention potential of soils and reduce the soil compaction.

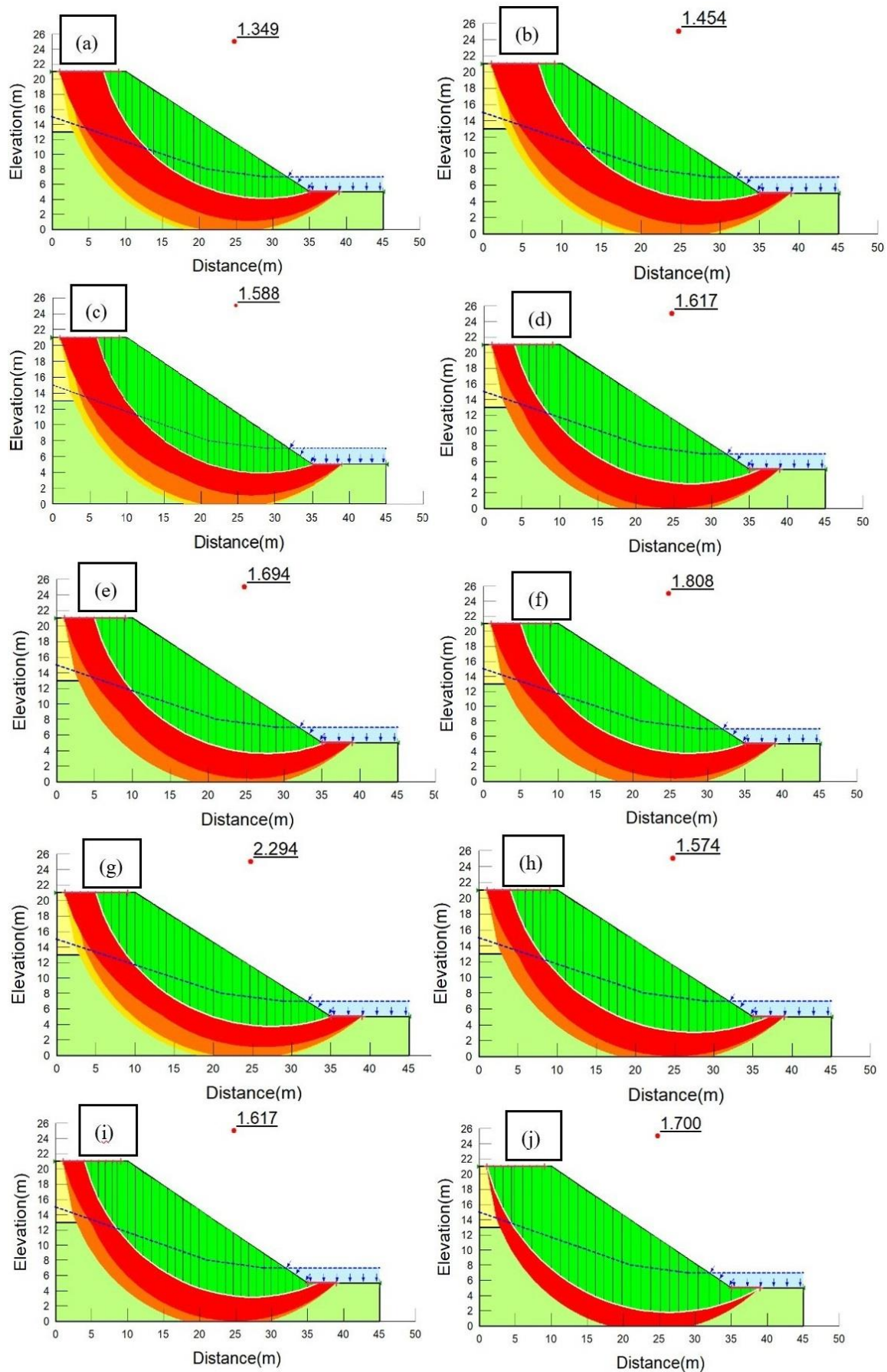


Figure 11. FOS for location 1 (a) raw soil (b) mix1 (c) mix2 (d) mix3 (e) mix4 (f) mix5 (g) mix6 (h) mix7 (i) mix8 (j) mix9

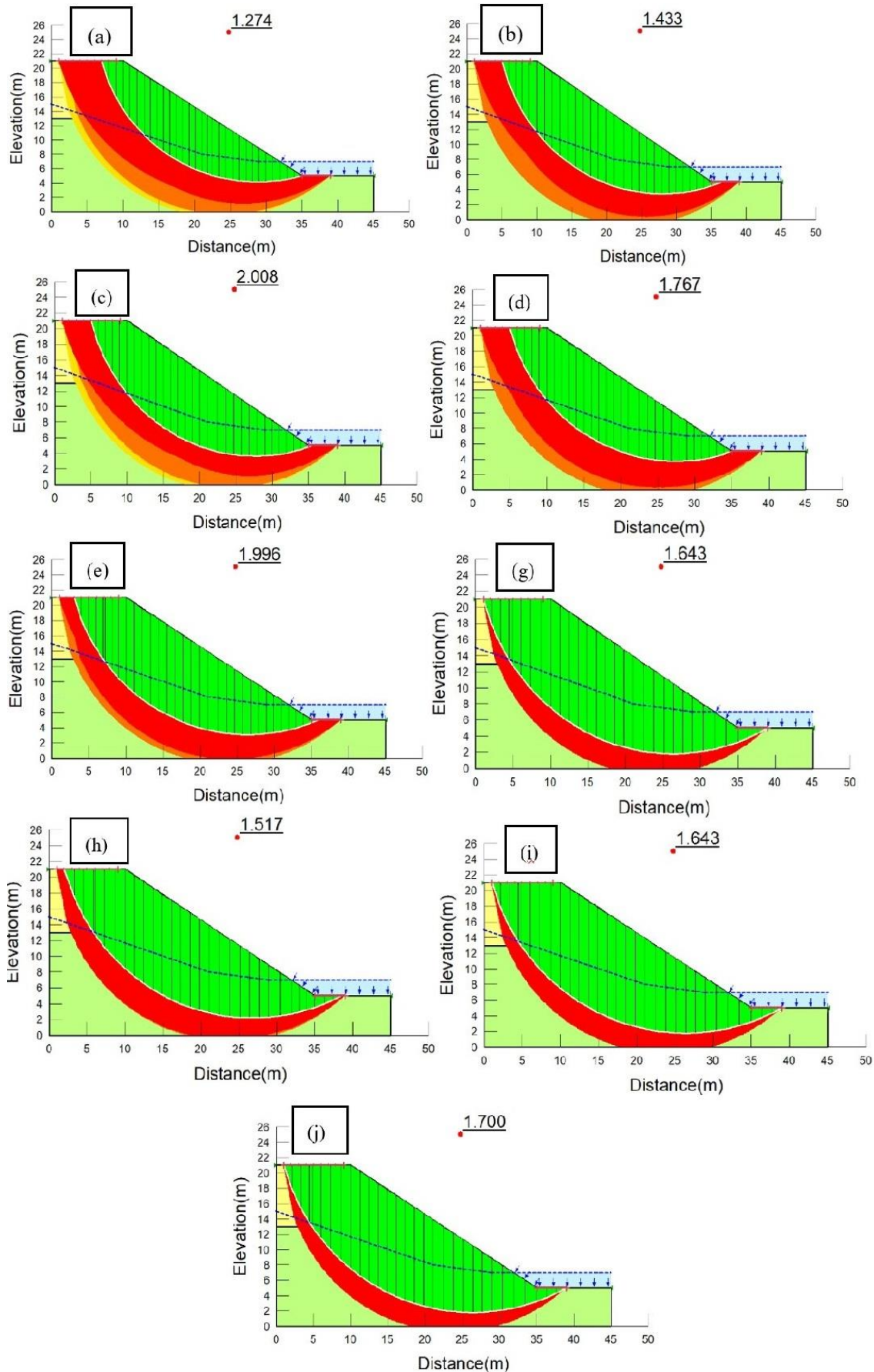


Figure 12. FOS for location 2 (a) raw soil (b) mix1 (c) mix2 (d) mix3 (e) mix4 (f) mix5 (g) mix6 (h) mix7 (i) mix8 (j) mix9

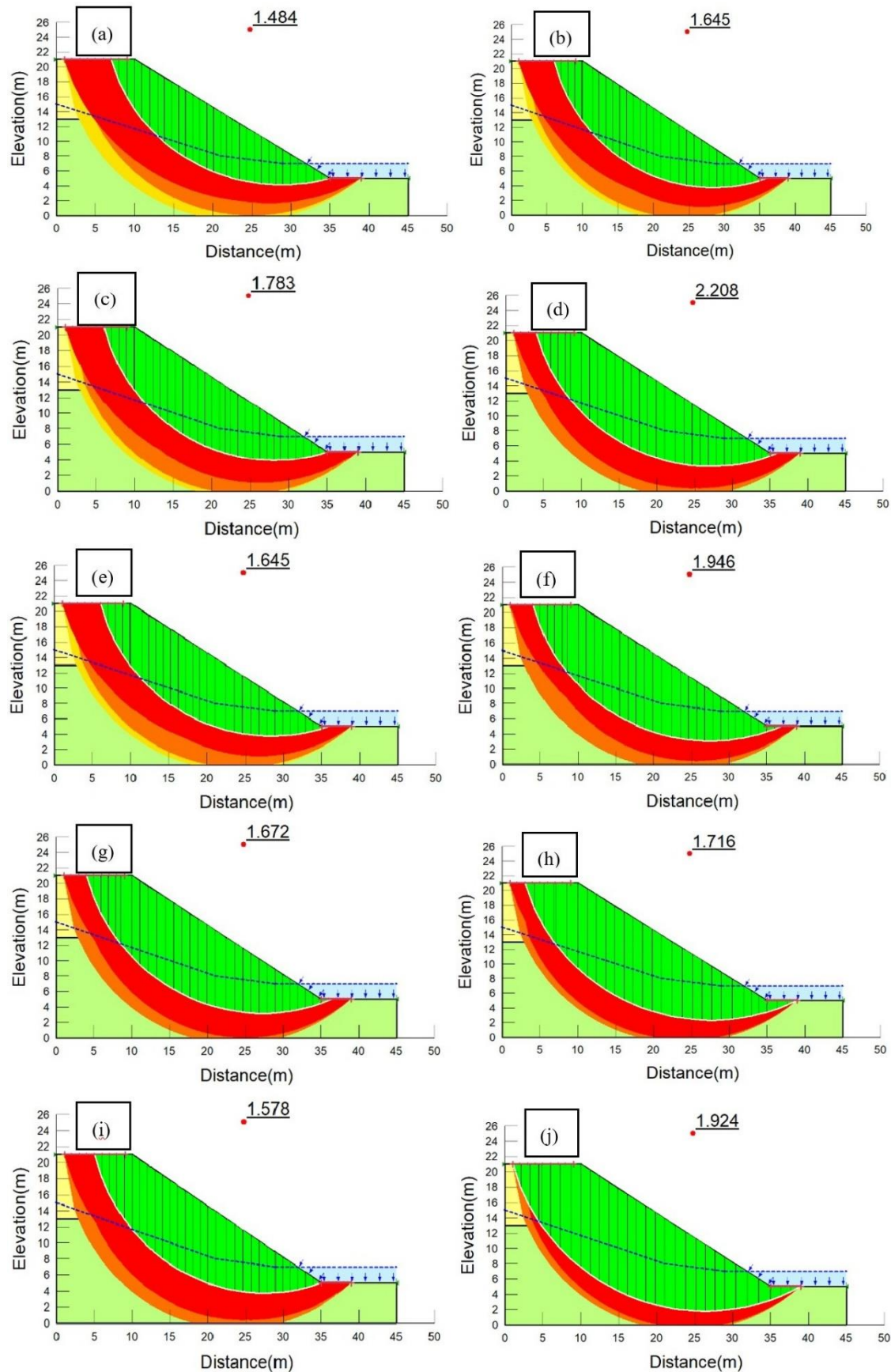


Figure 13. FOS for location 3 (a) raw soil (b) mix1 (c) mix2 (d) mix3 (e) mix4 (f) mix5 (g) mix6 (h) mix7 (i) mix8 (j) mix9

- ✓ Facilitated by the results of the permeability test (2.16×10^{-3} - 2.72×10^{-3} cm/s). The permeability of the soils is moderate and characteristic of silty sand mixtures.
- ✓ The field density test indicates moderate in-situ compaction that produces dry density values of 1.69 g/cm³ to 1.73 g/cm³ and relative compaction of 86.9% to 89.7%.
- ✓ Lower shear strength is confirmed through the Direct Shear Test of natural soil and this means that it requires reinforcement in order to enhance stability.
- ✓ The maximum shear strength is obtained with 5-10% biochar and 2% root content as a mixture and there is a good synergy between biochar and root content.
- ✓ At higher levels of biochar, the strength gain is somewhat reduced (15%) due to the increasing number of voids and less particle contact with roots although it is still positive.
- ✓ In general, the findings demonstrate that biochar and root reinforcement significantly enhance soil stability, cohesiveness and shear strength without altering the sustainable and environmentally friendly environment to sustain slope stabilization.
- ✓ Some further evidence of biochar and roots efficacy in enhancing slope stability is provided by numerical modelling in the GeoStudio Slope/W which also demonstrates that the factor of safety increases with the inclusion of biochar and roots.

Conflict of Interest Statement

The authors declare that there is no conflict of interest.

CRediT Author Statement

Md. Belal Hossain: Supervision, Conceptualization, Validation, Writing-Original draft preparation, **Md. Nazmul Islam:** Software, Methodology, Laboratory testing, Writing – review & editing **Md. Mahabub Rahman:** Supervision, Investigation, Validation, Writing-Original draft preparation **Ashikur Rahman Bhuiyan:** Data curation, Software, Writing – review & editing **Faiyaz Ur Rahman:** Data curation, Software, Writing – review & editing **Md. Ayat Islam Roke:** Data curation, Software, Writing – review & editing.

Declaration of Generative AI in the Writing Process

The authors declare that no generative AI or AI-assisted technologies were used in the preparation of this manuscript.

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