Stability Analyses of Alluvial Riverbanks of Majuli Island, Upper Assam, India

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Abstract. Riverbank erosion is a continuous process in which its stability is critical throughout the course of the river. The purpose of this study is to examine and assess the stability of the riverbanks of Majuli, the world's largest riverine island, which is encircled by the river Brahmaputra. Because the river Brahmaputra and its tributaries are primarily made up of alluvial composites, hence vast areas of riverbanks are vulnerable to instability and erosion. Riverbank stability evaluations are conducted utilizing Culman-type analyses of steep, cohesive riverbanks, as proposed by Osman and Thorne (1988). Bank angles ranging from 35^0 to 85^0 are evaluated for stability analyses. The factor of safety (F.O.S) for each riverbank and the critical bank angle (for F.O.S =1) are computed using the appropriate formulas. The outcome of these analyses revealed that the banks are in a highly unstable state and thereby adopting a suitable factor of safety, necessary measures should be adopted for the protection of the riverbanks from future erosion.

Keywords: Alluvial riverbank, Culman-type stability analyses, Factor of safety, Critical bank angle.

1 Introduction

Riverbank erosion and flood are recurring processes in fluvial dynamics as both are associated hazards with severe outcomes. The 1950 earthquake had a significant impact on the configuration of the rivers, flooding and sweeping away all its banks thereby making them more susceptible to erosion and bank instability. The world's largest riverine island, Majuli, is surrounded by the river Brahmaputra which is the world's 9th largest river by discharge and 15th by length. It has a highly braided channel with the second largest sediment carrier and is home to more than 15 million people. Repeated changes in flow behavior, sudden turbulence with whirlpools, intense braiding with sandbar formation along with meandering results in more instability and erosion of the banks. Alluvial composites have resulted in very low shear strength in the riverbanks leading to its instability. Majuli, which had 880 square kilometers (km) at the beginning has now only 352 square kilometers.

The present work proceeds with different properties of samples of riverbank collected from four different sites of Majuli island to analyze its stability. After the geotechnical investigations performed in the laboratory, the stability analyses of the riverbanks are carried out using the Culman-type analyses of steep, cohesive riverbanks as proposed by Osman and Throne (1988). The stability is checked for bank angles ranging from 35^0 to 85^0 at 5^0 interval. Using respective formulas, the Factor of Safety (F.O.S) for each bank is calculated and the critical bank angle (for F.O.S =1) is determined.

2 Materials and Methodology

2.1 Materials Used

The riverbank samples taken for this work are collected from four different vulnerable sites of Majuli island i.e., from Salmara area (0.5 km upstream from Salmara ghat), Afalamukh area (1.0 km upstream and 1.2 km downstream site from Afalamukh ferry ghat), Kamalabari area (1.0 km downstream site from Kamalabari ferry ghat, Majuli).

2.2 Methodology

Determination of geotechnical properties and parameters

As per the Indian standard soil classification system, coarse grain soils are classified based on their grain-size distribution and fine grain soils based on their plasticity. Grain size analyses are performed according to IS 2720 (Part 4) – 1975. The gradation curves (% finer vs. grain size distribution) of all the samples are graphically represented in Fig. 1.

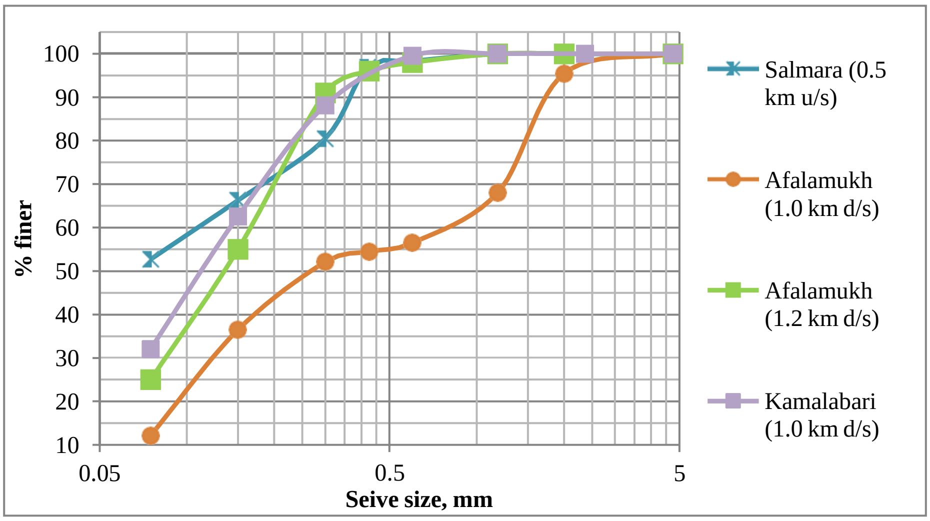

Fig. 1. Gradation curve of all the collected riverbank samples.

The liquid limit (LL), plastic limit (PL) and plasticity index (PI) were performed as per IS: 2720 (Part 5) – 1965. From the gradation curves (% finer vs. grain size) and the plasticity chart, the types of soil were determined. Table 1 shows LL, PL, PI and soil type of respective riverbank samples.

Table 1. Soil classification as per plasticity chart.

Riverbank sample collection site	Liquid limit (%)	Plastic limit (%)	Plasticity index	Sample type
Salmara (0.5 km u/s)	35.4	25.9	9.5	MI
Afalamukh (1.0 km u/s)	23.95	Non-Plastic	-	SP-SM
Afalamukh (1.2 km d/s)	25.73	Non-Plastic	-	SM-SC
Kamalabari (1.0 km d/s)	29.95	Non-Plastic	-	SM

The field density and water content of the samples have been determined using the core cuter method and carried out as per IS 2720 (Part 2) -1975. The Standard Proctor Test is carried out to determine the maximum dry density and the optimum moisture content as per IS: 2720 (Part 8) -1983 and determination of the effective cohesion and the internal friction angle is done using the Direct Shear apparatus and carried out as per IS: 2720 (Part 13)-1986 and are tabulated as shown in Table 2.

Table 2. Geotechnical properties and parameters of all collected riverbank samples.

Riverbank sample collection site	MDD (gm/cc)	OMC (%)	Eff. cohesion $C^{/}$ (KN/m^2)	Eff. friction angle, $\phi^{/}$ (Degree)	Bulk unit wt. (gm/cc)
Salmara (0.5 km u/s)	1.58	19	11.1	17	1.91
Afalamukh (1.0 km u/s)	1.77	12.5	3.8	27.5	1.75
Afalamukh (1.2 km d/s)	1.69	15.2	6.1	26	1.79
Kamalabari (1.0 km d/s)	1.72	13.3	4.5	27	1.74

The variation of MDD and OMC is graphically represented in Fig. 2 and the variation of cohesion and angle of internal friction is shown in Fig. 3.

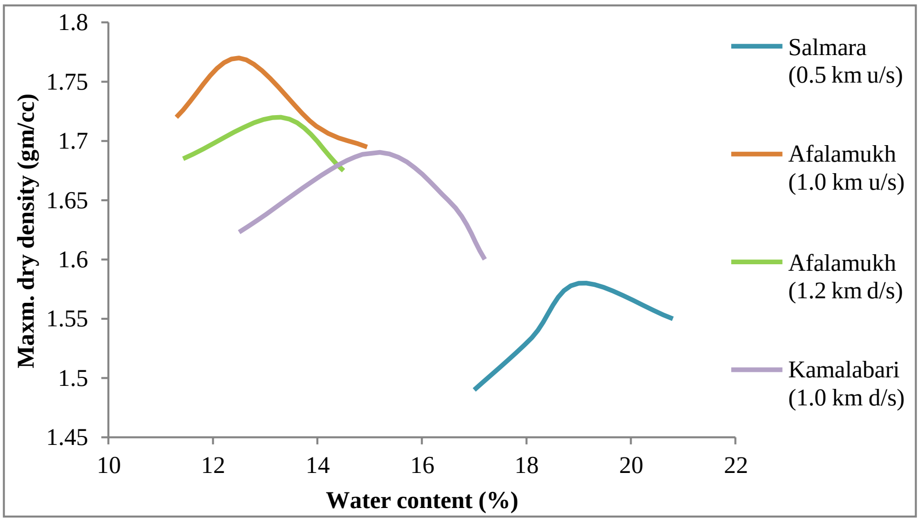

Fig. 2. Variation of dry density with water content of all the collected riverbank samples.

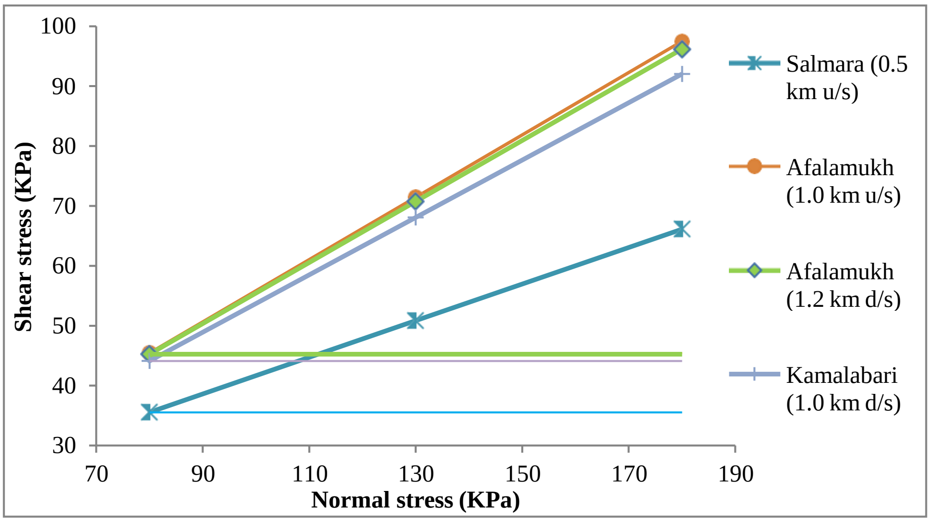

Fig. 3. Variation of shear strength parameters of all the collected riverbank samples.

Riverbank stability analyses

The riverbank stability analyses were carried out using the Culman-type stability analyses of riverbanks put forward by Osman and Thorne (1988). They made a slope stability analyses for steep banks in conjunction to calculate lateral erosion distance, to predict bank stability response to lateral erosion or bed degradation. The failure plane angle, failure block width, and volume of failed material per unit channel length were calculated for the critical case. The bank geometry is shown in Fig. 4 and Fig. 5.

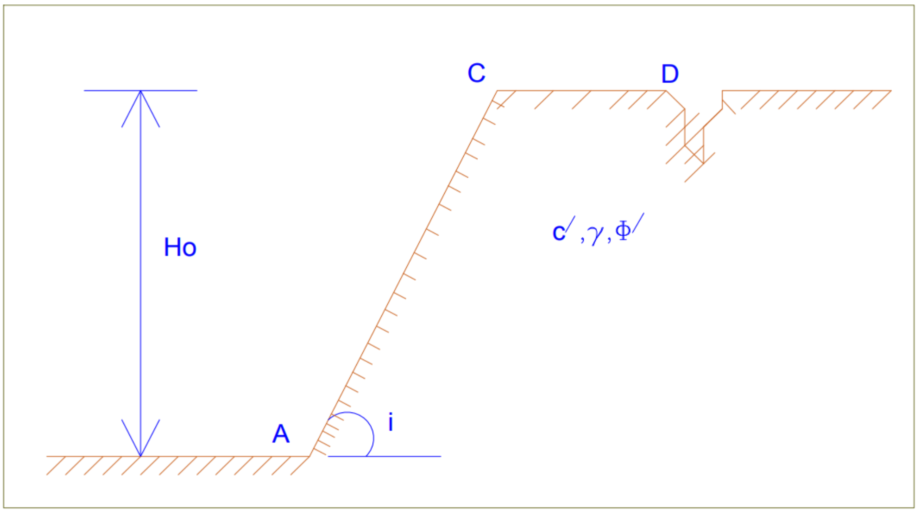

Fig. 4. Riverbank before erosion (Osman and Thorne (1988)).

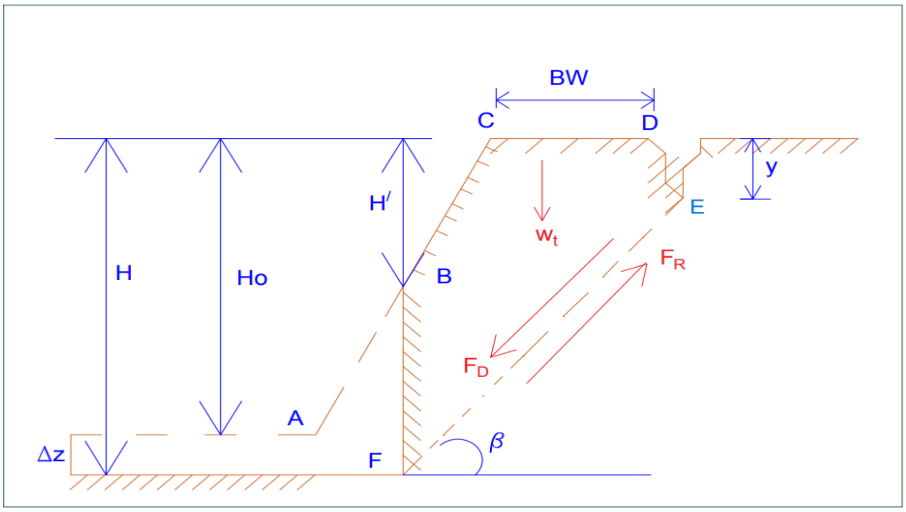

Fig. 5. Riverbank after erosion (Osman and Thorne (1988)).

In the above figure,

H_O = Initial bank height above the bed

Δz = Degradation depth

H = Total height of the riverbank from the bed level to the top of the bank surface

$H^{/}$ = 50% of H

i = initial bank angle.

G = Specific weight of soil

$C^{/}$= effective cohesion

$\emptyset^{/}$= effective angle of internal friction

BW = Failure plane width

ΔW = Change in river bed width due to lateral erosion

y = Tension crack depth = KH (1)

where, K is dependent on angle of internal friction

The weight of the failure block is given as

$$W_t = \frac{\gamma}{2}\left(\frac{H^2 - y^2}{\tan\beta} - \frac{H^{/2}}{\tan i}\right) \qquad (2)$$

Failure Plane angle for failure plane FE is given by,

$$\beta = \frac{1}{2} \times \left[\tan^{-1}\left\{\left(\frac{H}{H^{/}}\right)^2 (1 - K^2)\tan i\right\} + \emptyset\right] \qquad (3)$$

The driving force acting on the bank is given by,

$$F_D = W_t \sin\beta$$

$$\Rightarrow F_D = \frac{\gamma}{2}\left(\frac{H^2 - y^2}{\tan\beta} - \frac{H^{/2}}{\tan i}\right) \times \sin\beta \quad (4)$$

The resisting force acting against the driving force is given by,

$$F_R = c^{/} FE + N \tan\emptyset^{/}$$

$$\Rightarrow F_R = \frac{(H-y)C^{/}}{\sin\beta} + \frac{\gamma}{2}\left(\frac{H^2 - y^2}{\tan\beta} - \frac{H^{/2}}{\tan i}\right) \cos\beta \tan\emptyset^{/} \quad (5)$$

Where, N is the component of weight W_t, normal to the failure surface = $W_t \times \cos\beta$**,**

FE is the length of failure surface = $\frac{(H-y)C^{/}}{\sin\beta}$

Now Factor of safety (F.O.S) is given by, F.O.S $= \frac{\text{Resisting Force}}{\text{Driving Force}}$ (6)

If F.O.S computed is less than 1, the bank slope is taken to be unstable and if it is greater than 1 it is taken as stable. For F.O.S = 1, the bank slope is found to be critical.

The stability analyses consider the soil mass to be relatively homogeneous and isotropic in nature, so that average soil properties can be applied. Only toe failure is considered in the analyses as it is mostly observed. The analyses doesnot consider factors like water table, surface runoff, vegetation density and seepage although these may be important at certain locations but can be taken into account by modifying the analyses (Osman and Thorne, 1988).

The initial bank height and degradation depth of the riverbank sites were collected from Upper Assam Water Resource Investigation Department, Govt. of Assam as shown in Table 3.

Table 3. Geotechnical properties and parameters of all collected riverbank samples.

Riverbank sample collection site	Initial bank height H_0 (m)	Degradation depth, Δz (m)
Salmara (0.5 km u/s)	4.5	0.35
Afalamukh (1.0 km u/s)	3.55	0.3
Afalamukh (1.2 km d/s)	4.1	0.25
Kamalabari (1.0 km d/s)	4.16	0.3

The computation of Factor of safety (F.O.S) of the collected riverbank samples are tabulated as shown in Table 4.

Table 4. Computation of F.O.S of all riverbank samples as per Osman and Thorne (1988).

Riverbank sample collection sites	Bank angle, i (degree)	Critical bank angle, i_{cr} (degree)	Tension depth crack(m) y = KH	Failure plane angle, β (degree)	Driving force, F_d (KN)	Resisting force, F_r (KN)	Factor of safety, F.O. S
Salmara (0.5 km u/s)	35	78.5	2.5507	40.9151	33.3385	51.5398	1.5459
	40			42.8576	34.9173	49.8216	1.4268
	45			44.5178	36.2913	48.4638	1.3326
	50			45.9675	37.5174	47.3571	1.2622
	55			47.2418	38.6350	46.4292	1.2017
	60			48.4088	39.6731	45.6342	1.1509
	65			49.4726	40.6540	44.9365	1.1028
	70			50.4657	41.5958	44.3124	1.0659
	75			51.4082	42.5137	43.7454	1.0289
	80			52.3067	43.4218	43.2196	0.9953
	85			53.1848	44.3331	42.7258	0.9637
Afalamukh (1.0 km u/s)	35	53	1.3573	48.2093	16.9993	20.9843	1.2350
	40			49.9052	17.9923	20.6412	1.1472
	45			51.3339	18.8402	20.3512	1.0812
	50			52.5643	19.5798	20.1016	1.0266
	55			53.6478	20.2404	19.8896	0.9823
	60			54.6203	20.8438	19.6876	0.9445
	65			55.5086	21.4035	19.5107	0.9115
	70			56.3337	21.9338	19.3461	0.8822
	75			57.1128	22.4438	19.1905	0.8552
	80			57.8591	22.9420	19.0484	0.8391
	85			58.5847	23.4363	18.9033	0.8651
Afalamukh (1.2 km d/s)	35	58	1.5704	47.8398	21.0535	27.0097	1.2822
	40			49.5441	22.2756	26.5379	1.1913
	45			50.9808	23.3119	26.1431	1.1214
	50			52.2191	24.2163	25.8061	1.0656
	55			53.3095	25.0248	25.5126	1.0194
	60			54.2882	25.7629	25.2519	0.9801
	65			55.1825	26.4496	25.0161	0.9457
	70			56.0134	27.0998	24.7989	0.9150
	75			56.7976	27.7255	24.5958	0.8871
	80			57.5491	28.3370	24.4028	0.8618
	85			58.2792	28.9440	24.2167	0.8366
Kamalabari (1.0 km d/s)	35	64.4	1.7012	46.9616	24.6694	33.4272	1.3559
	40			48.6889	26.0531	32.7681	1.2576
	45			50.1469	27.2266	32.2252	1.1834
	50			51.4043	28.2543	31.7694	1.1241
	55			52.5142	29.1809	31.3732	1.0755
	60			53.5054	30.0291	31.0932	1.0356
	65			54.4154	30.8083	30.7108	0.9908
	70			55.2666	31.5544	30.4269	0.9612
	75			56.0522	32.2736	30.1984	0.9347
	80			56.8243	32.9764	29.9377	0.9071
	85			57.5668	33.6728	29.6781	0.8815

3 Result and Discussions

The bank stability analyses have been carried out for bank angles varying from 35^0 to 85^0 at a 5^0 interval by finding the driving force and resisting force based on the bank geometry and bank material properties of the collected riverbank samples and finally the critical bank angle is determined. From the analyses, a graph is plotted taking the bank angle as abscissa and the F.O.S as ordinate as shown in Fig. 6.

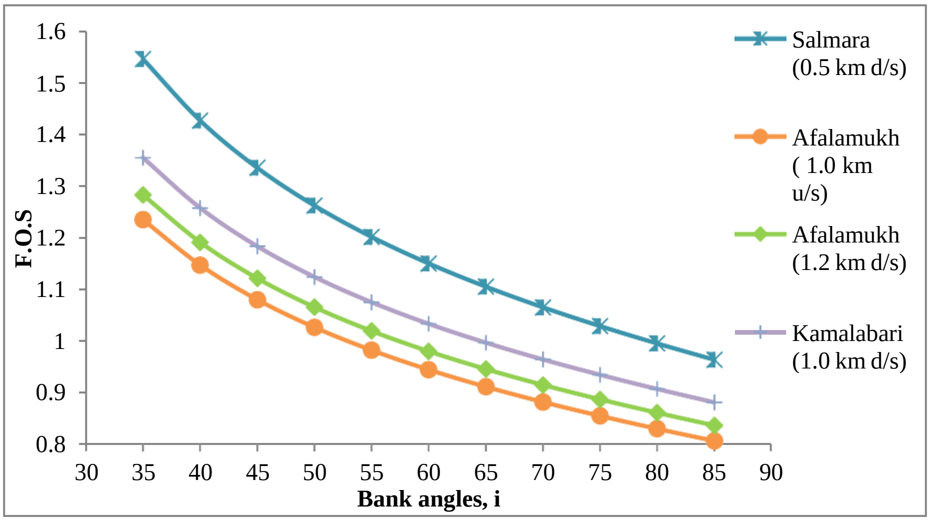

Fig. 6. Variation of F.O.S vs. bank angles for all the collected riverbank samples (Culman Type analyses, Osman and Thorne (1988)).

The stability of the riverbanks in descending order as per Culman stability analyses for critical bank condition is shown in Fig. 7.

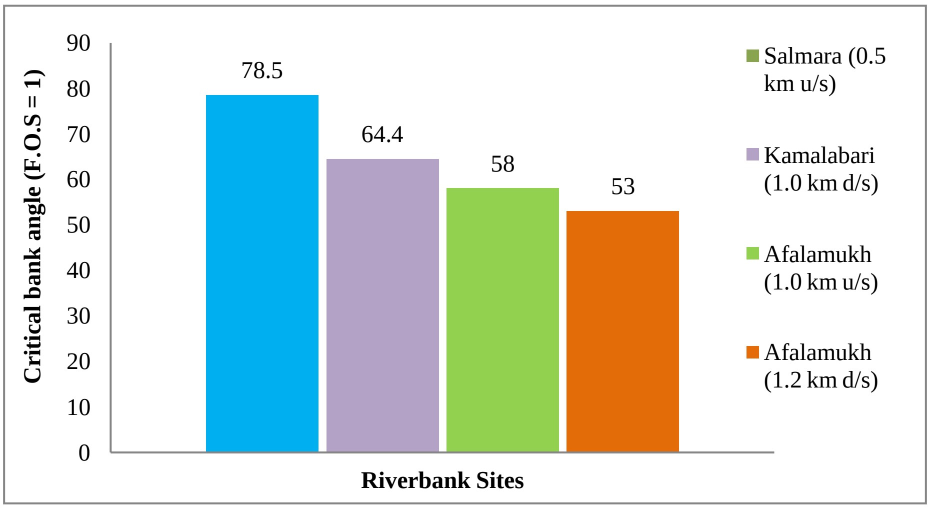

Fig. 7. Variation of critical bank angles for all the collected riverbank samples (Culman type analyses, Osman and Thorne (1988)).

From the analyses it was observed that the driving force increases with an increase in bank height, degradation depth and tension crack depth. Also, with the decrease in strength parameters, the driving force increases and the failure plane angle increases with increasing bank angles i.e. as the bank gets steeper. The four collected samples from the Brahmaputra riverbank are found mainly in the silt and sand category. They are found to be SP-SM, SM, ML, MI, SM-SC types with a very low value of cohesion which makes them easily detachable and prone to erosion.

3.1 Stability calculation for the riverbanks taking F.O.S = 1.25

The stability of the riverbanks needs to be further analyzed for practical purposes i.e., with a suitable and safe value of factor of safety. At the stage of critical angle, the bank is on the verge of failure or it cannot be justified as a stable condition. Hence a suitable factor of safety, F.O.S = 1.25 is adopted for further analyses. Table 5 shows the bank angles at F.O. S=1.25 along with its horizontal to vertical ratio of the bank.

Table 5. Resisting bank angle along with horizontal to vertical slope for F.O.S = 1.25.

Riverbank sites	Critical bank angle (at F.O.S = 1.00, in degree)	Resisting bank angle (at F.O.S =1.25, in degree)	Resisting slope (H:V)
Salmara (0.5 km u/s)	78.5	50.25	1H:1.203V
Afalamukh (1.0 km u/s)	53	34.15	1H:0.678V
Afalamukh (1.2 km d/s)	58	36.84	1H:0.750V
Kamalabari (1.0 km d/s)	64.4	40.52	1H:0.855V

4 Conclusions

The riverbank samples have been collected from different riverbank sites where continuous erosion has been taking place for the last few years. Initially, the geotechnical parameters of the collected samples are determined in the laboratory and the data obtained are further used in the stability analyses which were carried out using the Culman-type stability analyses of steep cohesive riverbanks (Osman and Thorne, 1988). The collected riverbank samples are found to be of MI, SM-SC, SP-SM and SM. The samples are found to have a very low cohesion and consist of sand particles leading to easy detachable and erodible. The Factor of safety (F.O.S) for bank angles ranging from 35º to 85º for the riverbank sites are calculated and the critical bank angle has been found at F.O.S = 1. A minimum factor of safely, F.O.S = 1.25 has been adopted for further analyses of the bank stability and thus it can be implemented directly by first trimming the banks to the necessary stable slopes. And for further maintaining its sta- bility, apron construction along with geomats/ geomatress can be provided near the bank toe so that the river current does not wash away or scour up the bank below the bank toe. Hence implementation of bank trimming, bank protection and river training works will be one of the major steps to mitigate the existing bank erosion problems.

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