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Research Article

Ecological and Bioengineering Studies for Stabilizing the Wad Medani-Sennar Roadside Slope Linking the Gezira and Sennar States

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The erosion of the highway embankment slope's soil along the Wad Medani-Sennar road is a significant issue, as there are many traffic accidents on this road, with an average of 15 to 25 fatalities per annum. It was thus decided to investigate this issue to find a method to protect slope from erosion on this road and to provide new approaches to slope erosion knowledge gap in Sudan. An engineering survey was carried out, followed by geotechnical studies, experimental work and interviews with academic experts regarding native vegetation in the survey area. These include measuring the eroded parts of the road; studying cross- sections of the road; soil experiments to check the strength, compaction and particle size distribution; and a native vegetation survey to check for suitable plants that could be used to control the slope erosion. It was found that an appropriate bio-engineering method to stabilize the slope soil against erosion due to rainfall was to cultivate the grasses Cynodon Dactylon and Vetiver on the slopes. In conclusion, that using native vegetation for eco -protection, was an excellent solution to the problem based on the climate, native vegetation, and type of soil in Sudan and it reduces the accidents.

1. Introduction

In order to meet the needs of a growing population and the emergence of new cities, new roads need to be built to meet the needs of the population and their right to travel and move from place to place and to transfer goods for both private and commercial enterprises. The budding economy in Sudan thus requires the construction of new roads; however, this has led to serious soil erosion problems around the roads [1].

The capital cities of the two most important states in Sudan, Gezira, and Sennar are linked by the Wad Medani-Sennar road. Sennar has a large dam for producing electricity and provides electrical power to all Sudanese states. Gezira is an agricultural state and has the largest agricultural scheme in Africa (Gezira Scheme) [2]. The Gezira Scheme is found in the area between the two capital cities. The Wad Medani-Sennar road is thus extremely important as it is used to transfer crops from production sites to wholesalers and retailers. The road is also the national carrier between the cities of the south and the north.

The simplest way and most cost-effective method to stabilize soil surfaces are to use vegetation, especially native vegetation, in order to prevent soil erosion. In general, local vegetation is not expensive, is easy to maintain, and is in harmony with the surrounding landscape. Native vegetation is also adapted to the local environment, which is dry, and thus are naturally water conserving. The use of native vegetation results in lower maintenance costs, conserves natural resources, and increases the biodiversity of the region, resulting in benefits for the local wildlife [3].

The main objective of this paper is to study the effectiveness of the ecoprotection method in reducing erosion to protect the Wad Medani-Sennar road, with the

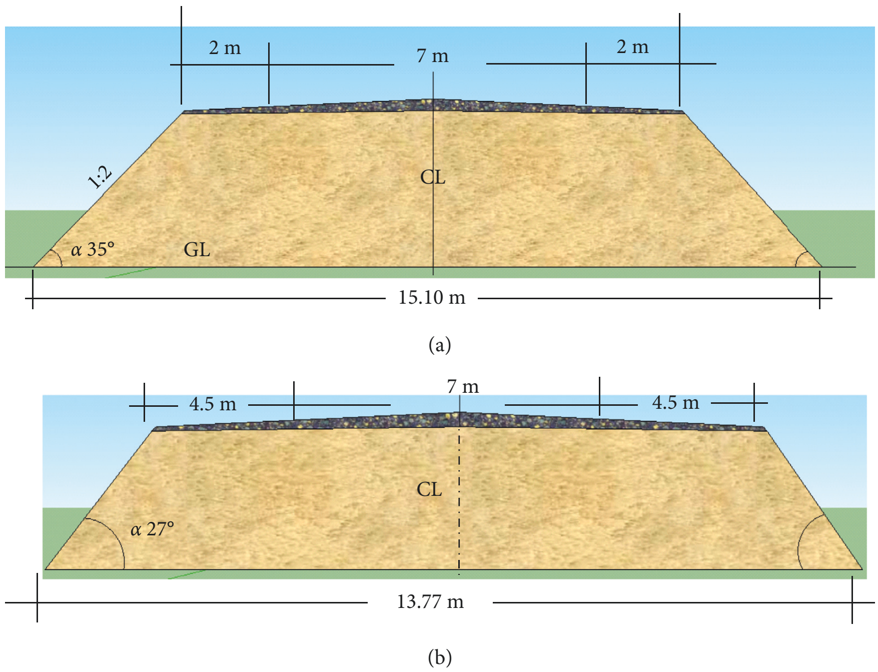

Figure 1: Cross sections of the Wad Medani-Sennar road.

added benefit of reducing the number of traffic accidents on this road.

2. Materials and Methods

2.1. Study Area. This research was conducted between two states in Sudan, Gezira, and Sennar. The study focused on the road linking the capital cities, Wad Medani and Sennar, of the two states. The Wad Medani-Sennar road is part of the long national road in central Sudan.

2.2. Site Description. The Wad Medani-Sennar road passes through most agricultural areas in Sudan, including the Gezira Scheme, and through Sennar State, which has Sennar Dam. A survey of the road shows that there is no surface water drainage system, neither main channels nor side ditches, to remove surface water from the road.

Figure 1 shows two cross sections of the Wad Medani-Sennar road. The engineering measurements showing the different angles of the slope are shown, as well as the variation in slope heights. The slopes range from 27° to 45° in different sections, and slope heights range between 2.5 m and 4.5 m.

2.3. The Problems of Wad Medani-Sennar Road. It is known that Sennar State enjoys a good autumn rainfall, contrary to other Sudanese states. The engineering measures found that the autumn season affects the materials of the side slope and causes soil erosion. The intensity of the rainfall during autumn works to erode the road slope, and this eroded part causes traffic accidents every year during autumn.

Based on the records of police traffic administration and highway and bridges authorities, it is very dangerous for vehicles to park on the roadside shoulders during the rainy season, as there are 15–25 accident victims annually.

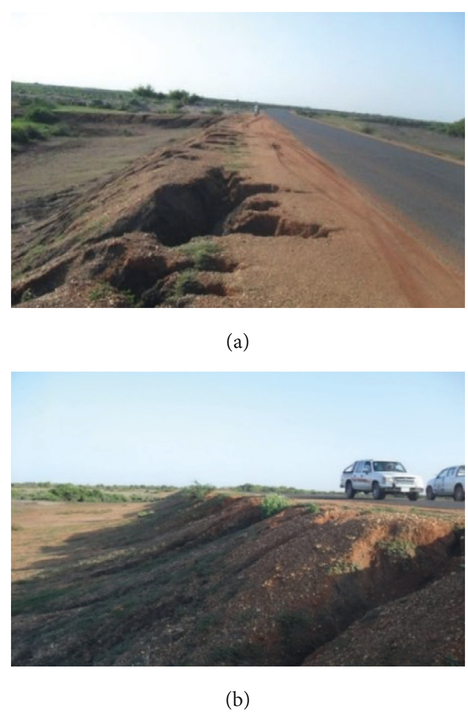

Figure 2: The eroded slope of Wad Medani-Sennar road.

This study focuses on the most eroded section of the Wad Medani-Sennar road. The total length of the eroded section was 650 m, and this can be considered the most dangerous section of the road. Typical examples of erosion along this section are shown in Figure 2. It is clear that the

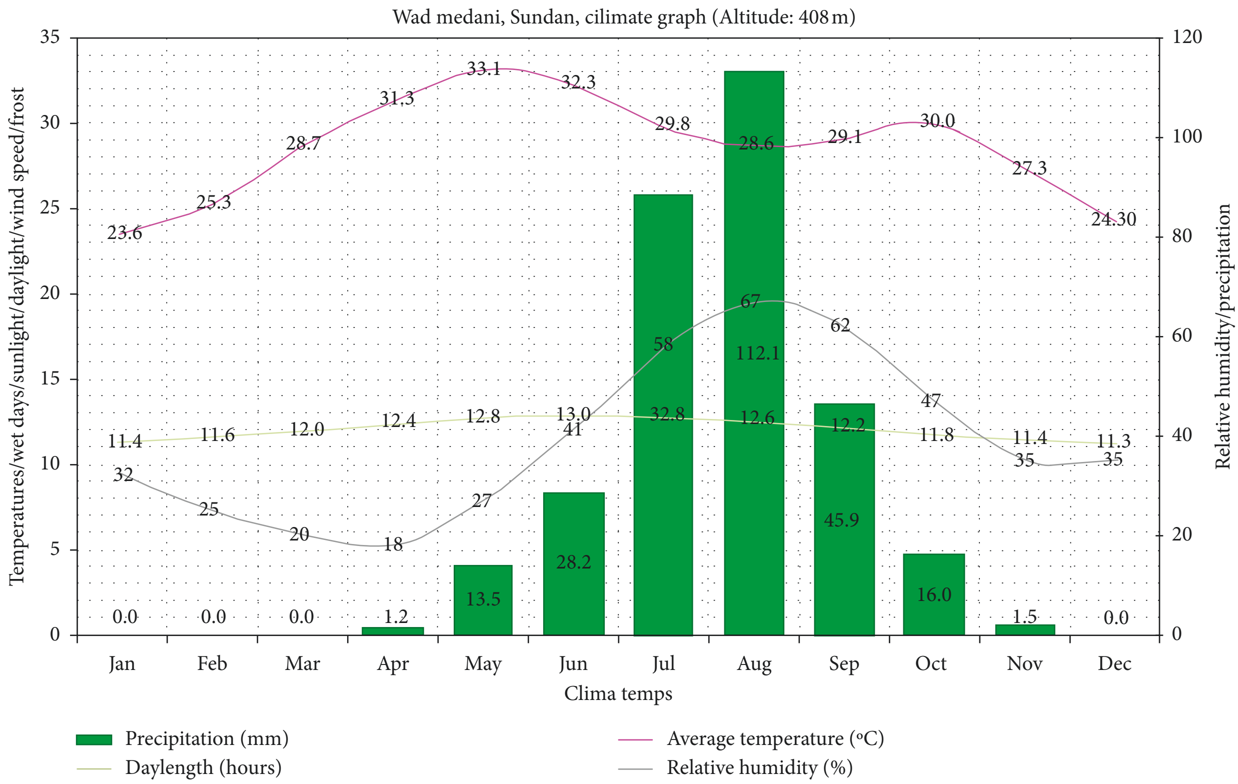

Figure 3: Wad Medani, Sudan, is at 14°24′N, 33°29′E.

situation was dire and that finding a suitable method to curb this erosion was very important [4].

2.4. The Climate of Gezira. The climate of Gezira State is tropical. Figure 3 shows the average temperatures for Wad Medani in Gezira, and climate characteristics for Gezira, based on official government data [5], are as follows:

(1) Rainfall was measured at four monitoring stations: Al Shabarga, Algeria, Al Hosh, and Umm Al Qura. The south of Gezira is an equatorial rainy zone which has its dry season from December to January. The most rainfall was recorded between July and September. The average annual rainfall is 350 mm to 373 mm.

(2) An average annual minimum temperature of 24.6°C and an average annual maximum of 36.5°C have been recorded.

(3) Bright sunshine on average of 7.5 h to 10 h per day.

(4) The humidity in Gezira ranges from 70% to 80%. This decreases in the dry season from 32% to 18%. Sudan is a high humid African country because it has two rivers, the Blue Nile and the White Nile, in the center of the country and the Red Sea in the eastern part of Sudan. The average humidity is 22%.

(5) Southerly and south-westerly wind predominate in summer, while northerly and north-westerly winds predominate in winter. This causes dust and reduces visibility during daylight hours.

2.5. The Climate of Sennar. Sennar City is located at 13°33′N, 33°37′E, and is in a semiarid zone, being very hot during summer. According to the claimate information [6], Sennar can also be classified as being situated in a tropical climate zone. The mean annual temperature of Sennar is 28°C; it has a monthly average temperature of 9.1°C and an annual precipitation of 420.1 mm [6]. The climate information is summarized in Figure 4.

The intensity of the rainfall in autumn creates hazards on the Wad Medani-Sennar road as the soil erodes from the slopes [7]. It is clear that there are no slope protections in places, such as side ditches or main channels, to remove surface water from the road. Gezira and Sennar states are both high rainfall zone regions, and usually, when constructing the fill slope for the road, mechanical protection is made. This lack of protection for the Wad Medani-Sennar road has caused the slopes to fail due to rainfall erosion.

The fill slopes for road construction are categorized as man-made slopes, and advanced research in many developed countries has shown the effectiveness of using native vegetation in stabilizing slope erosion [8]. This study has investigated the ecological method of using plant cover on the slopes to protect them from erosion. Various local plants were investigated as the best to use on the eroded section along Wad Medani-Sennar road. This will hopefully reduce human losses caused by traffic accidents as well as solve environmental problems due to soil erosion. Rehabilitation of eroded slopes is costly and is a natural disaster. Therefore, it is necessary to consider new ways to protect the slopes and reduce the loss of life. There is also

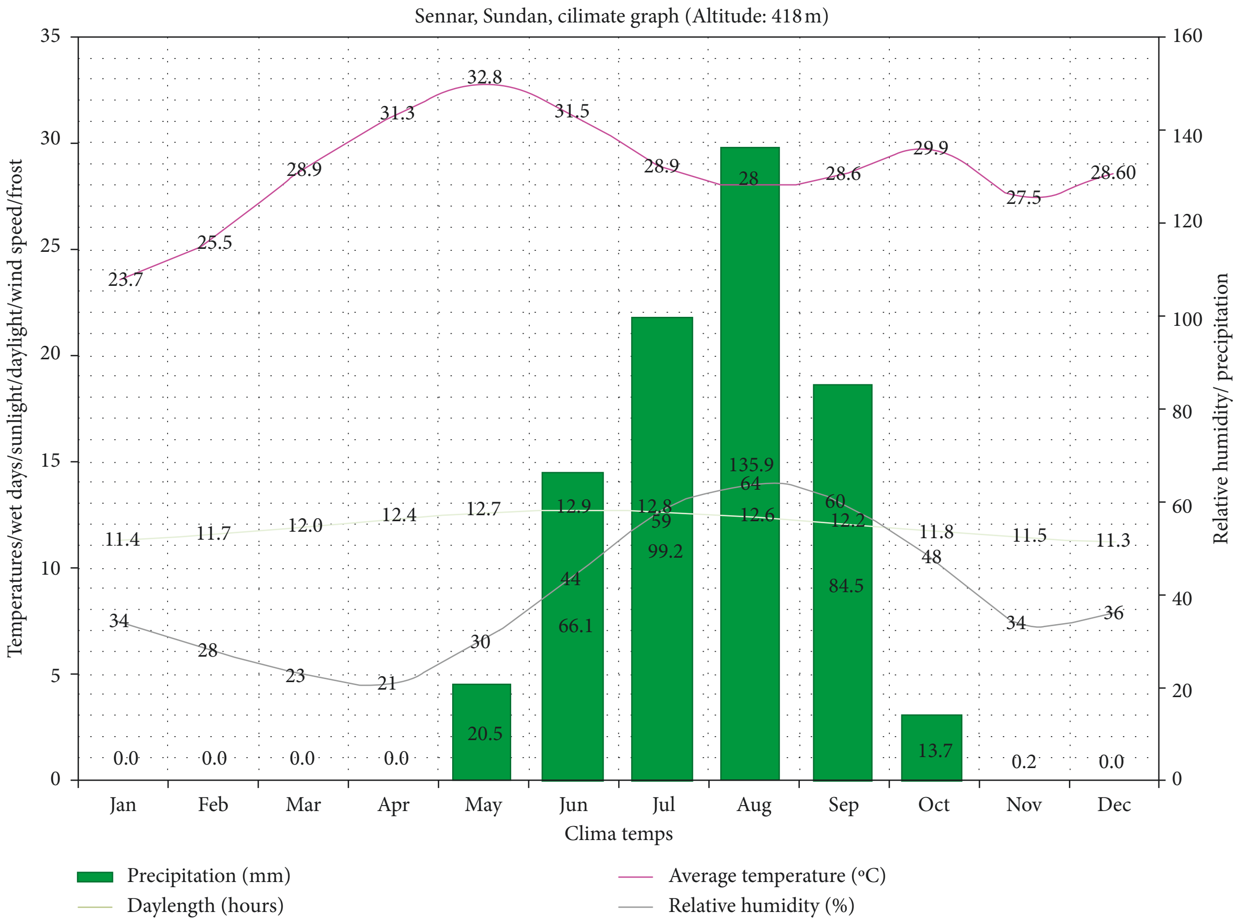

Figure 4: Sennar, Sudan, is at 13°33′N, 33°37′E.

a need for a cost-effective and sustainable solution, particularly because Sudan is a developing country. Ecological protection, using vegetation cover, is one of the most appropriate and cost-effective ways to solve the erosion problem of the Wad Medani-Sennar road. It is aesthetically pleasing, fill slopes are stabilized, and annual maintenance costs are low.

2.6. Objectives of the Study. The main aim of this study is choosing the most suitable native vegetation and species to plant in the Wad Medani-Sennar fill slopes. Plants found naturally in the region of the road were studied, and those most suitable for use as an ecological and bioengineering method of protection against slope failure were selected.

2.7. Classification of Soil and Slope Types. A study to classify the soil and soil types of the slopes along the Wad Medani-Sennar road was carried out using particle size distribution (sieve analyses) and Atterberg limit tests.

3. Methodology

A literature survey was conducted, followed by engineering measurements, and field experiments were then carried out on the road site in order to classify the soil types along the Wad Medani-Sennar road.

3.1. Literature Survey. The survey covered the related published work to clarify the methodology and to explain bioengineering methods and modern theories in the area of using vegetation to protect from and reduce erosion due to rainfall.

3.2. Determining the Native Vegetation. For identification of local plant species and vegetation occurring around the slope areas, the help of experts was required, because some vegetation was difficult to identify. Also, the experts can easily check the best plants to grow for the study and the costs of these plants.

3.3. Vegetation Properties. The properties of native vegetation, such as plant density, distribution, height, leaf shape, climatic condition, and soil surface covering, were investigated. All of this information is of use in selecting the most suitable local vegetation to use as ecoprotection on the Wad Medani-Sennar road.

Figure 5: Root system in the soil.

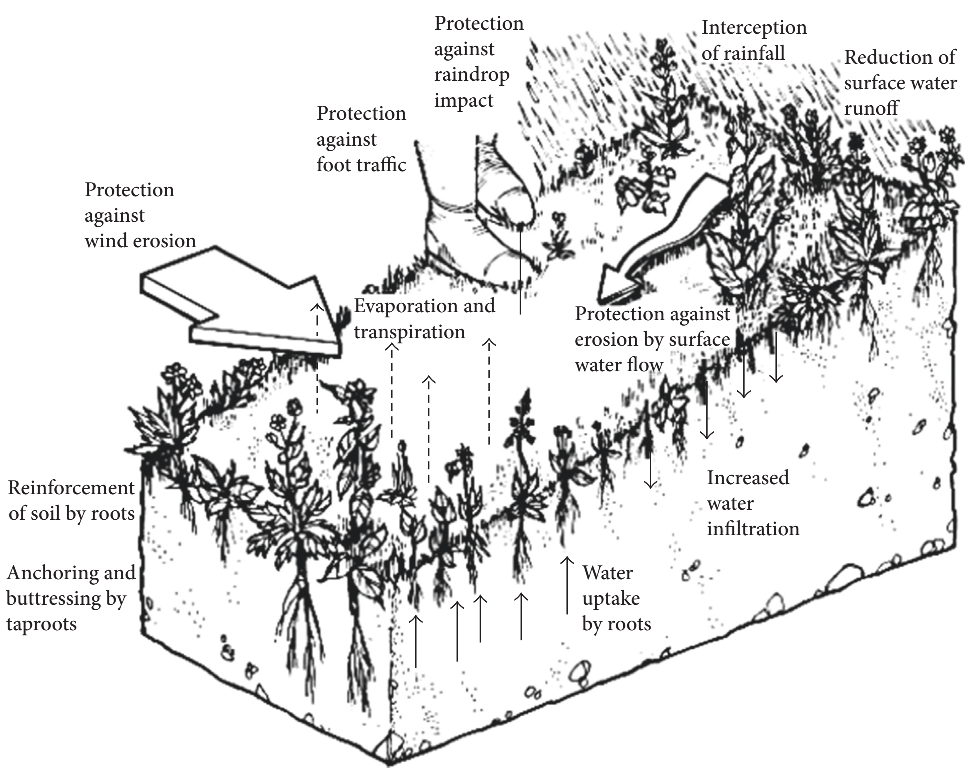

Figure 6: Influences of vegetation on the slope stability.

3.4. The Mechanism and Role of Vegetation in Stabilizing the Soil on the Slope. The traditional mechanical methods of protecting slopes against erosion have an immediate effect, but are costly, both to construct and to maintain. Bioengineering, or ecoprotection, that is, planting local vegetation on the slopes, is both cheaper and easier to maintain. One of the main benefits of using vegetation is that it is self-perpetuating [8].

Rainfall and runoff on the soil surface increase infiltration of pore water, and this is the main cause of erosion. Plant cover significantly reduces infiltration caused by rainfall, thus reducing erosion.

Figure 7: Field density test.

Figure 8: Soil classification tests at WMTC.

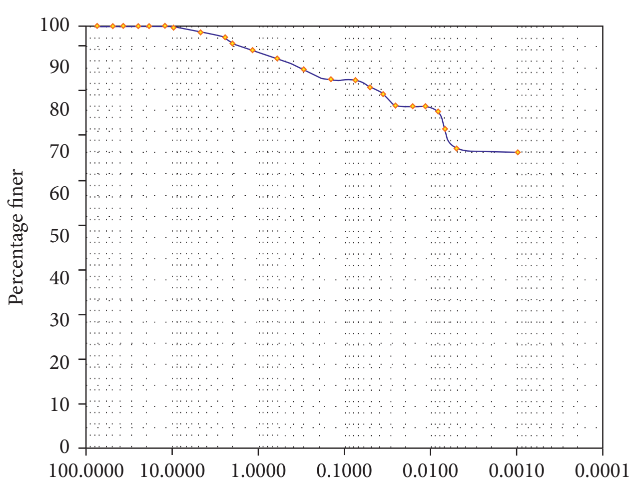

Figure 9: Sieve analysis diagram.

3.5. Slope Surface Protection. The protection of the surface of the slope is a method of reducing rainfall infiltration during autumn, and this can be done using shotcrete plastering, or using blocked masonry or applying rep rap techniques. All these methods have less aesthetic value and are costly compared to using ecological methods such as using plants. Slope stability and vegetation are interrelated; plants that are growing on a slope hinder slope erosion and increase the stability of the slope.

3.6. Vegetation. Based on data from the past few years, the importance of vegetation in protecting against soil erosion and in controlling slope failure is clear. Vegetation also plays the basic role of preventing the soil surface from erosion that occurs due to rainfall intensity, sunlight, and wind [9]. Vegetation covering a slope can control slope failure due to its root system mechanism, as depicted in Figure 5. It is clear that the roots penetrate quite deeply into the soil.

According to Singh and Rathod [9], there are four ways that vegetation influences slope stability. These are shown in Figure 6. Protection is given against wind erosion, foot traffic, the impact of rain, and removal of water, due to the mass of vegetation and the mechanical reinforcement of roots, as shown in Figure 5.

Sediment generation is controlled by vegetation and maintains the biodiversity. The kinetic energy of raindrops is the main cause of soil particle disturbance [8]. Figure 6 depicts the use of vegetation in civil engineering and shows how vegetation protects the soil on the slope [8]. The kinetic energy of the raindrops is dissipated by the vegetation. This is one of the advantages of using plants to prevent erosion. Another advantage is that plants can grow rapidly and cost less to maintain.

3.7. Vegetation Survey. Plants found on eroded sections of the Wad Medani-Sennar road were classified according to the kind of plant and general vegetation, their root systems, and other salient properties. Several different vegetation types were found on the side of the road, and it was found that the vegetation varied according to the height of the slope. Suitable plants were then identified according to their location on the road. Plants were photographed, and the common names, root systems, climatic conditions, ability to cover the slope, and so on were recorded. Residents assisted in the classification of some vegetation types. Important factors used to identify vegetations were the leaves, flowers, and whole plants.

In order to understand how local plants can stabilize embankment slope soil, information regarding slope stability as a function of the soil type, soil age, and soil compaction was required. The collected plant and soil data were discussed with botanical specialists, and based on the plants and plant density around the slope areas, suitable vegetation was selected in order to carry out this research.

4. Classification of the Soil

Soil samples were collected from various sections along the Wad Medani-Sennar road. Figure 7 shows how soil density testing was carried out in the field, and Figure 8 shows how

Table 1: Soil separated grain size and limits according to UCS, USDA, and AASHTO specifications.

Grain type	Gravel (mm)	Sand (mm)	Silt (mm)	Clay (mm)
Unified Soil Classification System	76.2–4.75	4.75–0.075	Fine silt and clay <0.075	
US Dept. of Agriculture (USDA)	>2	2–0.05	0.05–0.002	<0.002
AASHTO	75–2	2–0.05	0.05–0.002	—

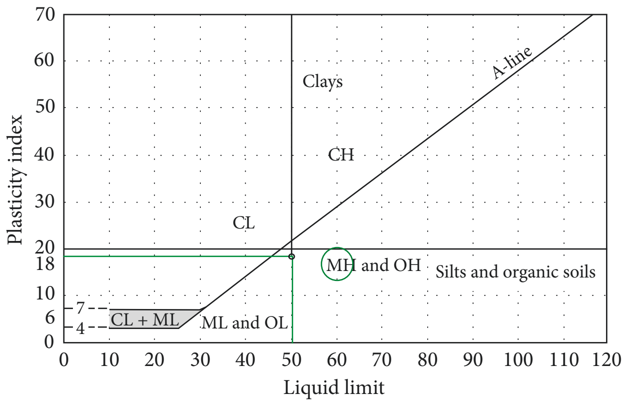

Figure 10: Liquid-plastic limit chart.

Table 2: Grain-size distribution results.

Type of soil	USCS	USDA
Coarse gravel	18%	26%
Sand	39%	32%
Sit and clay	43%	42.3%

the washed sieve analysis and hydrometer test was carried out at Wad Medani Technological College (WMTC). Washed sieve analysis allows for an accurate picture of particle size distribution in the soil. This distribution was determined according to USCS standards and is summarized in Figure 9. The different types of soils, classified according to grain size, are gravel, sand, silt, and clay.

The results have shown that there are no major differences in soil types. This is because the two states lie in the same semiarid zone and have similar climates. After conducting the soil classification experiments, the quantities of the different soil elements (gravel, sand, and silt and clay) were calculated based on the Unified Soil Classification System (USCS). Conducting liquid limit and plastic limit tests were carried out for the samples, and the soil was then further classified based on both the USCS and the United States Department of Agriculture (USDA) standards [10]. The American Association of State Highway and Transportation Officials (AASHTO) also developed soil size limits for gravel, sand, silt, and clay. These limits are all shown in Table 1.

As mentioned previously, the vegetation most suitable for experimenting was determined regarding their relevance to the climate and soil types. All vegetation information, including plant name, density, height, propagation rate, leaf shape, soil, and climate, was recorded in this research.

5. Results and Discussion

5.1. Soil Classification. In general, the soil is composed of varying amounts of gravel, sand, silt or clay, and is classified according to the size of the soil particles. Sieve results revealed that more than 50% of the particles are finer than 75 μm. According to the USCS, this is below A-line in Figure 10, and the soil is thus MH (silt with high plasticity). Table 2 shows the sieve analysis of a selected sample, classified according to USDA and USCS standards [11]. The average particle size distribution in the soil was gravel = 4.1%, sand = 8.6%, silt = 75.3%, and clay = 12%.

The moisture content of the soil was determined to be WC = 22.1%, PI = 18%, PL = 32%, and Ll = 50%. Soil field density tests showed a bulk density γd of 1.510 and a dry density γd of 0.939. Chemical testing and soil nutrient experiments have shown that the OM 0.4-0.5 less than 1%, and N is 0.03-0.4% nitrogen in the soil, P is 2–4 ppm phosphorous, and K is 0.5-0.6 m/100 g potassium/100 g of soil. The soil pH was found to range between 7.5 and 8.5.

In this section, the study illustrates the soil analysis, along with a detailed description of the type of soil according to sieve analysis, moisture content, density (field density by sand cone method), hydrometer and (Liquid Limits) tests.

The geotechnical properties of soil, such as grain-size distribution, plasticity, compressibility, and shear strength, can be assessed using proper laboratory [10] is summarized in Table 3, which shows the sieve analysis results for slope soil found on the Al Hosh highway.

Using the water content results, liquid-plastic limits and shrinkage limits were determined. Applying the Atterberg limits to these results allowed for the determination of the soil type based on AASHTO Designation T89, which was modified for use by the New York State Department of Transportation. Figure 10 is a liquid-plastic limit chart for the various soil types. It shows a sample 'flow curve' that can be used to determine the liquid limit. The water content corresponding to 25 blows was reported and was read from the "flow curve" as the liquid limit.

The determination of the percentage of water content in soil is an important factor in soil classification. DAS 2002 presents a clear procedure for the calculation of moisture content. Table 4 shows the average moisture content for the Wad Medani-Sennar road, for some test samples.

Casagrande proposed the Unified Soil Classification System (USCS) in 1942, which was later revised by the Army Corps of Engineers. This system is currently used in all geotechnical work [12]. Table 5 summarizes the symbols used by the USCS to describe the different soil types.

Table 6 shows the results of different soil experiments, using DAS 2004 to classify the soil [13]. A hydrometer was

Table 3: Sieve analysis test result.

Sieve no.	Sieve opening (mm)	Mass: sieve (g)	Mass: sieve + retained soil (g)	Mass: retained soil (g)	Retained soil (%)	Cum. retained soil (%)	Pass-ing (%)
3″	75.0	1057.0	1057.0	0.0	0.0	0.0	100
2″	50.0	1199.0	1199.0	0.0	0.0	0.0	100
1.5″	37.5	1084.0	1084.0	0.0	0.0	0.0	100
1″	25.0	1187.0	1187.0	0.0	0.0	0.0	100
¾″	19.0	716.0	716.0	0.0	0.0	0.0	100
½″	12.5	584.0	584.0	0.0	0.0	0.0	100
$^3/_8$″	9.5	586.0	590.0	4.0	0.5	0.5	99.5
No. 4	4.75	567.0	577.0	10.0	1.3	1.8	98.3
No. 8	2.36	390.0	399.0	9.0	1.1	2.9	97.1
No. 10	2	355.0	365.0	10.0	1.3	4.1	95.9
No. 16	1.18	313.0	325.0	12.0	1.5	5.6	94.4
No. 30	0.6	287.0	303.0	16.0	2.0	7.6	92.4
No. 50	0.3	462.0	482.0	20.0	2.5	10.1	89.9
No. 100	0.15	261.0	281.0	20.0	2.5	12.6	87.4
No. 200	0.075	424.0	425.0	1.0	0.1	12.8	87.3
Pan	—	—	435.0	698.0	87.3	100.0	—

Table 4: Water content test.

Number	Item content no.	Content no. (W)	Test weight (kg)
1	Mass of empty Cont.	W1	0.070
2	Mass of cont. + wet soil	W2	0.134
3	Mass of cont. + dry soil	W3	0.122
4	Mass of moisture	W2–W3	0.012
5	Mass of dry soil	W3–W1	0.052
Moisture content	$((w_2 - w_3)/(w_3 - w_1)) \times 100$	W%	22.1

Table 5: Symbols are used for identifying the soil types.

Symbol	G	S	M	C	Pt	H	L	W	P
Description	Gravel	Slit	Sand	Clay	Peat and high organic soils	L-P	W-G	P-G	Peat and high organic soils

Table 6: Soil type classification under (USCS) (Das 2004).

Observation	Results
The % finer than 200 (F200) = 75.3% > 50%	Finer grained soil
Sand % = 8.6% > gravel % = 4.1%	Group symbol starts with prefix S
Fines % = 75.3%	Using the plasticity chart, it is MH
Soil type-MH–silt with high plasticity	

used to test the fine-grained soils. Table 7 shows the experimental results for some samples from the Wad Medani-Sennar road.

It is important to collect chemical data regarding soil nutrients in order to determine whether the soil on the slope is fertilized or needs chemical treatments when planting the vegetation. The soil chemistry was determined at the University of Gezira (College of Agricultural Sciences and Water Resources), and the results are given in Table 8. Based on these results, teachers at the University of Gezira collaborated with those at Wad Medani Technological College to decide on which vegetation and native plants to use for testing of the bioengineering methods that should be used to protect the Wad Medani-Sennar road.

6. The Selected Vegetation Types

According to engineering surveys and soil classification and chemical experiments carried out on the Wad Medani-Sennar road and vegetation around the road, some plant types had higher population densities than others. *Cynodon dactylon* was selected because it was noticed that its root structure and shear strength significantly decreased soil

Table 7: Hydrometer analysis readings (specific gravity of soil 2.67; test temperature 24°C).

Elapsed time (min)	Actual hydrometer reading	Composite correction	Corrected hydrometer reading	Effective depth (cm)	Coefficient K	Grain size (mm)	Finer (%)	Finer combined (%)
0.25	1.0325	−0.0019	1.0306	7.70	0.129	0.0506	97.85	85.37
0.5	1.0320	−0.0019	1.0301	7.84	0.0129	0.0506	96.25	83.98
1	1.0310	−0.0019	1.0291	8.10	0.0129	0.0260	93.05	81.19
2	1.0310	−0.0019	1.0291	8.10	0.0129	0.0164	93.05	81.19
5	1.0310	−0.0019	1.0291	8.10	0.0129	0.0116	93.05	81.19
10	1.0305	−0.0019	1.0286	8.23	0.0129	0.0083	91.45	79.79
20	1.0300	−0.0019	1.0281	8.36	0.0129	0.0068	89.85	78.40
30	1.0290	−0.0019	1.0271	8.63	0.0129	0.0069	86.66	75.61
60	1.0275	−0.0021	1.0254	9.03	0.0129	0.0050	81.22	70.86
1440	1.0270	−0.0019	1.0251	9.16	0.0129	0.0010	80.26	70.03
480	1.0070	−0.0027	1.0043	14.45	0.0129	0.0022	13.75	12.00
1440	1.0060	0.0027	1.0033	14.71	0.0129	0.0013	10.55	9.21

Table 8: Chemical test and soil nutrients.

Fertility	Amount (%)
OM	0.4-0.5 less than 1%
N	0.03-0.4%
P	2–4 ppm
K	0.5-0.6 me/100 g
pH	7.5–8.5

erosion [14], enhancing the stability of shallow soil [15]. Other plants, such as trees or bushes, were also found near the project area. However, many of these had low-population densities. Plants with lower densities were omitted, and only those with large densities, such as *Cynodon dactylon* and *Vetiver* [14, 16], were used for the investigation. Truong [12] found that *Vetiver* grass was fast-growing and cultivates profusely. Its root system helps to prevent erosion and for shallow surface movement in the soil [13]. The root system is strong and has an average tensile reach of 75 Mpa. This is approximately one-sixth of the strength of mild steel. Truong argued that the massive root system also increased the shear strength of soil. *Vetiver* can also grow in soil with extreme pH levels and high temperatures such as those found in Sudan. *Vetiver* has been proven to help stabilize soil and control soil erosion [13].

Many of the plants observed can be analyzed easily. *Mesquite* is often found and has many benefits. It can contribute to soil conservation, environmental stability through stabilization of dunes, hedging, and windbreaks and provides shelter belts around villages and agricultural schemes. *Cassia angustifolia* can grow in low rainfall areas [9], and *Striga hermonthica*, or *Striga lutea* as known in Sudan and many other African countries, is a very harmful plant that has deleterious effects on corn, sorghum, and sugarcane crops [17]. The local vegetation types selected are shown in Figure 11. They are (a) *Cassia angustifolia*, (b) *Cynodon dactylon*, (c) *Striga hermonthica*, and (d) *Vetiver*.

According to the plant density data, two types of grass, two shrubs, and one type of tree were selected. These are summarized in Table 9. Surface coverage data for the native plants selected (grass or shrubs around the Al Hosh location where the studies in this research occurred) are summarized in Table 10.

The soil determines the growth of a particular plant. For soils with a unique particle size distribution, the plant best suited for the soil must be selected. The best particle size range for each plant type is known, and thus using the maximum and minimum percentages obtained from the particle size distribution charts of each selected plant, the best plants for the soils were chosen. The ranges of soil needed for both creepers and trees or bushes were thus defined. According to the USCS, the most common soil type that could be used for the selected plants were classified as MH or OH as shown in Figure 10.

At most of the locations, the range of the slope angles varied from 27° to 45°. However, at a few other locations, the slope angle increased to 60°. According to the above analysis, *Cynodon dactylon*, *Vetiver,* and *Cassia angustifolia* can be recommended for erosion control of the soil slope surface and to improve slope stability. However, both the positive and negative effects that occur by growing these plants in filled and natural slopes need to be further analyzed. Both *Striga hermonthica* and *Mesquite* need to be excluded, as *Striga hermonthica* is extremely harmful to cultivated crops, and it can rapidly creep to farms, growing over and destroying crops. *Mesquite* grows quickly and can grow up to many meters in height, thus affecting visibility on the Al Hosh highway. This could lead to an increase in traffic accidents.

7. Conclusion and Recommendation

Based on the results of the study, the following were found:

(i) Although not all plants were considered, the study has proven through vegetation surveying, geotechnical

(a) (b) (c) (d)

Figure 11: Different types of native vegetation in the area of Al Hosh highway. (a) *Cassia angustifolia*; (b) *Cynodon dactylon*; (c) *Striga hermonthica*; (d) *Vetiver*.

Table 9: Suitable plant selection according to native plant around Al Hosh highway.

Plant type	Common name	Scientific name	English name
Grasses	Bermuda grass Bunchgrass	*Cynodon dactylon*	Vilfa stellata Vetiveria zizanioides
Plants	Alexandrian senna Asiatic witchweed	*Cassia angustifolia* *Striga hermonthica*	*Cassia* officinalis Witchweed
Trees	Alexandrian senna Prosopis	*Mesquite*	Prosopis juliflora

Table 10: Native plant identification summary.

Native vegetation	Climate condition	Root system	Soil surface coverage
Cynodon dactylon	Warm climate and dry	Deep creeping	✓
Vetiver	Warm climate and dry	Massive, deep, fibrous root	✓
Cassia angustifolia	Warm climate and dry	Fibrous root	x
Striga hermonthica	Warm climate and dry	Host root	✓
Mesquite	Warm climate and dry	Deep	✓

studies (soil properties and classification), and chemical soil data (soil nutrients, pH, etc.) that there were suitable plants and grasses available around the research area that could be used to stabilize the slopes.

(ii) All the work mentioned above has shown that the vegetation suitable for ecoengineering slope protection was three native plants, *Cynodon dactylon*, *Vetiver*, and *Cassia angustifolia*. These were recommended based on climatic and soil conditions and provide a new method to reduce slope surface erosion and increase slope stability in Sudan.

(iii) Using vegetation allows for the protection of the sedimentation soil of the Al Hosh Highway. Vegetation also has many benefits, including the improvement of the landscape surrounding the highway, and helps to reduce the impact of high-intensity rainfall. Used in large open areas, vegetation can thus reduce soil erosion due to rainfall intensity and improve the meteorological situation in Gezira.

(iv) The study recommends applying ecoprotection techniques to protect the highways from slope failure due to erosion resulting from the intense rain showers in autumn, and this reduces the number traffic accident victims because of highway failure at this time of year.

Conflicts of Interest

The authors declare that the funding provided did not lead to any conflicts of interest regarding the publication of this manuscript.

Authors' Contributions

Altaeb Mohammed participated in the sequence alignment, drafted the manuscript, conceived the study, participated in its design and coordination and collection of data, and helped to draft the manuscript. Xu Wennian participated in the sequence of the manuscript, acquired most of the funding, and supervised the research group. Xia Zhenyao participated in the design of the study and revised most of the experimental work for the study. All authors read and approved the final manuscript.

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