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Geotechnical Properties of the Bank Sediments along the Dhansiri River Channel, Assam

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Abstract: The bank sediments along the extremely meandered Dhansiri River channel, a south bank tributary of the mighty Brahmaputra River, with erosion potentiality have been investigated to evaluate its certain geotechnical characteristics. The study has shown that the bank sediments are basically composed of CL and ML types of soil. These types of sediments are very much prone to liquefaction which in turn related to erosion susceptibility. The bank stability analysis has differentiated the studied stretch into unstable, at risk and stable zones. Most of the erosion affected zones along the channel reach under study are located within the unstable or at risk zones. The field study around Butalikhowa, Barguriagaon, Golaghat and Duchmuagaon areas along the channel with active erosion activity has supported our contention and practical utility of the present study. It is expected that such type of study will help in providing certain inevitable baseline information for various channel management practices for this extremely flood prone areas of Northeast India.

Keywords: Bank sediments, Geotechnical properties, Dhansiri River, Erosion, Assam.

INTRODUCTION

Geomorphological attributes of channel form and associated geotechnical characteristics of the bank materials play a great role in triggering the bank erosion processes. The mechanics of failure is invariably connected to the geotechnical properties of bank materials and the geometry of the bank at the point of collapse (Thorne and Abt, 1993). The erosion processes include direct removal of bank materials by the shearing action of the flow, as well as mass wasting of banks under the influence of gravity. The later processes are intimately connected to geotechnical characteristics of the sediments in question and invariably the most serious from the perspective of water resource management problem of global significance because mass wasting involves rapid channel widening and the delivery of large volumes of sediment to the channel. Moreover, extensive mass wasting is usually an indicator of river channel instability, associated in particular with incision of the riverbed (Darby and Simon, 1999).

Although considerable effort has been devoted in analysis of river bank instability, most of them have a number of technoeconomical, conceptual and practical shortcomings limiting their applicability in geologically varied conditions. However, recent studies (Rinaldi and Casagli, 1999; Simon et al. 2000) have made immense contribution in minimizing the associated practical problems with realistic understanding expected along the bank profile. The recent studies (Takaldany, 2003; EPA, 2003) on river bank stability analysis have accounted the effect of multiple horizontal layers of soil with different physical properties.

Since time immemorial the flood and erosion are two most important natural hazards of the northeastern region of India with mighty Brahmaputra River system. The objective of present study is to evaluate certain geotechnical characteristics of the bank sediments along the Dhansiri River channel and to correlate them with the erosion susceptibility. The stability of riverbanks is an issue where property ownership and land use interests seek for long term use.

GEOMORPHOLOGY OF THE AREA

The Dhansiri River Basin is situated in a varied geomorphic setup. From the regional geomorphic viewpoints, two major geomorphic units can be distinguished for the entire Dhansiri River Basin as shown in Fig.1. Regional slope, geological formations, structure and topography are the criteria applied to divide the units. Plains

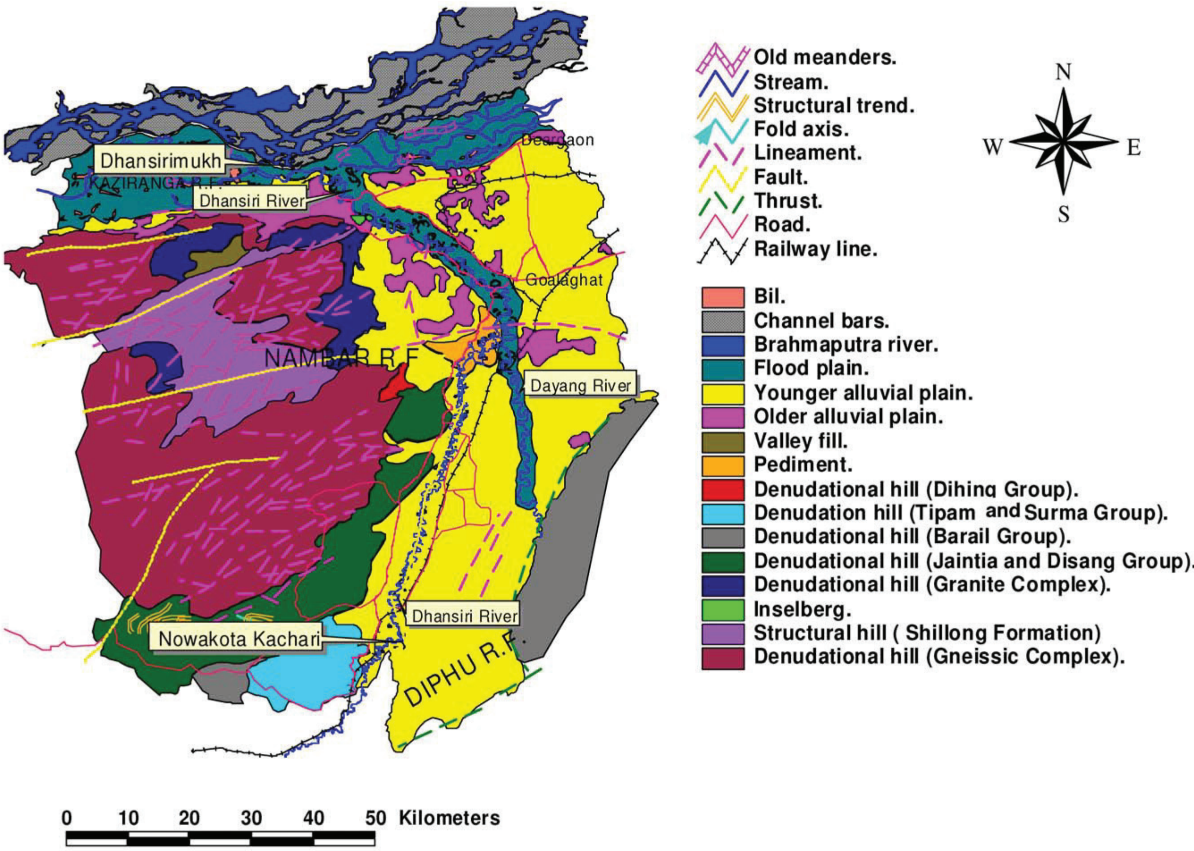
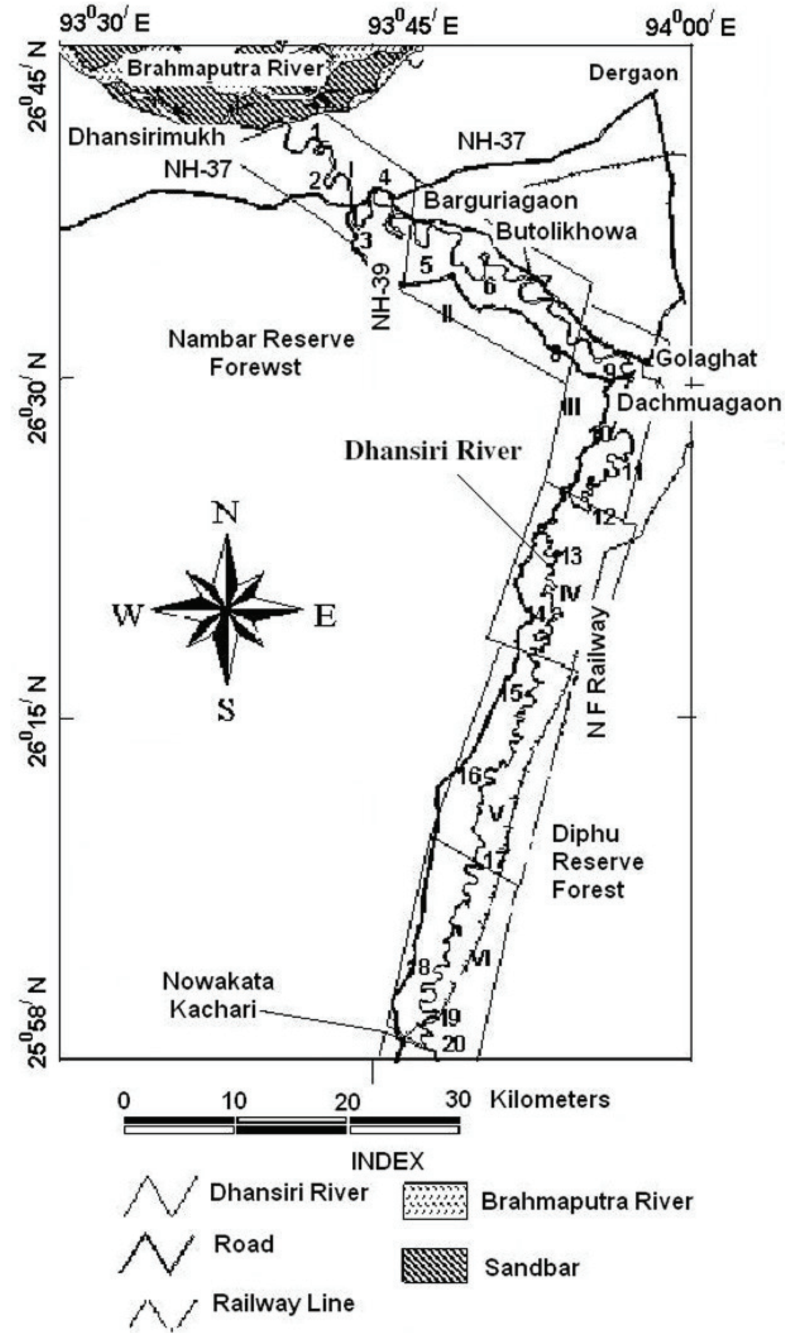


Fig.1. Geomorphological map of the area under study. (Compiled and modified from hydrogeomorphological maps prepared by Assam Remote Sensing Application Centre, Guwahati, India, 1990).

and Hills are the major geomorphic units of the area, which can further be divided into different subgroups depending on their geochronological status, nature of occurrence and associated structures. The plains and hills can be differentiated into flood plain, younger alluvial plain, valley fills and older alluvial plain and denudation hills, inselberg and structural hills respectively.

METHODOLOGY

Thematic maps of the study area (Fig.2) from Dhansirimukh to Nowakata Kachari ($93^{0}30^{/}$ - 94^{0}E Long. and $25^{0}58^{/}$ - $26^{0}45^{/}$ N Lat.) are prepared on the basis of Survey of India (SOI) toposheets of 1914, 1975 and Indian Remote Sensing (IRS) satellite imageries of 1990, 1995, 2000 and 2008 on 1:50,000 scale. The satellite images and topographic maps are registered and georeferenced on the basis of certain ground control points (GCP) with the help of ERDAS IMAGINE 8.5 software. Thematic maps are integrated and prepared using Arc View GIS. The entire channel length is divided into six equal sectors. The erosion-deposition activities are determined through sequential analysis with the help of geomorphological maps for different periods (viz. 1914 to 1975; 1975 to 1990; 1990 to 1995; 1995 to 2000 and 2000 to 2008). The annual rate of erosion and deposition are determined for six different sectors by dividing the amount of erosion/deposition by the elapsed time. On the basis of erosion/deposition activities as observed from the present study the sites for sampling are selected covering a stretch of 216 km (taking 1975 toposheet as base map) along the Dhansiri River channel within Assam. Twenty numbers of undisturbed bank sediment samples along the proposed stretch are collected for the study of geotechnical properties of the bank materials. The sediment samples are then subjected to physical fractionation by sieving into three fractions viz. sand(2.0 to 0.625 mm), silt(0.625 to 0.002 mm) and clay(<0.002 mm) by utilizing ASTM standard sieves. The fraction of the samples obtained below -325 mesh size or 0.031 mm are employed for particle size analysis utilizing Na_2CO_3/NaHMP as dispersing agents. CILAS 1180 Particle Size Analyzer was used to analyse the fraction at the range of 0.04 µm -2500 µm/100 classes. The Unified Soil Classification (USC, 1962) system adopted by the Bureau



Sample Locations	
1	93°42′E 26°40′N
2	93°43′E 26°39′N
3	93°44′E 26°37′N
4	93°46′E 26°38′N
5	93°47′E 26°37′N
6	93°50′E 26°34′N
7	93°53′E 26°34′N
8	93°55′E 26°31′N
9	93°57′E 26°30′N
10	93°57′E 26°28′N
11	93°57′E 26°26′N
12	93°55′E 26°24′N
13	93°54′E 26°22′N
14	93°53′E 26°19′N
15	93°52′E 26°16′N
16	93°50′E 26°13′N
17	93°50′E 26°08′N
18	93°47′E 26°03′N
19	93°48′E 26°02′N
20	93°48′E 25°58′N
Sectors	
I	93°36′E 26°42′N to 93°48′E 26°36′N
II	93°48′E 26°36′N to 93°56′E 26°31′N
III	93°56′E 26°31′N to 93°54′E 26°25′N
IV	93°54′E 26°25′N to 93°52′E 26°16′N
V	93°52′E 26°16′N to 93°50′E 26°07′N
VI	93°50′E 26°07′N to 93°48′E 25°58′N

Fig.2. Location map of the study area.

of Indian Standard (BIS) was utilised for their classification (IS: 1498-1970: Classification and Identification of soils for general engineering purposes). The longitudinal slope of the riverbed (within the range over which the samples were collected and studied) was determined using Dumpy Level and Staff. The liquid limit, plastic limit and plasticity index of soils were determined following established standard procedure (Singh and Chowdhary, 1994; IS: 2720, Part V, 1965).

Erosion–Deposition Processes

The activities of erosion/deposition processes along the Dhansiri River with average annual rate are presented in Table 1. It is observed from the study that the erosion was maximum (24.28 km^2) in sector I, whereas, it was least in sector III (9.14 km^2).

The sector IV has evidenced lowest amount of deposition (7.96 km^2). However, the sector III have also evidenced comparatively lower rate of erosion and deposition activities

Table 1. Erosion and deposition along the study area

Sectors	Erosion (km^2)						Deposition(km^2)					
	1914-1975	1975-1990	1990-1995	1995 2000	2000 2008	Total	1914-1975	1975 1990	1990 1995	1995 2000	2000-2008	Total
I	5.59	3.92	2.59	1.99	10.19	24.28	3.65	3.44	2.46	1.67	3.24	14.46
II	7.55	5.98	1.96	2.52	3.09	21.10	5.07	5.52	2.62	2.09	2.90	18.20
III	3.44	1.96	1.34	1.23	1.17	9.14	2.53	2.22	1.46	1.01	0.84	8.06
IV	2.10	1.81	1.61	1.56	2.45	9.53	1.63	1.66	1.67	1.46	1.54	7.96
V	1.91	3.12	1.39	1.97	2.10	10.49	1.04	3.12	1.43	2.39	1.12	9.10
VI	1.90	2.92	1.81	1.58	1.38	9.59	1.24	2.73	1.95	1.56	1.24	8.72

(9.14 km^2 and 8.06 km^2). The total average annual rate of erosion and deposition observed during the period are 1.56 km^2/yr and 1.29 km^2/yr respectively with corresponding ranges from 0.37 to 2.54 km^2/yr and 0.25 to 1.93 km^2/yr (Table 2). The nature of soft alluvial bank and contribution from the major tributaries might have played a major role in inhomogeneous nature of erosion/deposition activities operating over the basin. From the data of the Table 2, it is also evident that the rate of annual bank erosion per km length of the river course ranges from 0.0015 km^2/km/yr to 0.0102 km^2/km/yr, whereas, the rate of average annual deposition per km length of the river ranges from 0.0010 km^2/km/yr to 0.0546 km^2/km/yr. The average rate of bank erosion and deposition per km length of river channel, considering the data of the entire period of study, are found as 0.02558 km^2/km/yr and 0.01584 km^2/km/yr respectively.

Table 2. Average annual rate of erosion and deposition in the study area

Period	Average Annual Erosion (km^2/yr)	Average Annual Deposition (km^2/yr)	Rate of Avg. Annual Erosion (km^2/km/yr)	Rate of Avg. Annual Deposition (km^2/km/yr)
1914-1975	0.37	0.25	0.0015	0.0010
1975-1990	1.31	1.25	0.0061	0.0058
1990-1995	1.78	1.93	0.0089	0.0096
1995-2000	1.81	1.65	0.0090	0.0082
2000-2008	2.54	1.36	0.0102	0.0546
Mean	1.56	1.29	0.02558	0.01584

The ground observations along the studied stretch have revealed that in areas near Kuruabahi, fluvial erosion of the basal area of bank leads to severe undercutting and resulted subsequent cantilever failure. In these areas banks with slope approaching 90° and even more with overhangs are observed. This type of over steepening always enhances the failure of the bank. During the receding stage of the river, different types of shear failure also took place and observed around Kamargaon, Golaghat areas along the Dhansiri River channel (Dutta, 2007). As water level receded in the channel, saturated levee material lost support from the channel side. These resulted in shearing of blocks from the saturated bank due to its own weight.

In localities near Numaligarh-Butalikhowa areas fine-grained over bank deposits with mud cracks are present along the banks. The process of formation of mud cracks can directly be attributed to sub-aerial erosion processes, which include wetting and drying of the soil (and associated desiccation). These preparatory processes help to weaken the surface of the bank prior to fluvial erosion, thus increasing the efficacy of erosion. The blocks are separated by mud cracks. The cumulative effect of blocks separation of fine-grained sediments enhances the activity of shearing, which may ultimately lead to large scale bank failure. The soil moisture content has a strong relationship with the inter-particle forces within the material, which in turn related to pore-water pressure. The increase in soil moisture content act to decrease the 'resistance' of the bank to the shear forces associated with the flow. On the other hand, the decrease in soil moisture content also causes volumetric shrinkage resulting generation of 'pad fabric' with blocks separated by the desiccation cracks. This desiccation provides lines of weakness in the bank face, as cohesion is greater within the pads than between them. The affect of similar features enhancing the intensity of erosion along the studied stretch of the Dhansiri River channel is clearly visible around Kuruabahi, Butalikhowa and Golaghat areas.

Texture

The texture of sediments is an important parameter in determining erodibility. The data obtained through physical fractionation were plotted on ternary diagram to evaluate soil characteristics. The plot (Fig.3) has clearly indicated that the samples contain 76% as sandy clay-loam and 24% as sandy-loam to loamy sand types.

Further, particle size analysis applied to the clay fraction has evidenced that the mean diameter of the particle size ranges from 11.39 µm to 12.58 µm. The cumulative

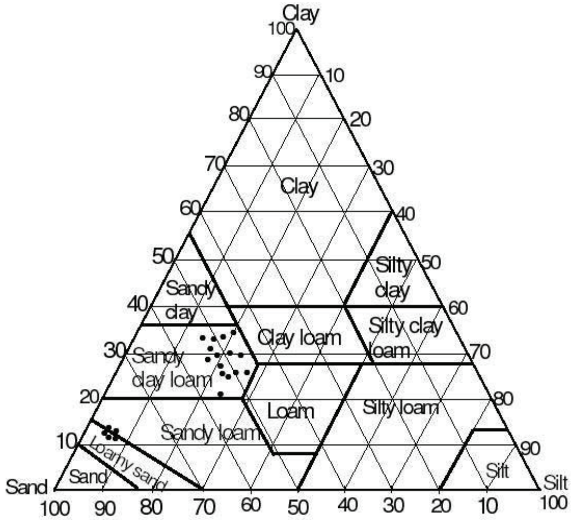


Fig.3. Classification of sediment texture.

distribution (%) of particle sizes in relation to their size ranges has shown that 90% and 50% diameter of the samples located within 26.44 µm to 28.72 µm and 8.27 µm to 9.64 µm respectively. The study has clearly attributed that the samples are mainly composed of finely divided clayey materials.

The characteristics derived from plasticity index vs. liquid limit (Table 3) has attributed that the samples are of CL and ML types. The water content of the samples under study varies from 12.6% to 35.4% with an average of 27.33%.

Table 3. Typical classification of sediment type on the basis of associated geotechnical properties

S. No	Liquid Limit (LL) %	Plastic Limit (PL) %	Plasticity Index (LL-PL)	Permeability cm per sec	Classification (Soil Type)
1	28	25	3	$5.1x\ 10^{-5}$	ML
2	29	20	9	$0.8x\ 10^{-6}$	CL
3	27	22	5	$7.2x\ 10^{-5}$	CL-ML
4	22	19	3	$5x\ 10^{-4}$	ML
5	31	24	7	$9\ x\ 10^{-5}$	ML

A run-off rate decreases with the rise in sand fraction, and are more easily detached, but less easily transported than silty samples. However, samples with higher clay fraction are not easily detached, but lower infiltration rates may lead to greater run-off and thereby increases the rate of erosion. Since particles are easily detached and transported in case of finer fraction it tend to have the greatest erodibility, and on consolidation it can lead to greater run-off.

Shear Strength Analysis

The shear strength is its maximum resistance to shearing stresses. As the permeability of the samples is varying from $0.8x10^{-6}$cm/sec to $7.2x10^{-5}$cm/sec, thus direct shear test (IS: 2720) was carried out under un-drained condition, to find out the cohesion (C_u) and angle of internal friction (Ö$_u$) (Table 4). On the basis of normal stress and shear stress data, stress-strain curve and failure envelope (Figs.4 and 5) were constructed for all the samples for analysis of bank failure.

The shear parameters, effective cohesion intercept ($c^/$) and effective angle of shearing resistance or friction (Ö$^/$) are derived on the basis of C_u and Ö$_u$ relationships from the failure envelop curves and utilized to study the behaviour of samples under saturated and unsaturated conditions. The shear parameters calculated for two specific conditions have shown undrained cohesion as (c_u) =1.35 N/cm^2 and undrained angle of internal friction (Ö$_u$) = 30^0. The calculated normal stress (ó) and shear stress (ô$_m$) at failure obtained, varies from 7.848 to 17.658(N/cm^2) and 5.769 to11.453 (N/cm^2) respectively. Since, it appears difficult to ascertain a definite peak for the sample under the present approach shear strain at failure (ô$_m$), was considered at a strain of 15% of the lateral dimension of the sample.

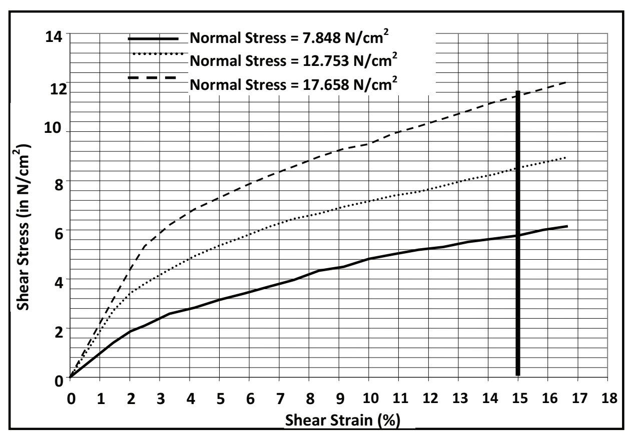


Fig.4. Typical Stress-Strain curve for bank sediments.

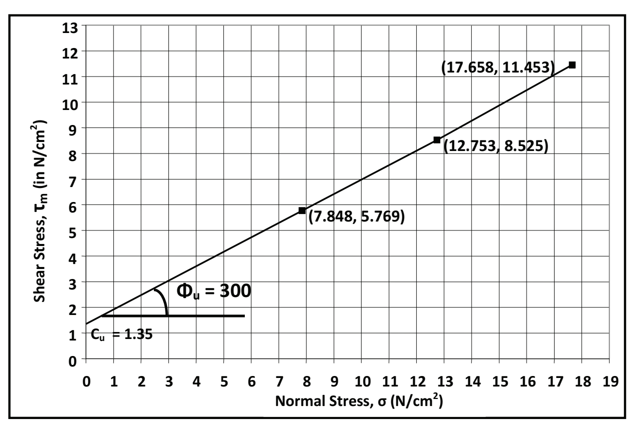


Fig.5. Typical failure envelope for sample as in Fig.4.

Table 4. Sample locations, angle of internal friction (Φ) and cohesion (c) determined for the samples under study

Sample Number	Location	Angle of internal friction (Φ)	Cohesion (c)
1	93°42' E 26°40' N	22°	0.50 N/cm^2
2	93°43' E 26°39' N	17°	6.00 N/cm^2
3	93°44' E 26°37' N	33°	3.03 N/cm^2
4	93°46' E 26°38' N	28°	1.60 N/cm^2
5	93°47' E 26°37' N	27°	2.60 N/cm^2
6	93°50' E 26°34' N	30°	1.05 N/cm^2
7	93°53' E 26°34' N	36°	0.42 N/cm^2
8	93°55' E 26°31' N	17°	1.32 N/cm^2
9	93°57' E 26°30' N	36°	2.20 N/cm^2
10	93°57' E 26°28' N	28°	2.00 N/cm^2
11	93°57' E 26°26' N	18°	1.32 N/cm^2
12	93°55' E 26°24' N	20°	0.64 N/cm^2
13	93°54' E 26°22' N	18°	0.34 N/cm^2
14	93°53' E 26°19' N	17°	0.63 N/cm^2
15	93°52' E 26°16' N	16°	0.51 N/cm^2
16	93°50' E 26°13' N	23°	1.03 N/cm^2
17	93°50' E 26°08' N	15°	0.80 N/cm^2
18	93°47' E 26°03' N	18°	0.67 N/cm^2
19	93°48' E 26°02' N	26°	0.45 N/cm^2
20	93°48' E 25°58' N	18°	0.31 N/cm^2

Bank Stability Analysis

To achieve acceptable results in bank stability analysis, a few conditions have been considered and assumed for the present study. The alluvial sediments are almost homogeneous and isotropic in nature. The riverbank bears a semi-infinite slope, i.e. consisting of infinite lateral extent and a finite depth.

Sediment is considered to be most susceptible to erosion during saturated conditions. Due to rapid decline in river water level the shear strength reaches to zero. Hence, saturated condition is taken as the most potential situation by considering friction to be zero, i.e. $\phi_{sat} = \phi'_{sat} = 0$. Since the sediment is mainly of CL-ML type, it can safely be assumed that the water content (W.C.) at saturation is roughly equal to liquid limit. This is based on the fact that, from slope failure point of view; the saturated condition exhibits maximum possible saturated unit weight, corresponding to maximum possible water content nearer or equal to the liquid limit.

$$W_{sat} = W_L$$

therefore,

$$\gamma_{sat} = \gamma_d (1 + W_L)$$

where, W_L is Liquid limit, W_{sat} is water content at saturation and γ_d is dry unit weight of the alluvial samples.

Following Singh and Chowdhary (1994) the average values of different parameters of bank sediments are calculated and reported in Table 5. Since, at saturated condition, the strength exhibited is the combination of its shear resistance as well as excess pore pressure, hence, here the effective shear parameters(c' and Φ') are considered instead of apparent values (c_U and Φ_U). Moreover, at such condition the effect of local shear failure predominates hence instead of taking c_U and Φ_U, their corresponding mobilized values (c_m and Φ_m) are taken for calculation (Singh and Chowdhary, 1994).

The stability number (N_s) was calculated for a range of bank angles (β) ranging from 25° to 90° using the relationship:

$$Sn = (4\mathrm{Sin}\beta\mathrm{Cos}\boldsymbol{\Phi})/\{1\text{-}\mathrm{Cos}(b\text{-}\boldsymbol{\Phi})\}$$

The critical bank height (H_c) was then calculated as a function of the geometry of the riverbank, the soil properties and soil moisture condition using the relationship:

$$H_c = (4c\mathrm{Sin}\beta\mathrm{Cos}\Phi)/\gamma\{1\text{-} \mathrm{Cos}(b\text{-}\Phi)\}$$

where, c= Cohesion and γ = Bulk Unit Weight.

Critical bank heights were estimated assuming conditions: (1) saturated bank and a rapid decline in river stage where friction reaches to zero, i.e. $\Phi_{sat} = \Phi'_{sat} = 0$ (since at saturation sediment/soil can be considered as almost frictionless) and (2) unsaturated conditions. Accordingly, the process was repeated using a friction angle of zero to estimate stability in saturated condition. Utilising the calculated data for two different conditions i.e., saturated and unsaturated for alluvial bank sediments with higher silt fraction at 0 to 3% slopes bivariant lognormal plot of Critical Height (Hc) vs. Bank Angles (β) was constructed and tabulated. The resulting bank stability chart (Fig.6) shows the relationship between the critical bank height and the bank angle. The upper line in the figure represents critical bank heights for unsaturated conditions. Bank angles and heights above this line represent an "Unstable" condition. The lower line refers to critical bank heights for saturated conditions and bank geometry conditions below this line represent "Stable" conditions. Bank geometry conditions between the two lines represent "At risk" stability conditions.

It is evident from the study that, any point lying above the upper line for any given bank angle will represent a bank height, which is higher than the corresponding critical bank height, even in unsaturated condition and hence will always be unstable. On the other hand, any point lying below the lower line will represent a bank height, in saturated condition and hence will always be stable under any condition of inundation. Also, any point, which lies in between the two lines, will thus represent a bank height, which remains stable only in unsaturated conditions, and hence will be at risk in saturated condition.

Table 5. Parameters in relation to bank stability at two different conditions for the Dhansiri River channel sediments

β	Saturated					Unsaturated				
	Φ'	S_n	c' (N/cm^2)	γ_{sat} (N/CC)	H_c (cm)	Φ_m	S_n	c_m (N/cm^2)	γ (N/CC)	H_c (cm)
25°	0°	18.04	0.91	0.019	864.16	21.29°	751.60	1.31	0.0172	57244.25
30°	0°	14.93	0.91	0.019	714.98	21.29°	161.59	1.31	0.0172	12306.94
35°	0°	12.69	0.91	0.019	607.61	21.29°	075.03	1.31	0.0172	5714.38
40°	0°	10.99	0.91	0.019	526.36	21.29°	045.33	1.31	0.0172	3452.73
45°	0°	09.66	0.91	0.019	462.51	21.29°	031.22	1.31	0.0172	2377.98
50°	0°	08.58	0.91	0.019	410.85	21.29°	023.22	1.31	0.0172	1768.79
55°	0°	07.68	0.91	0.019	368.03	21.29°	018.16	1.31	0.0172	1382.90
60°	0°	06.93	0.91	0.019	331.84	21.29°	014.69	1.31	0.0172	1119.04
65°	0°	06.28	0.91	0.019	300.72	21.29°	012.19	1.31	0.0172	0928.50
70°	0°	05.71	0.91	0.019	273.61	21.29°	010.30	1.31	0.0172	0784.24
75°	0°	05.21	0.91	0.019	249.67	21.29°	008.82	1.31	0.0172	0671.81
80°	0°	04.77	0.91	0.019	228.32	21.29°	007.64	1.31	0.0172	0581.63
85°	0°	04.37	0.91	0.019	209.07	21.29°	006.67	1.31	0.0172	507.60
90°	0°	04.00	0.91	0.019	191.58	21.29°	005.85	1.31	0.0172	445.55

The present investigation along the channel of the Dhansiri River has revealed that the samples collected from the site of extreme erosion, fall either in the unstable or at risk zones (Table 6) whereas, the samples from less eroded places fall in the stable zone of the bank stability chart .

RESULTS AND DISCUSSION

In Dhansiri River Basin two different geomorphological units can be distinguished as Plains (Flood Plain, Younger Alluvial Plain, Valley Fill and Older Alluvial Plain) and Hills (Denudation Hill, Inselberg and Structural Hill). Differential rate of erosion and deposition was observed in different sectors under study. The highest rate of erosion was confined

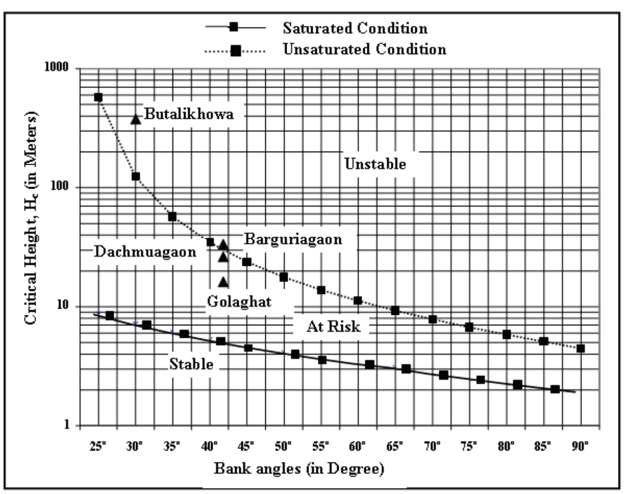


Fig.6. Bank Stability Chart for Sediment samples along the Dhansisri River channel.

within sector I and least in sector IV. The location of the sector I near the mighty Brahmaputra River have given significant attribute to the increasing erosion of the Dhansiri River channel. The total average annual rate of erosion and deposition observed during the period are 1.56 km^2/yr and 1.29 km^2/yr respectively, with corresponding ranges from 0.37 to 2.54 km^2/yr and 0.25 to 1.93 km^2/yr.The inhomogeneity in bank sediments and contribution from the major tributaries might have played a major role in erosion/deposition activities operating over the basin. The average rate of bank erosion and deposition per km length of river channel, considering the data of the entire period of study, are found out as 0.02558 km^2/km/yr and 0.01584 km^2/km/yr respectively. The significant affect of erosion activity along the Dhansiri River channel is clearly visible around Numaligarh, Butalikhowa, Kuruabahi, and Golaghat areas.

The characteristics of the Dhansiri River sediments as evident from the study have attributed certain significant characteristics. Texturally, the sediments of the Dhansiri River channel have clearly indicated that the samples contain 76% as sandy clay-loam and 24% as sandy-loam to loamy sand types. Sands with fine and uniform grain size are found to be more susceptible to liquefaction, since the permeability of such soil is low enough to prevent dissipation of the pore pressure developed under each cycle. However, this depends on duration of dynamic loading, drainage path and relative density of the sediments. Fabric or the structure imparted an additional support to the loose state is an important factor for liquefaction.

The alluvial sediments are classified as CL and ML types on the basis of related geotechnical properties. These low-

Table 6. Different geotechnical parameters and critical height for a few locations along the bank of the Dhansiri River

Sample Location	γ (gm/cc)	β	c_u (N/cm^2)	Φ_u	$c' = 2/3c_u$ (gm/cm²)	$\varnothing' = \tan^{-1}$ ($2/3\tan\varnothing u$)	H_c (meter)	Zone
Barguriagaon	1.79	41.25°	2.60	27°	173	18.76°	31.74	Risk
Butalikhowa	1.87	31.63°	2.20	36°	147	25.84°	290.91	Unstable
Golaghat	1.54	41.25°	1.05	30°	70	21.05°	18.19	Risk
Dachmuagaon	1.53	41.87°	2.00	28°	133	19.52°	29.12	Risk

density loose sediments with variable permeability are characterized by poor stability, susceptible to liquefaction and having poor drainage characteristics. These types of sediments are characterized by low erodibility susceptible to rate of run off which in turn related to erosion activities. Sediment with higher clay contents are generally characterized by its lower sensitivity and low plasticity index. The previous study has reported Kaolinite as the dominant clay fraction associated with the sediments of the Dhansiri River channel. They are always in a state of open packing, on disturbance they are weakened and tends to flow plastically.

Basically, the limit of the fine-grained sediments is a reflection of both strength and deformity**.** The water content, field unit weight and dry unit weight of the samples are found as 12.6 to 35.4%, 1.56 to 2.05gm/cc and 1.32 to 1.61gm/cc respectively. The liquid limit, plastic limit and plasticity index of the studied samples are varies from 22 to 31%, 14 to 26% and 2 to 10 respectively. The permeability for such type of sediments/soils with different limits, usually characterized with different values and ranges from $5x10^{-4}$ to$1x10^{-6}$cm/sec. Such type of sediments/soil under similar condition of compressibility may experience a greater degree of probability in failure under similar load conditions. These types of soils are also characterized by the low to medium cohesive strength.

The bank stability analysis has been done in relation to critical bank height and the critical bank angle for both saturated and unsaturated conditions. The analysis has differentiated the conditions by means of constructing a set of graphs into unstable, at risk, and stable zones. Any point above the upper line represents a condition, which is unstable even in unsaturated condition. The points between the lower and upper lines attributed condition, which is at risk only in saturated condition. However, the points below the lower line denote a stable condition with lesser erosion susceptibility. Thus the study has attributed that the set of graphs constructed can very well be utilized to understand the erosion susceptibility of areas after determining and extrapolating the two parameters viz. critical bank angle and critical bank height for future probability analysis without going through elaborate litho-geological approaches. The samples collected from Butalikhowa, Barguriagaon, Golaghat and Duchmuagaon where erosion potential is very high were used to understand the practical utility of the present study. The study has clearly demonstrated that all the samples are located within the risk or unstable zones. Moreover, the study related to engineering properties of the bank sediments helps to understand many important aspects in relation to the associated erosion mechanisms. It is expected that such type of interdisciplinary study along with other geomorphological studies, will help to attribute necessary baseline information for management approaches, in relation to land-use planning and erosion potentials.

CONCLUSION

The geotechnical properties of the bank sediments and bank stability analysis along the Dhansiri River channel have provided valuable information in land resource evaluation. Texturally dominant Sandy-Clay-Loam (76%) with subordinate Clay-Loam (24%), ranging permeability from $5x10^{-4}$ to $1x10^{-6}$ cm/sec has characterized the bank sediments with poor stability susceptible to liquefaction. The geotechnical properties of the bank sediments also have classified them as CL and ML types. Such type of sediments under similar condition of compressibility may experience a greater degree of variability in failure under similar load conditions. These are highly susceptible to erosion during rise of water level in the channel. Because of the envelopes of water surrounding individual finer particles (clay) such sediments exhibit a state of open packing, on disturbance they are weakened and imparts plasticity. The bank stability analysis has allowed classifying the bank sediments into three zones unstable, at risk, and stable zones. Location of samples within the risk or unstable zones collected from the areas with significant erosion, along the Dhansiri River channel have proved our contention and practical utility of the study. Moreover, the present investigation related to geotechnical properties of the bank sediments of the Dhansiri River, helps to understand many important aspects in relation to the associated erosion mechanisms. It is expected that correlating the findings of such interdisciplinary studies, with other geomorphic attributes attempt can be made to regulate the gap towards collection of necessary baseline information for practically viable erosion management practices.

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