Gully Erosion of Coastal Plain Sediments of SE Nigeria
Final Summary Technical Report

Peter P. Hudec
Earth Sciences Department
University of Windsor, Windsor, Canada

ABSTRACT: Coastal plain sediments of SE Nigeria are prone to rapid and extensive gullying. Gully advances of 157m in length, 50m in width, and 5m in depth per year have been measured, and have cut through roads, isolated villages, disrupted water supplies, and caused major landslides. The gullying rates have increased in recent years because of increased population pressures and resultant vegetative cover denudation and poor drainage channelization. Studies were carried out in nine different sites over four different gully-prone formations. The gully-prone areas are underlain by lateritic coastal sands of very specific geotechnical properties, such as similar grain size and grain size distribution, uniformity, and dispersivity. Correlations indicate that the gully advance and dispersion rate is governed mostly by the sands' grain size distribution and uniformity. The CaO, K_2O, MnO and MgO content of the weak lateritic cement also have a significant statistical relationship to the gullying process.

1 INTRODUCTION

Gullying has long been a problem in the portion of SE Nigeria underlain by poorly consolidated coastal plain sands. There is a good correlation between gully density, population density, and easily erodible lateritic sands. The gully growth has been accelerated by population increases in recent years. Much of the gullying is initiated by poor or improperly maintained drainage, by denudation of forests for farming and grazing, and by construction. The main roads have been constructed with box-shaped concrete-lined ditches. Gullies often developed where the draining ditches have been allowed to clog with debris, causing the water to overtop them. Lateral erosion then undermined and collapsed the concrete drains, and the gulling process then continued unabated.

Gullies not associated with roads begin as rills over bare soil. Soil is bare because of foot traffic (paths), local dirt access roads, local construction, and farming. One rainy season is sufficient to initiate a severe gully. Once initiated, the gullies are difficult to control and stop.

The most important index of erodibility, according to Wischmeier and Mannering (1969) is particle size distribution. He has found that the soils that are high in silt, low in clay, and low in organic matter are the most erodible. Usually a soil type becomes less erodible with decrease in silt fraction, regardless of whether the corresponding increase is in the sand fraction or the clay fraction.

Bruce and Lal (1975) conducted his studies on erodibility of soil on two tropical soil types from western Nigeria. The soils were tested by the raindrop technique to determine their erodibility indexes. They tested aggregate size, initial soil moisture potential and raindrop temperature for their effect on structural stability of the soil and found significant effect of soil texture on the structural stability of soil. The energy requirement for disruption was directly proportional to clay and inversely proportional to sand content. Similar observations were done by Bouyoucos (1930) whereby sand to silt and clay ratio was found to have a significant effect on structural stability. Donker (1984) found that gully sites have a considerably lower gravel content (30%) than non-gully sites (50%). This is consistent with many other authors. Lamb and Chapman (1943) and Lamb et al. (1944) found that surface stones increased water intake and decreased soil erosion by protecting the surface from the puddling and erosive action of raindrop impact.

It is significant to note that the Coastal formations in this study have virtually no gravel content, and quite low silt and clay content, making them ideal candidates for erosion.

1.1 Acknowledgments

The technical information on which this report is based has been contributed by the Nigerian project leaders Enuvie. Akpokodje and Meshach. Umenweke. Much of the data compilation and correlation has been carried out by Martin Ondrasik at the University of Windsor. My colleague, Frank Simpson, reviewed the paper and the data, and provided gully prevention and rehabilitation suggestions.

2 STUDY AREA, GEOLOGY AND GULLY DEVELOPMENT

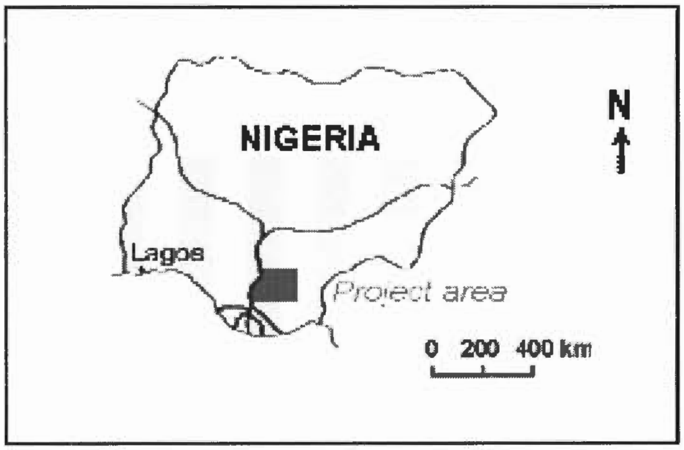

Figure 1. Location of project area.

The gullying is developed over flat-lying to gently dipping coastal sands of Tertiary and Cretaceous age. The location of the problem area, is given in Figure 1.

The geologic map of area, including the location of the gullies studied, is given in Figure 2. As can be seen, the gullying extends across a number of formational units. However, the units have a number of parameters in common, which contribute to the gullying process. The gullying process is extremely rapid; rills can develop into gullies within one major rain event. The gullying is initiated as a rill, which is progressively steepened, as shown in the diagram of Figure 3. The gully begins as a rill. Erosion progresses downward, cutting near vertical walls in the partially cemented lateritic soil (step1 in Fig. 3). When the gully reaches the unconsolidated, loose, unweathered coastal sands (step 3 in Fig. 3), erosion in the sands accelerates by lateral undercutting, resulting in slumping.

The next several figures illustrate the various stages of gully development. Figure 4 shows the development of rills into gullies within less than one rainy

igure 3: Progressive development of a gully in lateritic

Figure 4. Rill to gully development.

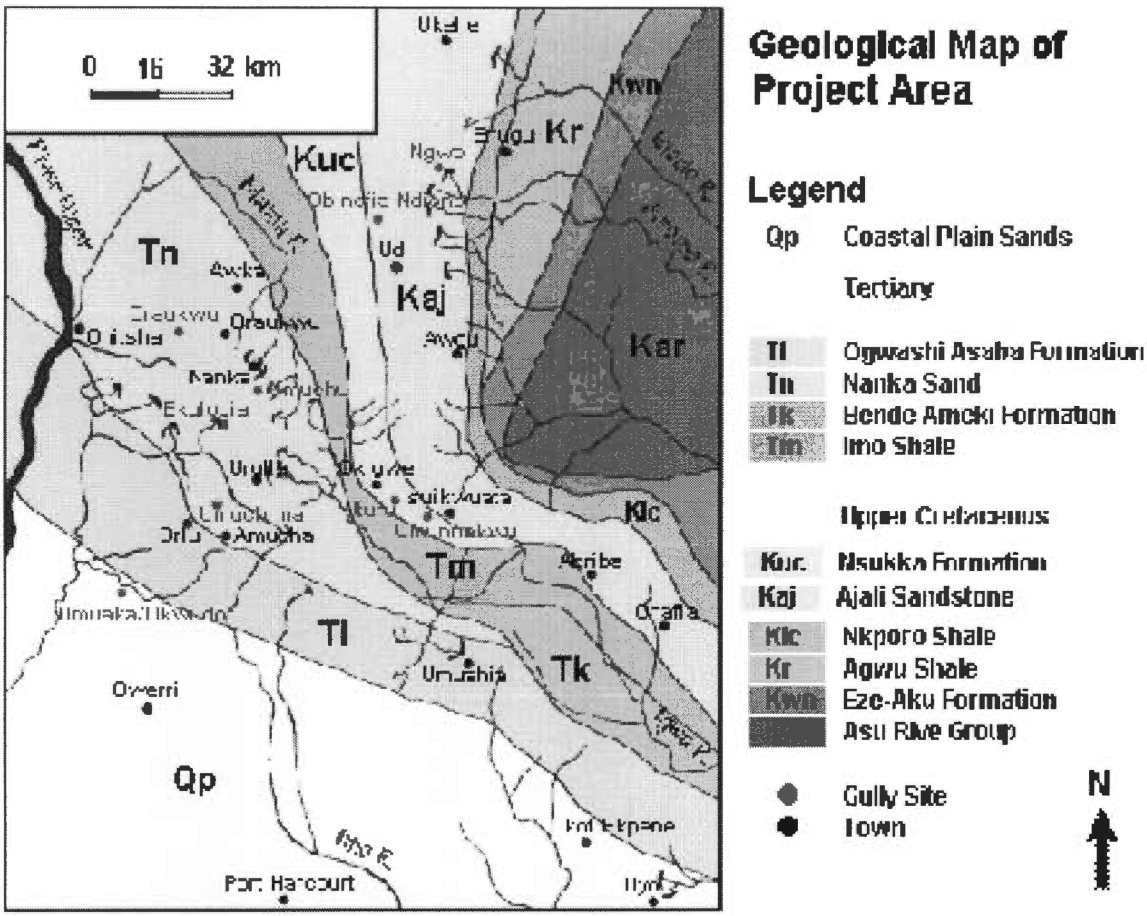

Figure 2. Geologic map of the area, showing location of gully sites studied.

season. Note the attempt at stabilization by planting of bamboo stakes. Figure 5 shows a fully developed gully in which has been measured to advance several tens of meters per rainy season. Note the rotational sliding of the left bank, which is the typical failure leading to breadth advance of the gully. Figure 6 illustrates the 'badlands' topography that develops in a mature gully system. Note that the gully continues to widen by block rotational slumping. Figure 6 also shows the lateritic cover over the lighter coloured coastal sands.

Figure 5. Deepening and widening of the gully by down-cutting and lateral slumping.

Figure 6. Fully developed gully system which continues to enlarge mainly by lateral slumping.

Table 1. Gully advances in 1994, 1995 and 1996.

Gully Complex	Sampling Site	Annual gully growth rate [m]				
		1994			1995	1996
		Length	Breadth	Depth	Length	Length
Umuaka	Umuaka-1	50.0	30.0	5.0		157.2
	Umuokwara-1	60.0	35.0	7.0		40.0
	Umukwandu	30.0	15.0	3.0		
	Average	**46.7**	**26.7**	**5.0**		**157.2**
Umuchima	Umuchima-1	25.0	10.0	4.0		8.6
	Umuchima-2	40.0	18.0	4.0		
	Umuchima-3	15.0	2.0	0.8		
	Average	**26.7**	**10.0**	**2.9**		**8.6**
Uturu	Uturu	22.0	5.0	0.5		
	Asut					10.7
	Average	**22.0**	**5.0**	**0.5**		**10.7**
Umunnekw	Umunnekwu - 1	15.0	10.0	1.0		
	Umunnekwu - 1	60.0	35.0	4.0	110.0	
	Amiyi - 1	29.0	13.0	2.4		31.3
	Amiyi - 2	19.0	10.0	2.1		20.1
	Amiyi - 3					17.2
	Igbere-1	20.0	15.0	2.0		22.9
	Igbere-2	17.0	10.0	1.4		
	Average	**26.7**	**15.5**	**2.2**	**110.0**	**22.9**

The rate gully advancement has been measured over three rainy seasons. Several gullies have been surveyed, and their increase in dimensions is shown in Table 1. Not all gullies advance at the same rate, and some not at all. Although the amount of rainfall received in the region is approximately the same (as measured by rain gauges installed at the sites), the rate of advance is governed mostly by efficiency of drainage, and the geotechnical properties of the lateritic soils. The drainage is most important: where water is allowed to concentrate and flow over unprotected soils, gully formation and advance is accentuated.

3 GEOTECHNICAL PROPERTIES OF COASTAL SANDS

Gradation analyses, Atterberg limits, dry bulk density, dispersivity, and moisture contents were determined from soil samples of the gully systems. In some cases, vertical sampling along the gully walls was done to ascertain changes in soil properties with depth. Gradation analysis reveals that the coastal sands are very uniform. Figure 7 shows the combined percent passing curves of all the analyses. With few exceptions, all tend to follow the same path.

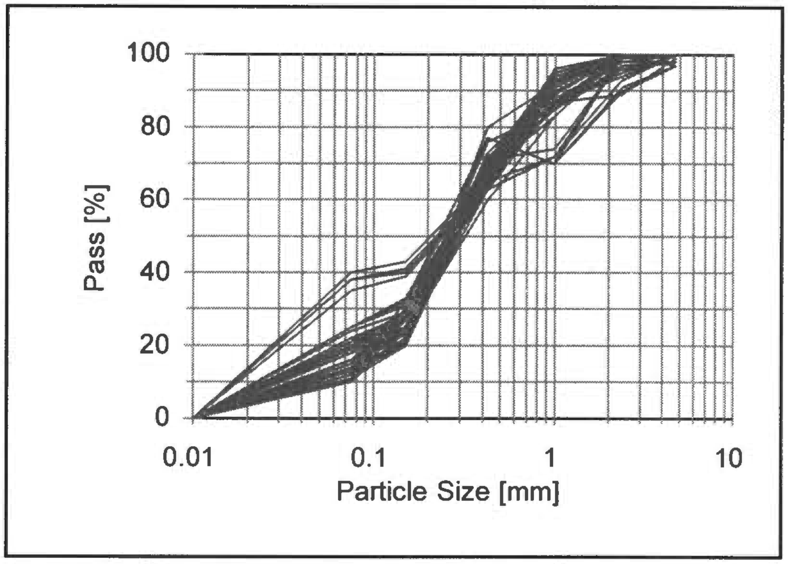

Figure 7. Gradation analysis of Coastal Sands formation.

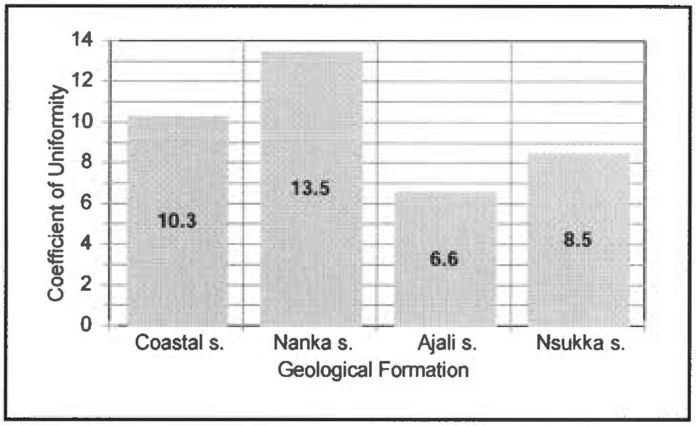

Figure 8. Average uniformity coefficients of the four formations.

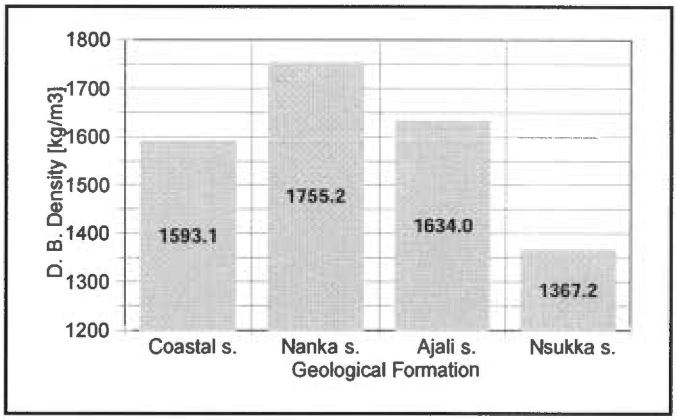

Figure 9. Average bulk density, kg/m^3 of the four formation units.

The size distribution can also be expressed as the coefficient of uniformity (the ratio d60/d10). Figure 8 shows that there is relatively minor variation in the size distribution among formations. The size analysis and the coefficient of uniformity indicate a uniform fine to medium grained sand. It will be shown later that size and size distribution has a significant effect on the rate of gully advance.

Since the origin of the lateritic sand is relatively pure quartz sand, the variation in bulk density is likely due to the difference in packing and, more significantly, the degree and amount of oxide cementation. The bulk density averages for the four formations are shown in Fig. 9.

The nature and type of cement correlate with gully advance, as shown in correlation tables (Table 2). CaO, MgO, MnO, Na_2O and K_2O have the most significant correlations with gully advance and dispersion time (a measure of time it takes for a cohesive sample to dissociate in water into constituent sand grains). All correlations are negative, i.e., indicating that the less of these oxides present, the greater the gully increase. The oxides are cements normally contributed by pore water. Therefore, the degree of cementation by these oxide cements governs the cohesion and resistance to erosion. Surprisingly, iron cement of the laterite, although not significantly correlated, shows a reverse trend, i.e., the more iron cement, the greater the advance.

Table 2. Correlation coefficients of oxide and mineral content with dispersion and gully advance.

	A	B	C	D	E
SiO2	0.45	0.75	0.65	0.56	0.10
Fe2O3	-0.09	-0.25	0.10	0.27	0.19
Al2O3	-0.11	-0.22	-0.41	-0.49	-0.18
CaO	-0.19	-0.55	-0.22	-0.05	-0.80
MgO	-0.74	-0.95	-0.82	-0.71	-0.49
MnO	-0.80	-0.96	-0.90	-0.82	-0.85
K2O	-0.72	-0.94	-0.77	-0.65	-0.41
Na2O	0.07	-0.30	0.05	0.23	-0.70
Quartz	0.30	0.66	0.44	0.30	0.48
Hematite	-0.45	-0.77	-0.59	-0.47	-0.47
Kaolinite	-0.11	-0.50	-0.23	-0.08	-0.45

A Gully Breadth increases in 1994
B Gully depth increase in 1994
C Gully length increase in 1994
D Gully length increase in 1996
E Dispersion time
Correlation is significant at the 0.01 level (2-tailed).
Correlation is significant at the 0.05 level (2-tailed).
Correlation is significant at the 0.1 level (2-tailed).

The soil dispersion time results indicate the time it takes for a given amount of soil to disperse in water. Dispersion involves separation of particles (deflocculation) in the clay fraction of a sediment or sedimentary rock on contact with water. It results from the weakening of chemical bonds between clay particles, caused by ion exchange and leaching. Commonly, dispersion takes place, when fresh water is introduced into the pore systems of Earth materials, in which monovalent Na cations have replaced divalent cations, such as Ca and Mg, on the exchange complexes of clays (Selby, 1993). Deposits that exhibit rapid dispersion are susceptible to erosion and gullying under the influence of hydraulic action.

Figure 10 indicates the average dispersive times obtained on samples from the four formations.

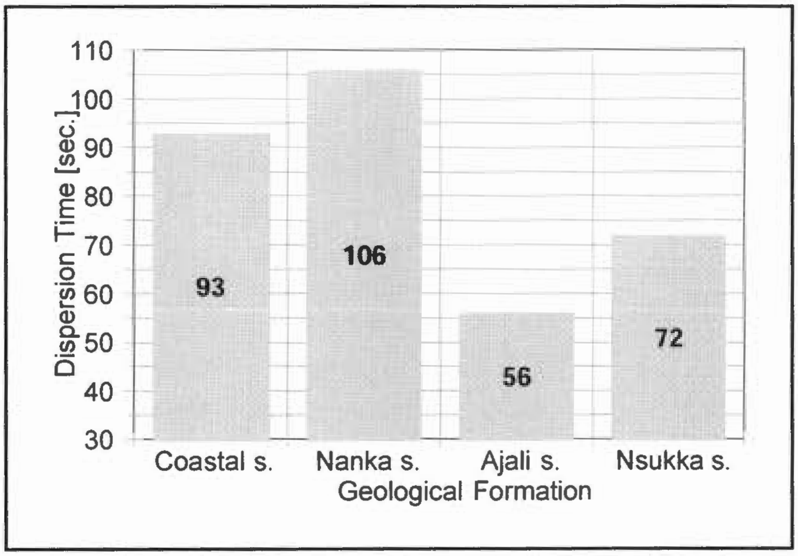

Figure 10. Average soil dispersion times in the four geological formations.

The Nanka Sand is a poorly consolidated unit of fine- to medium-grained sands and sandstones with subordinate shales. The unit is an important aquifer. In the Nanka area, the sands include a grey paleosol, at which sliding is localized. This augments the factors, contributing to gully formation locally. Leaching of the sporadically distributed cement in the sandstones and dispersion of clays in the interbedded, argillaceous layers are seen as the main factors, giving rise to gully formation in this unit.

Though not investigated in the present study, the expanding clays of the underlying Imo Shale. are likely to exhibit strong dispersion effects. This is a ready mechanism for speeding the propagation of gullies, initiated at higher levels in the ridge-forming Nanka Sand, especially in the Awka-Orlu uplands.

The Nsukka Sandstone comprises medium- to coarse-grained sandstones with subordinate carbonaceous shales, sandy shales and coal seams. The underlying Ajali Sandstone consists of medium- to coarse-grained sandstones, poorly consolidated in places, with subordinate shales. The Ajali Sandstone is extensively cross-bedded. These two units exhibit the shortest dispersion times of the four investigated. It is to be expected that dispersion is a significant factor in gully development in these units, rendering the deposits disaggregated and more susceptible to erosion.

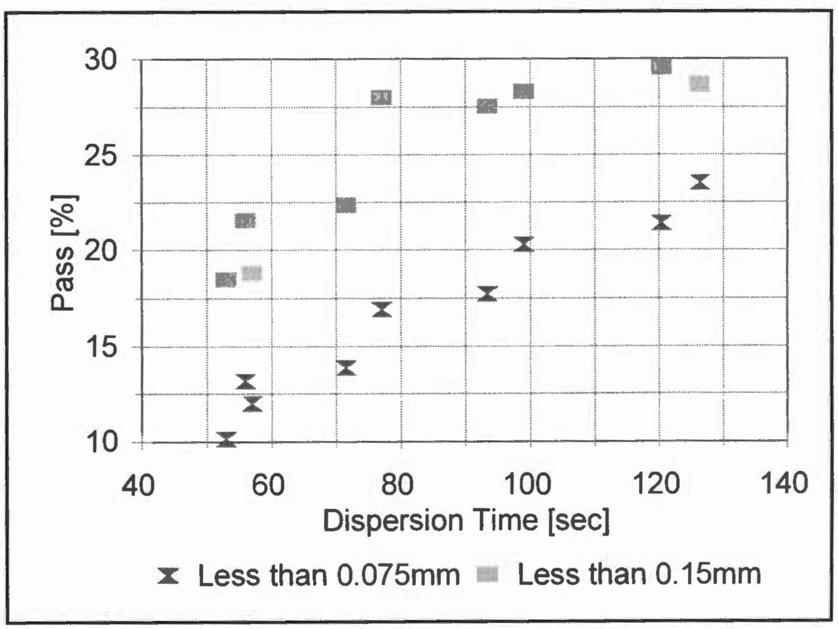

Figure 11. Relationship between dispersivity and the proportion of sand size passing 0.15mm and 0.075mm sieves.

Soil dispersivity does have a significant effect on erosional potential, and thus the gully development. Figure 11 shows the relationship between particle size and dispersivity. As the proportion of the finer sizes (<0.15 and <0.075) increases, so does the dispersion time. In other words, the 'cleaner' (less fines) and more uniform the sand is, the more prone it is to erosion.

This is shown in Figure 12, in which the proportion of particles smaller than 1mm is related to gully advance. The gully advances in all three directions (GR94L = length, GR94B = breadth, and GR94D = depth) for the year 1994 is significantly related to the proportion of particles greater than 1mm in diameter. The more coarse sand present, the greater the gully advance.

The rate of gully enlargement in length, breadth, and depth can be predicted from the equations of the lines of best fit shown in Figure 12, based on proportion of sand size greater than 1mm in diameter.

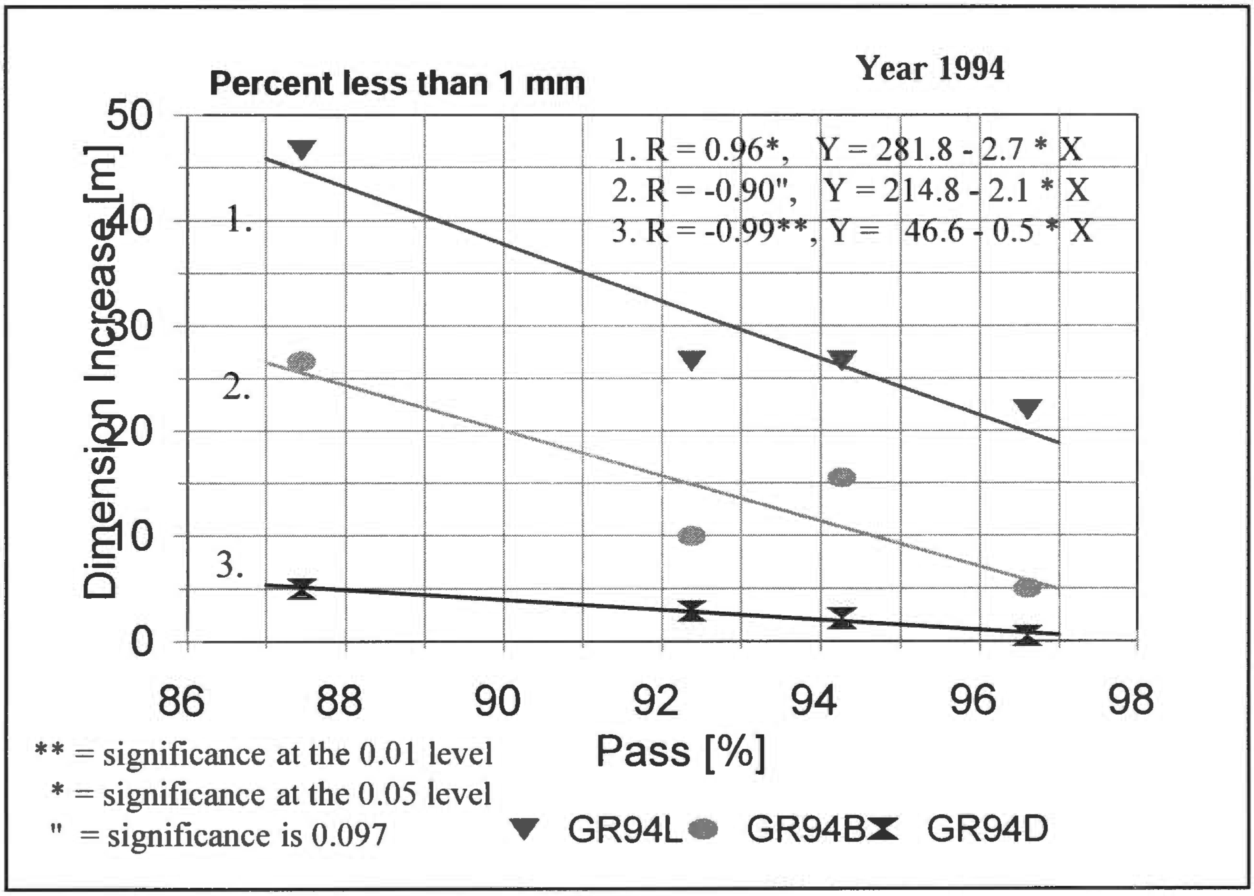

Figure 12. The influence of the proportion of sand of sand greater than 1mm in diameter on the gully advance.

4 DISCUSSION

The above results suggest that all other conditions being equal, once the gully has formed, the advancement is controlled by the soil characteristics of grain size, grain size distribution, and the nature of the soil cement within the laterite zone. The rate of gully advancement can be predicted from the equations in Figure 12 by determining the proportion of sand passing the 1mm diameter sieve.

It should be borne in mind that the predictive equations are only valid for the particular formations. It is necessary to study the rate of advance and the grain size distribution for each gully system in order to establish predictive equations for each.

5. CONCLUSIONS

Simple geotechnical tests such as grain size analysis and rate of soil dispersion or slaking can provide a measure of gully development or advancement. Soils with a uniform fine to medium gradation are most susceptible to erosion. Soils that are weakly cemented with soluble cements and can therefore slake or disperse when in contact with water are also quickly erodable.

6 REFERENCES

Bouyoucos, G.J, 1935: The clay ratio as criterion of susceptibility of soils to erosion. J. Am. Soc. Agronomists. 27, pp. 738-741.

Bruce - Okine, E., Lal R., 1975: Soil erodibility as determined by raindrop technique. Soil Science, 119, 149-156.

Donker, N.H.W. and Damen, M.C.J, 1984: Gully system development and an assessment of gully initiation risk in Miocene deposits near Daroca-Spain. Z.Geomorph. N.F. Suppl. Bd. 49, pp.37-50.

Lamb, J. Jr., Chapman, J.E., 1943: Effect of surface stones on erosion, wvaporation, soil temperature, and soil moisture. Journal of Amer. Soc. Agron., Vol. 35, pp. 567-578.

Lamb, J..Jr., Andrews, J.S., Gustafson, A.F., 1944: Experiments in the control of soil erosion in southern New York. Cornell Univ. Agr. Exp. Sta. Bull. 811.

Selby, M.J., 1993. Hillslope Materials and Processes (Second Edition). Oxford, Oxford University Press, 451 pp.

Wischmeier, W.H., J.V. Mannering, 1969: Relation of soil properties to its erodibility. Soil science society of America Proc, 33, pp.131-137.