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Discriminant Function and Critical Shear Stress Investigations Differentiate Depositional Environment in the Western Part of Nigeria

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Abstract

Linear discriminant analysis is necessary to investigate the environment of deposition of sediment or transport. 14 samples [from locations A1, A2, OL1, OL2, O1, O2, AG1, AG2, A3, A4, AG3, AG4, O3 and O4] were taken from four villages in Kwara state for the study. Textural parameters were first investigated from the result of grain size analysis performed using German standard sieve set of mesh with shaker. These results enhanced the determination of critical shear stress as well as linear discriminant analysis. The critical shear stress accounts for sediment transport and deposition including their environments, the following results were obtained: The critical shear stress ranges from 0.33Nm^{-2} to 1.31Nm^{-2}. The highest value (1.31065877 Nm^{-2}) is observed in OL2 and the lowest (0.32766469 Nm^{-2}) is from the environments of A3 and O4. The stress which rolls or actually transports the particle varies within 0.1 Nm^{-2} to 0.3 Nm^{-2} except in OL2 and AG3 environments whose value is approximately 0.4. The linear discriminant analysis shows that the dregs were deposited by collective effects of marine, as well as those of fluvial activities due to the influence of turbidity in the beach environment. The multivariant discriminant plot confirms strongly, the environment of deposition as beach in this region.

Key words:

Deposition, Critical shear stress, Sediment, Discriminant analysis, Environment.

Citation:

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1. Introduction

The recommended approach of transporting capacity for slope movements is based on the laws of physics and hydrodynamics [1]. Instigation of motion has to do with mass, force, friction and stress. Gravity and friction are the two key forces responsible for water to flow through a channel. Gravity exerted on water to transport it down slope. Friction applied on the water by the bed and banks of the passage slows the motion of water. Samples found in the water current may agitate local hydraulics adequately generating irregular high or low transport environments [2]. When the force of gravity is the same and contrary in direction to the force of friction, water moves through the channel at a constant velocity. When the force of gravity is better than that of friction, the water accelerates [3].

The shear stress exceeding a threshold suggests entrainment of sediment that may possibly lead to the ruin of the banks of the waterways [4-7]. The shear stress that is responsible for this can be investigated considering Duboys expression [8]. Forms like shielding or armoring and overlapping and deviations in sorting can correspondingly upset obstacle such that the critical shear stress become essential to entrain the sediments [9]. The grain size determines the angle of friction [10].

The magnitude of shear stress necessary to transport a certain particle is the critical shear stress. The size of the particle will impact its weight. Shear caused by a certain flow could be enough to transport sand particles, but not enough to transport gravels. At moderately low shear stress, the particles roll with constant contact with the bed (contact load). As shear stress is increased further, the particles may go in suspension due to the stormy instabilities till they are moved downstream by stream flow (suspension load).

[11] concluded that the critical shear stresses of finer particles strongly relied on the particle size and the bulk density as well; for the larger particles, the critical shear stresses strongly depend on the particle size alone. [12] Resolved in his outcome that appreciative characteristics of sediment transport aids a lot of applications such as estimation of the effects of land use or flow regime alteration and channel rebuilding efforts among others. The link among discharge and bedload transport rate through a reach and the capability of the current channel to transport the bedload (sediment transport capacity) is critical to the formation of river stability in river corridor protection and restoration efforts. According to [2], efforts to calculate or measure shear stress standards in Mountain Rivers are difficult due to channel bed irregularity and the related turbulence and velocity variations. Turbulence leads to significant inconsistency in velocity as well as shear stress at the time of constant discharge.

The aim is to investigate the critical shear stress responsible for transportation and deposition of sediments including their environments which could be fluvial (terrestrial or continental), marginal marine if it is the boundary or marine [13]. An important feature of sediment transport is the entrainment and transport by the flow of the material forming the streambed. The environs of deposition may be considered by its level of oxygen including energy. A high energy environment (if includes rivers, sand dunes, beaches and described by swift sedimentation and coarse grain sizes (sandstones and conglomerates)) is one that involves agitated and fast flowing water where large sizes of particles are transported; it holds much oxygen. Also, with respect to low energy environment, very deep and quiet water describe this case where particles moved only include finest grains. This low energy environment may have high oxygen (such as soils, flood plains, shallow lakes and most marine regions); their grain sizes are reduced than sediments in the high-energy environment (mudstones, siltstones, fine-grained sandstones and limestones) or low-oxygen environment (like deep lakes, deep ocean basins, coal swamps and tar seeps) if they are characterized by sediments such as clays, mudstones and shales.

1.1 Location and geology

Agunji, Ogunniyi, Olayinka, Araromi are different villages in Kwara State, situated in the South Western part of Nigeria. These villages and others constitute Ifelodun local government area in the State (Figure 1) with headquarters in the town of Share. It lies between latitudes $8^{0}45^{1}$N and $8^{0}5^{1}$N and longitudes $4^{0}46^{1}$E and $5^{0}6^{1}$E. The climatic state of the area is within the warm-horrid tropical climate region where the wet season and the dry period are experienced mostly. The dry season is frequently observed about November to March annually; the rainy or wet season is commonly experienced between April and October [14]. The topographic structures are unique. The geology is of crystalline pre-cambrian basement complex rocks [15]. As recorded in the National Population Census data, the population of this Local Government is nearly 2.04975×10^{5} [16]. Ifelodun has an area of about 3,435,000 m^{2}.

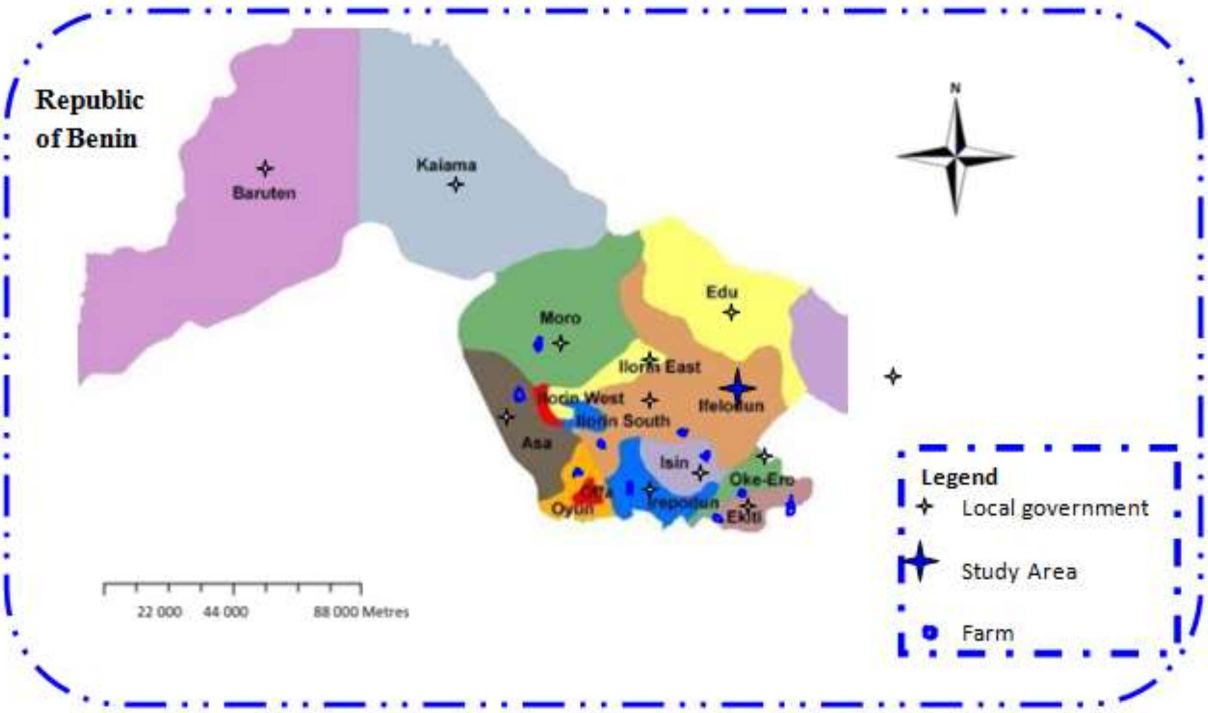

Figure 1: Map describing the area of study [14].

1.2 Theory

As clearly stated by [17], the fluctuation in the energy and fluidity influences correlate better with the different processes and the environment of deposition. Sahu's linear discriminant functions of Y_1 (involves Aeolian, beach), Y_2 (Beach, shallow agitated water), Y_3 (shallow marine, fluvial) and Y_4 (turbidity, fluvial) are used to interpret the process and environment of deposition. These functions are used for differentiation between the depositional environments [18]. To identify the environment of deposition, Equations 1 to 4 may be considered.

$$Y_1 = -3.5688M + 3.7016S_d^2 - 2.0766S + 3.1135K \quad (1)$$

$$Y_2 = 15.6534M + 65.7091S_d^2 + 18.1071S + 18.5043K \quad (2)$$

$$Y_3 = 0.2852M - 8.7604S_d^2 - 4.8932S + 0.0482K \quad (3)$$

$$Y_4 = 4.5129M - 1.2837S_d^2 + 3.5904S + 4.1038K \quad (4)$$

Where M is the mean, S_d is standard deviation, S is skewness, K is kurtosis. If $Y_1 \geq -2.7411$, it indicates the beach environment; $Y_1 < -2.7411$ indicates the Aeolian condition; $Y_2 \geq 65.36$ represents shallow agitated conditions; $Y_2 < 65.36$ represents the beach deposition; $Y_3 \geq -7.41$ shows shallow marine environment; $Y_3 < -7.41$ indicates the fluvial environment; $Y_4 \geq 9.81$ represents the fluvial deposit; $Y_4 < 9.81$ represents the influence of turbidity current.

Shear stress (τ_0) (ratio of force to unit area) may be calculated following Duboys equation (Equation 5).

$$\tau_0 = \rho g ds \quad (5)$$

τ_0 is the shear stress, density of water is ρ, acceleration due to gravity is g, ds is uniformity of the bed which is 10% of the diameter of the median.

[19] Defines for a uniform bed situation, the product (ds) as stated in Equation 6. This means that this product should be 10% of the diameter of the median.

$$ds = 0.1M_d \quad (6)$$

τ_0 is the shear stress, density of water is ρ, acceleration due to gravity is g, ds is uniformity of the bed, M_d is the diameter of the median.

More recent research has shown that most natural streams have mixed grain-size bed [20]. This gives rise to Equation 7 which means the product would be almost 5 percent of the diameter of median particle.

$$ds = 0.05M_d \quad (7)$$

The amount of critical shear stress (τ_c) (amount of force needed to transport the sediment of a particular size) has been calculated following Shields formula [21] (Equation 8).

$$\tau_c = Kg(\rho_s - \rho)M_d \quad (8)$$

Where ρ is the water density = 10^3kgm^{-3}, g is acceleration due to gravity (9.80665m/s^2), hydraulic radius (m) is d, with s as the slope, ρ_s is sediment density (typically 2.650 x 10^3kgm^{-3}) [22], M_d is the median grain size in meter. Median divides the population into two equal parts such that the intercept at 50 percentile gives the value. K is the constant (4.5 x 10^{-2}) [23].

Sediment approaching may be like the sediment that is already entrained; if this happened, sediment coming into a given reach may replace the entrained deposit [4 and 24 and 25]. This is in agreement with Archimedes' principle. Sediment size reworks hydraulic features closer to waterway, as it impacts flow resistance [26]. Substrate solidity depends on the shear stress threshold that is experienced before entrainment happens, known as critical shear stress [27]. Information on critical bed shear stresses can be seen in Table 1.

Table 1: Particle classification according to names, diameters and corresponding critical shear stresses [28].

S/N	Particle classification name	Ranges of particle diameters Phi	mm	Critical bed shear stress (Tau$_c$) Nm^{-2}
1	Coarse cobble	-7 to - 8	128.00 to 256.00	112.00 to 223.00
2	Fine cobble	- 6 to -7	64.000 to 128.00	53.800 to 112.00
3	Very coarse gravel	-5 to - 6	32.000 to 64.000	25.900 to 53.800
4	coarse gravel	- 4 to -5	16.000 to 32.000	12.200 to 25.900
5	Medium gravel	- 3 to - 4	8.0000 to 16.000	5.7000 to 12.200
6	Fine gravel	- 2 to - 3	4.0000 to 8.0000	2.7000 to 5.7000
7	Very fine gravel	-1 to -2	2.0000 to 4.0000	1.3000 to 2.7000
8	Very coarse sand	0 to -1	1.0000 to 2.0000	0.4700 to 1.3000
9	coarse sand	1 to 0	0.5000 to 1.0000	0.2700 to 0.4700
10	Medium sand	2 to 1	0.2500 to 0.5000	0.1940 to 0.2700
11	Fine sand	3 to 2	0.1250 to 0.2500	0.1450 to 0.1940

12	Very fine sand	4 to 3	0.0625 to 0.1250	0.1100 to 0.1450
13	Coarse silt	5 to 4	0.0310 to 0.0625	0.0826 to 0.1100
14	Medium silt	6 to 5	0.0156 to 0.0310	0.0630 to 0.0826
15	Fine silt	7 to 6	0.0078 to 0.0156	0.0378 to 0.0630

2. Materials and Method

Sediment samples were obtained from different streams in random locations in the study area [as stated in the geology and location section] with the help of major materials like sample bags, Weighing balance, German Standard Sieve of sizes and were analyzed after drying and sieving them with the German Standard Sieve of sizes: 2.00mm, 1.00mm, 0.85mm, 0.71mm, 0.60mm, 0.50mm, 0.30mm, 0.25mm, 0.112mm, 0.09mm, 0.075mm, 0.063mm and less than 0.063mm. This approach enables the determination of textural parameters, definition of environment of deposition and critical shear stress assessment.

3. Results and Discussion

3.1 Results

In order to carry out linear discriminant analysis and determine critical shear stress, sediment sizes in phi corresponding to cumulative frequency curves are needed. Table 2 and Figure 2 presents this results. We also plotted Figure 3 to show the Ogive with respect to sieve size in milimetre (mm) to be able to deduce the true value of the median in mm to enable used solve for the critical shear stress and shear stress. These results are in Table 4. The textural parameters are important to enable the assessment and interpretation of the environment of deposition as seen in Table 3. Figure 4 displays the curve on the pressure information at each location. The plot of environment variations due to discriminant functions is Figure 5. The clarity of environment of deposition can be represented due to Eigen vectors like V_1 and V_2 (Figure 6).

Table 2: The ogive data in tabular form

Phi	A 1	A 2	OL 1	OL 2	O 1	O 2	AG 1	AG 2	A 3	A 4	AG 3	AG 4	O 3	O 4
-1	19.4361	21.2319	23.1855	41.7294	30.4851	5.22613	2.71767	24.2485	0.33565	5.61122	15.83008	8.089797	2.30692	0.30268
0	53.8771	49.7747	38.9113	84.9634	54.6525	22.8141	21.842	47.6954	3.46834	16.2325	89.26962	40.34786	13.5406	5.54905
0.23	58.9124	50.1753	41.5323	88.4743	58.6637	27.6382	28.0825	52.004	6.48915	20.2405	92.5759	47.12307	18.4554	8.97938
0.49	59.2145	56.9855	41.9355	88.6749	59.2654	28.5427	28.8073	52.4048	7.16044	21.5431	92.77628	47.83092	19.4584	9.28205
0.74	64.4512	73.9109	44.8589	91.6842	62.374	34.2714	34.4439	56.4128	11.0763	27.0541	95.08066	56.83082	26.2788	13.6204
1	75.1259	90.4357	54.4355	96.0979	75.2098	52.2613	54.8364	67.9359	38.2636	52.9058	97.98618	78.7744	48.1444	36.0184
1.74	84.0886	93.0396	68.3468	98.4051	88.6473	70.8543	78.0876	77.9559	84.4708	79.4589	99.38884	93.23491	69.6088	69.81718
2	86.9084	98.5478	74.5968	98.706	92.7588	78.191	86.4419	80.6613	85.9253	86.2725	99.58922	96.47083	75.5266	79.80548
3.16	95.2669	99.349	93.246	99.8094	99.8787	96.8844	97.7152	94.3888	98.7917	98.497	99.88979	99.70675	94.985	98.47048
3.47	96.4753	99.5493	96.4718	99.8495	99.9789	99.2965	99.8289	96.6934	99.7986	99.5992	99.98998	99.90899	98.3952	99.88297
3.74	97.281	99.6495	97.7823	99.8997	99.987	99.598	99.8994	98.2966	99.8881	99.7996	99.99399	99.93933	99.2979	99.96368
3.99	97.9859	99.7997	98.5887	99.9398	100	100	99.9396	99.1984	99.9441	99.8998	99.996	99.95955	100	100
4	100	100	100	100			100	100	100	100	100	100		

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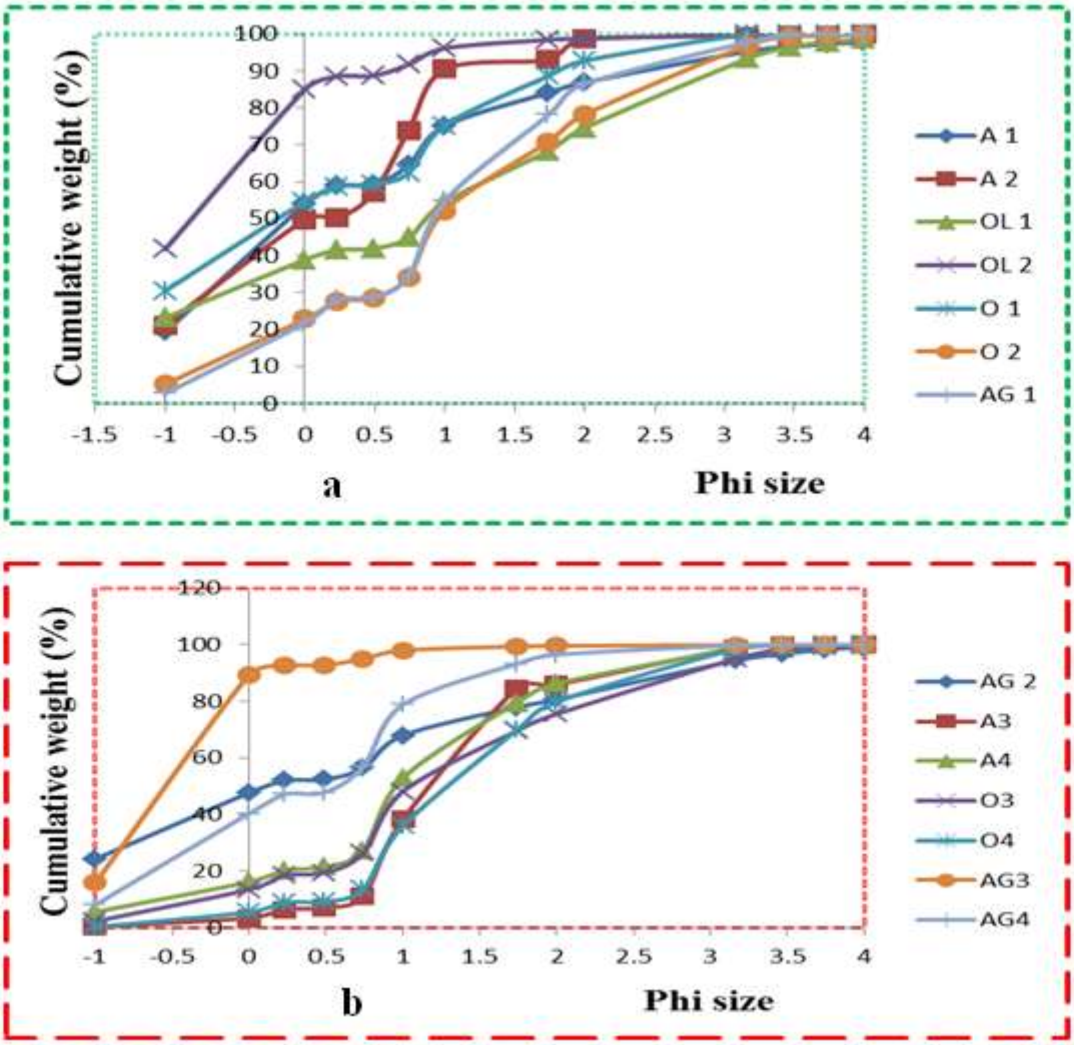
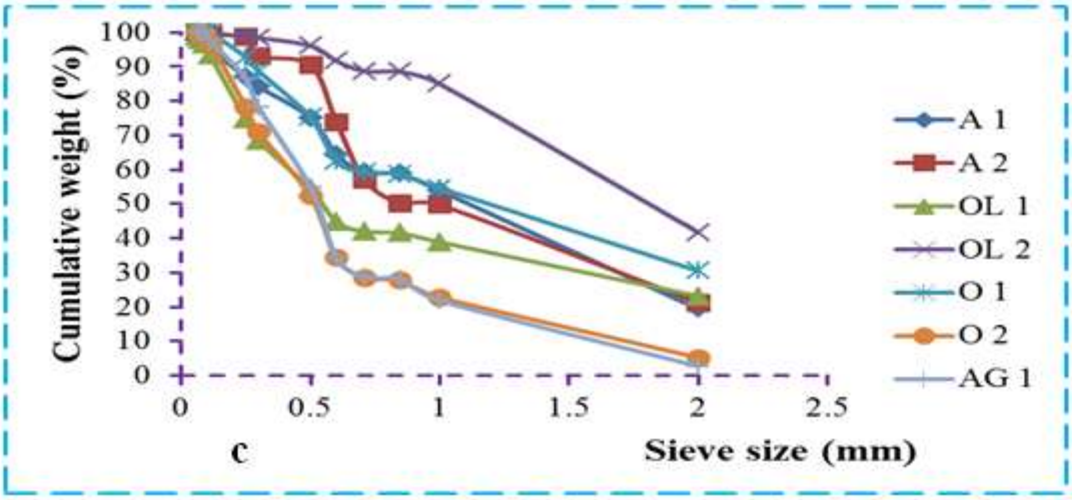


Figure 2: Cumulative curves (a and b) with respect to sieve size in phi



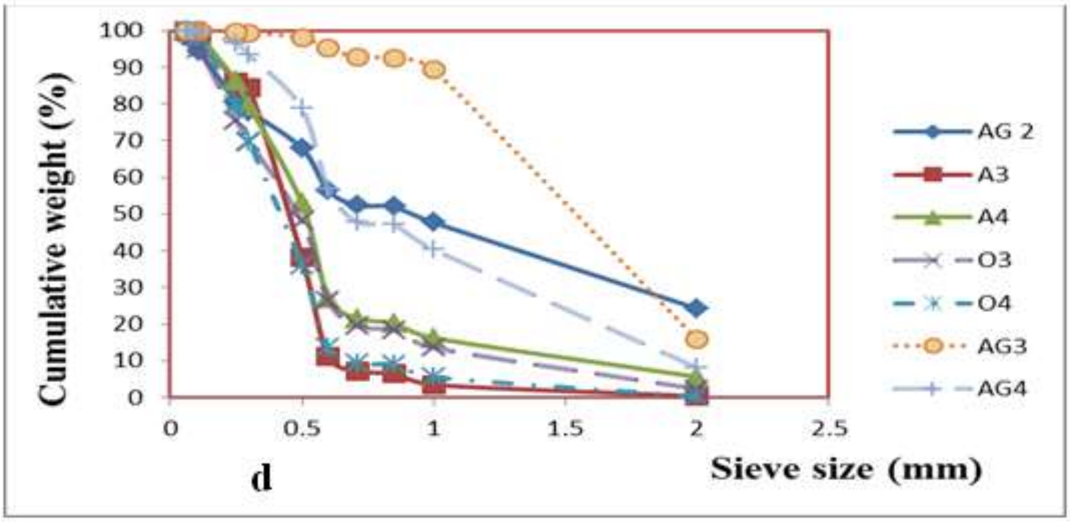


Figure 3: Cumulative curves (c and d) with respect to sieve size in mm.

Table 3: Result of corresponding textural parameters with the environments

S/N	Locations	Mean	SD	Sort	Skew	Kurt	Y1	Y2	Y3	Y4
1	A 1	0.18333	0.7125	1.41705	0.3588	1.03013	3.68708	61.786	-6.101	5.69136
2	A 2	-0.11667	0.5375	1.05265	-0.03728	0.8709	4.27476	32.5979	-2.3398	2.54277
3	OL 1	0.68333	1.0125	1.85341	-0.1298	0.7981	4.11047	90.4766	-8.1123	4.57704
4	OL 2	-0.81667	0.3875	0.81932	0.09791	0.97336	6.2976	16.8671	-1.9805	0.46769
5	O 1	-0.08333	0.7625	1.43674	0.14165	0.82899	4.73643	54.8039	-5.7703	2.78816
6	O 2	0.96667	0.6875	1.30871	0.03348	0.93352	1.13672	64.0697	-3.9838	7.70689
7	AG 1	0.83333	0.55	1.12576	-0.01914	1.03825	1.41808	51.787	-2.2687	7.56448
8	AG 2	0.36667	0.9	1.65758	0.25111	0.81967	3.72033	78.6783	-8.1806	4.88029
9	A 3	1.23333	0.225	0.64167	0.15556	1.61007	11.2017	55.2423	-0.7753	12.6668
10	A 4	0.95	0.475	1.06591	0	1.68249	11.5666	60.8296	-1.6245	10.9022
11	AG 3	0.7	0.55	1.0803	-0.15065	0.95628	11.576	45.8019	-1.6671	6.15422
12	AG 4	-0.13333	0.45	0.79849	0.0773	0.62842	11.6966	24.247	-2.1599	1.99476
13	O 3	1.23333	0.6	1.19091	0.1218	1.22951	14.2719	67.9177	-3.3387	10.5867
14	O 4	1.43333	0.375	0.83712	0.17432	1.25	15.8462	57.9636	-1.6159	12.0436

Table 4: The shear stress and critical shear stress results

S/N	Locations	Median (m)	Tau (Nm^{-2})	Tau_c (Nm^{-2})	Tau_c - Tau (Nm^{-2})
1	A 1	0.0011	0.5393658	0.80095814	0.261592389
2	A 2	0.00085	0.4167826	0.6189222	0.202139573
3	OL 1	0.00055	0.2696829	0.40047907	0.130796194
4	OL 2	0.0018	0.8825985	1.31065877	0.428060273
5	O 1	0.00115	0.5638824	0.83736533	0.273482952
6	O 2	0.0005	0.2451663	0.36407188	0.118905631
7	AG 1	0.00055	0.2696829	0.40047907	0.130796194
8	AG 2	0.0009	0.4412993	0.65532939	0.214030136
9	A 3	0.00045	0.2206496	0.32766469	0.107015068
10	A 4	0.00055	0.2696829	0.40047907	0.130796194
11	AG 3	0.00155	0.7600154	1.12862283	0.368607457
12	AG 4	0.00065	0.3187161	0.47329345	0.154577321
13	O 3	0.0005	0.2451663	0.36407188	0.118905631
14	O 4	0.00045	0.2206496	0.32766469	0.107015068

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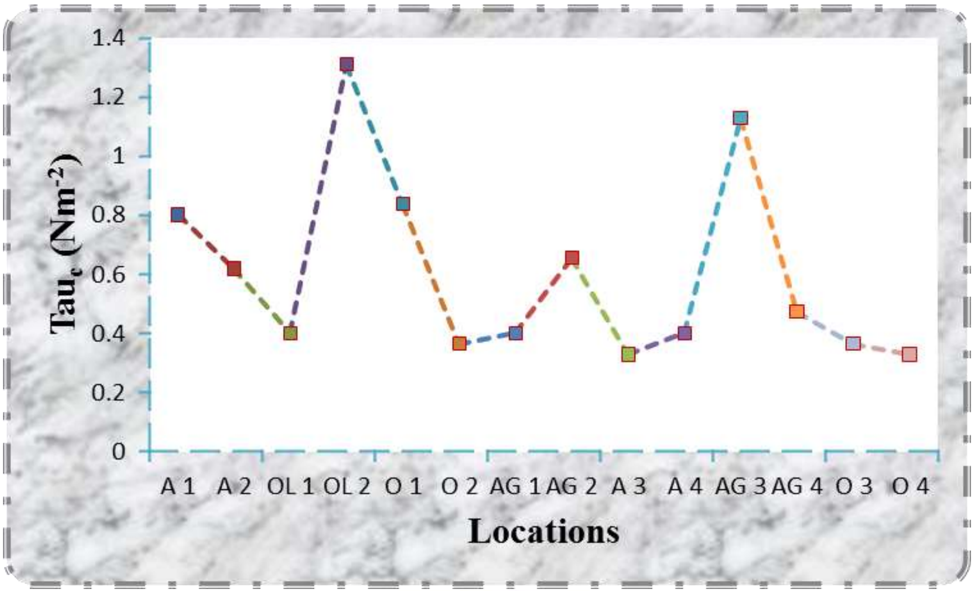

Figure 4: Pressure differentiation on sediments at each location.

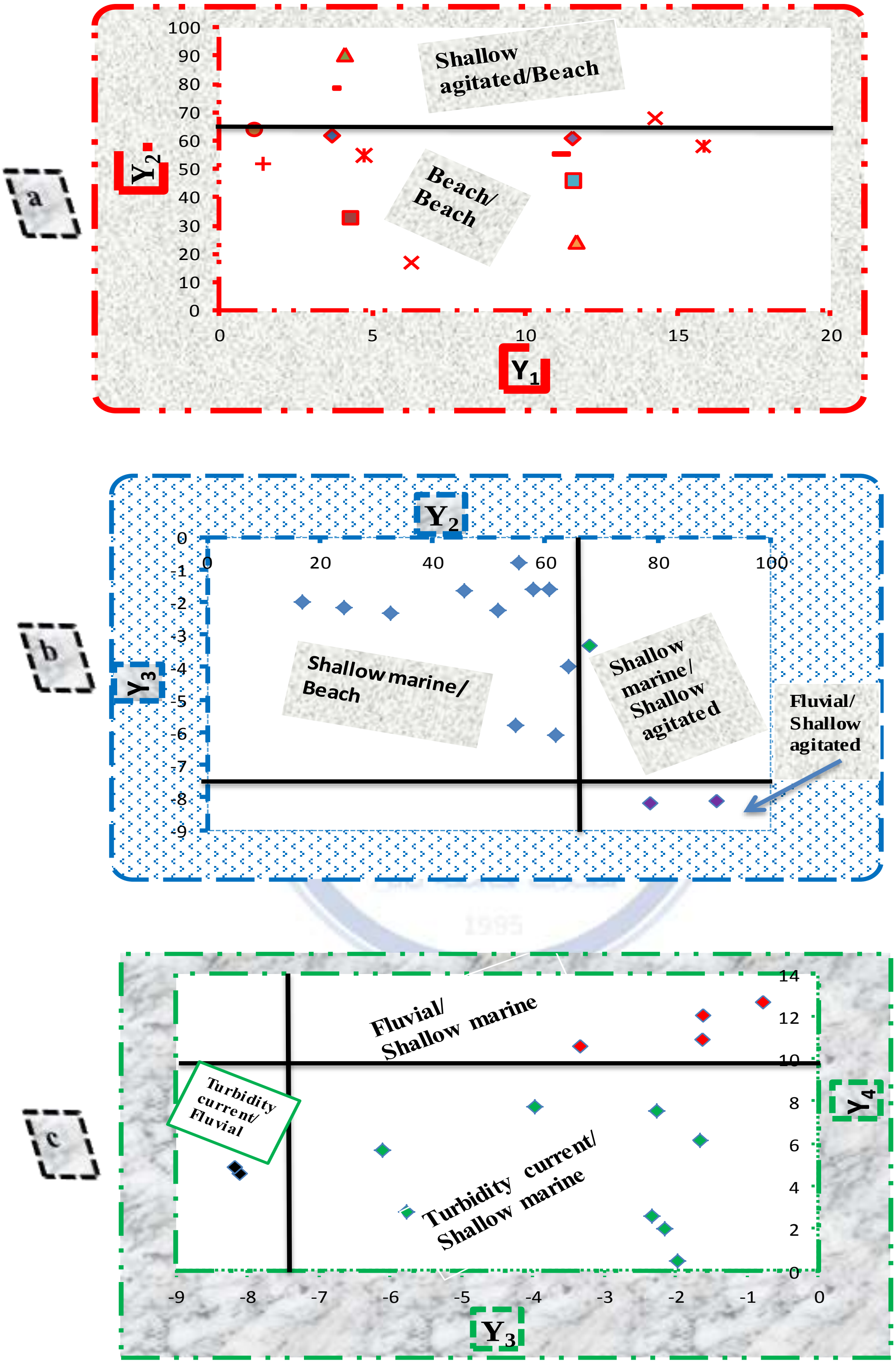

Figure 5: Environment of Deposition of Sediment as defined by (a) Y_2-Y_1 (b) Y_3-Y_2 (c) Y_4-Y_3 plots.

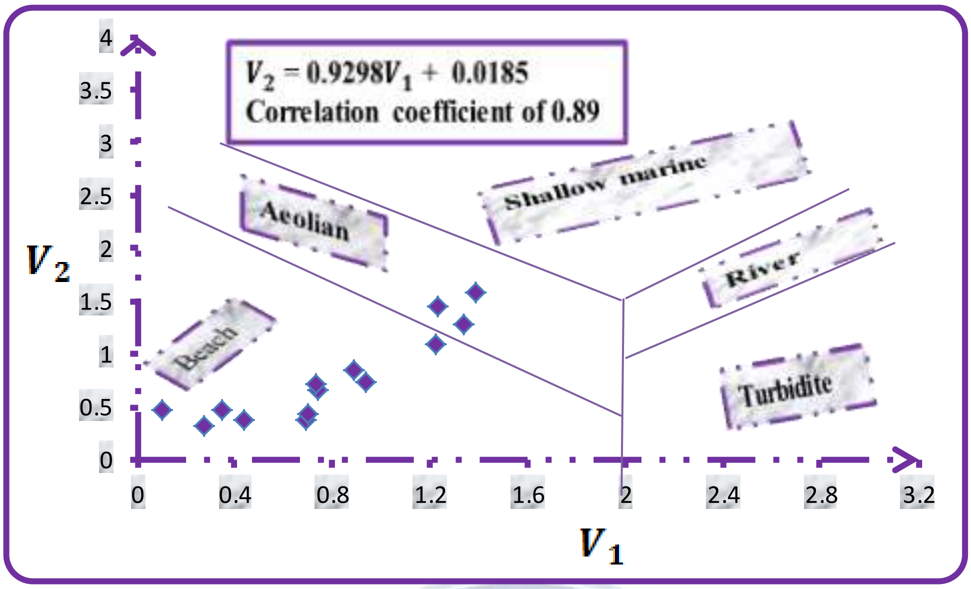

Figure 6: Discriminant plot of Eigen vectors.

3.2 Discussion

A survey has been conducted in order to carry out linear discriminant analysis and as well investigate the critical shear stress of sediment transport in 14 locations (four from Agunji with symbol AG, four from Ogunniyi with symbol O, two from Olayinka with symbol OL, four from Araromi with symbol A). These locations are all in Kwara state (South Western part of Nigeria).

The interpretation of Tables 3 and 4 is seen in Table 5 using Table 1 for identification of the particle (or sediment) class. The linear discriminant parameters (Y_1 to Y_4) have been discussed in the theory section and obtained using Equations 1 to 4 correspondingly. The average critical shear stress (0.600718604 Nm^{-2}) determined, which is the amount of force needed to transport sediment in the environment indicates, very coarse sand class of sediment. Equation 8 was employed to determine each location critical shear stress. Equation 7 was considered to compute the shear stress considering the special case of a mixed-size bed. The result of both shear stress and critical shear stress is tabulated in Table 4.

The class of sand sediment is mostly very coarse from the average result, although the class varies from very coarse to coarse sand. Influence of turbidity is felt in most environments except those of A3, A4, O3 and O4 experiencing fluvial deposit. Shallow marine environment exists in the area except in locations OL1 and AG2 with fluvial situation. The deposition in all locations is beach with OL1, AG2 and O3 also experienced shallow agitated condition. The environment is clearly beach as confirmed by function Y1 and the class of sand sediment is defined as very coarse grain sizes from the average result (0.600718604 Nm^{-2}). This environment is usually defined as one with high energy as it holds much oxygen; involves fast moving water and agitated in some locations. The critical shear stress ranges from 0.33Nm^{-2} to 1.31Nm^{-2}. The highest value (1.31065877 Nm^{-2}) is observed in OL2 and the lowest

($0.32766469\ Nm^{-2}$) is from the environments of A3 and O4. The stress which rolls or actually transports the particle varies within $0.1\ Nm^{-2}$ to $0.3\ Nm^{-2}$ except in OL2 and AG3 environments whose value is approximately 0.4. The linear discriminant analysis shows that the dregs were dumped by both of marine and fluvial actions or activities due to the influence of turbidity in the beach (marine) environment. Figure 5 highlights the variation of one discriminant function against the other to clearly present the environment of deposition. From Figure 6, a linear relationship between the two Eigen vectors has been obtained from regression analysis indicating a correlation coefficient of 0.89. This shows a complete dominance of beach deposits and that these two vectors are strongly related. This curve is necessary to completely decipher the deposition environment [17]. [29] Defined the Eigen vectors as stated in Equations 9 and 10.

$$V_1 = 0.48048M + 0.06231S_d + 0.40602S + 0.44413K \quad (9)$$

$$V_2 = 0.24523M - 0.45905S_d + 0.15715S + 0.83931K \quad (10)$$

Table 5: Interpretation of results (BE is Beach Environment, BD is Beach Deposition, SAC is Shallow Agitated Condition, SME is Shallow Marine Environment, FE is Fluvial Environment, ITC is Influence of Turbidity, FD is Fluvial Deposit).

S/N	Locations	Environments				Particle class
		Y1	Y2	Y3	Y4	
1	A 1	BE	BD	SME	ITC	Very coarse sand
2	A 2	BE	BD	SME	ITC	Very coarse sand
3	OL 1	BE	SAC	FE	ITC	Coarse sand
4	OL 2	BE	BD	SME	ITC	Very fine gravel
5	O 1	BE	BD	SME	ITC	Very coarse sand
6	O 2	BE	BD	SME	ITC	Coarse sand
7	AG 1	BE	BD	SME	ITC	Coarse sand
8	AG 2	BE	SAC	FE	ITC	Very coarse sand
9	A 3	BE	BD	SME	FD	Coarse sand
10	A 4	BE	BD	SME	FD	Coarse sand
11	AG 3	BE	BD	SME	ITC	Very coarse sand
12	AG 4	BE	BD	SME	ITC	Coarse sand
13	O 3	BE	SAC	SME	FD	Coarse sand
14	O 4	BE	BD	SME	FD	Coarse sand

4. Conclusion

- The class of sand sediment is majorly very coarse from the average result of critical shear stress. The class varies from very coarse to coarse sand.
- Discriminant function Y_4 indicates influence of turbidity is felt in most environments. Beach environment exists in the area as confirmed by function Y_1 as well as deposition due to shallow agitated condition.
- This environment is generally defined as one with high energy as it holds much oxygen; involves fast moving water.
- The confirmation of complete dominance of the environment of deposition of the sediments is beach from multivariant discriminant diagram. Therefore, the sediments were deposited by combined effects of marine and fluvial processes under the influence of turbidity in the beach environment.

Conflict of interests.

There are non-conflicts of interest.

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الخلاصة

يعد التحليل التمييزي الخطي ضروريًا للتحقيق في بيئة ترسب الرواسب أو النقل. تم أخذ 14 عينة [من المواقع A1 و A2 و OL1 و OL2 و O1 و O2 و AG1 و AG2 و A3 و A4 و AG3 و AG4 و O3 و O4] من أربع قرى في ولاية كوارا للدراسة. تم فحص المعلمات النسيجية أولاً من نتيجة تحليل حجم الحبوب الذي تم إجراؤه باستخدام شبكة غربال قياسية ألمانية مع شاكر. عززت هذه النتائج تحديد إجهاد القص الحرج وكذلك تحليل التمايز الخطي. يمثل إجهاد القص الحرج نقل الرواسب وترسبها بما في ذلك بيئاتها، وتم الحصول على النتائج التالية: يتراوح إجهاد القص الحرج من 0.33 نيوتن متر إلى 1.31 نانومتر −2. أعلى قيمة (Nm−2 1.31065877) لوحظت في OL2 وأدناها (Nm−2 0.32766469) هي من بيئات A3 و O4. يختلف الضغط الذي يدور أو ينقل الجسيم فعليًا في حدود 0.1 نانومتر −2 إلى 0.3 نانومتر −2 باستثناء بيئات OL2 و AG3 التي تبلغ قيمتها حوالي 0.4. يوضح التحليل التمييزي الخطي أن الثمالة قد ترسبت من خلال التأثيرات الجماعية للبحرية ، وكذلك تلك الناتجة عن الأنشطة النهرية بسبب تأثير التعكر في بيئة الشاطئ. تؤكد المؤامرة التمايزية متعددة المتغيرات بقوة ، بيئة الترسب كشاطئ في هذه المنطقة.

الكلمات الدالة:

الترسيب ، إجهاد القص الحرج ، الرواسب ، التحليل التمييزي ، البيئة.