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Observation of hysteresis behavior for the bank strength on cohesive flood-plain

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The fluctuations of the bank strength against erosion were observed in the recent experiments conducted on the cohesion mixed flood-plain with the layered sediments. Time dependent consolidation, cohesion variation and the discharge fluctuations are the main parameters that effect the bank strength fluctuations. The cohesive material properties and its self consolidation behavior lead to the self increment of the density and the corresponding failure stresses. On increasing the cohesion in the mixture, the failure stress was found to increase up to certain extent and reaches maximum values around 30% of cohesion and then decreases for further increase in cohesion in the mixtures. Also, the judgment during discharge fluctuations in the channel shows significant variations in the failure stresses for high and low flow cases. Finally these phenomena drive towards the hysteresis behavior due to cohesive sediment transport considering the process as erosion and transport, deposition and settling and consolidations etc.

Key Words: *Shear failure, consolidation, layered flood-plain, hysteresis etc*

1. Introduction

The role of cohesive sediment on the river planform evolution or bedform generation has been identified as an important parameter[1), 2), 3)]. Numbers of research[4), 5), 6)] not only identified many explicable direct and indirect effects on the channel morphological evolutions but also put some limitations regarding the hysteresis effect of cohesive sediment during its response to erosion, suspension, deposition and finally consolidation. The present work is trying to produce some general facts of the hysteresis effect based on the results from the series of experiments conducted recently.

Not only there were very limited work about cohesive sediment influences and effects on the river engineering process, but also the accountability of the cohesion on the river channel process had not dealt in full extent.

Though the influence of cohesion on the morphological evolutions of the rivers were found on many published works[7)], but those are limited only with the experimental simulations. Among them, Smith[6)] pointed that cohesion from suspension transport and deposit brings hysteresis like property with the shear stress needed to erode a stabilized bar was observed to be higher than that needed to create the bar initially.

Evidence in the literature that supports the idea of hysteresis can be found in the cohesive deposits in estuaries. Partheniades[8)] found that the erosion rates were independent of the shear strength of the bed and of the concentration of suspended sediment, but that they depend strongly on the shear stress, increasing rapidly after critical value had been reached. Mehta et.al.[9)] pointed out physical process constituting fine, cohesive sediment transport which includes settling and deposition, consolidation, erosion and transport in suspension is typically interlinked by cyclic nature of the tide dominated environments. Dulal and Shimizu[10)] recently conducted experiments with variation of cohesive sediment with the mixture of non cohesive sediments in the flood-plain. The experiments were able to simulate different planforms with dependability on cohesion variation.

Kothyari and Jain[11)] conducted several experiments on incipient motion using clay and gravel mixtures and found that the critical shear stress of cohesive sediments can be up to 50 times larger then the critical shear stress of cohesionless sediment having similar arithmetic mean size as the cohesive sediments.

Large number of works based on experiments[12), 13)] were conducted on the cohesive mixed sediments with different

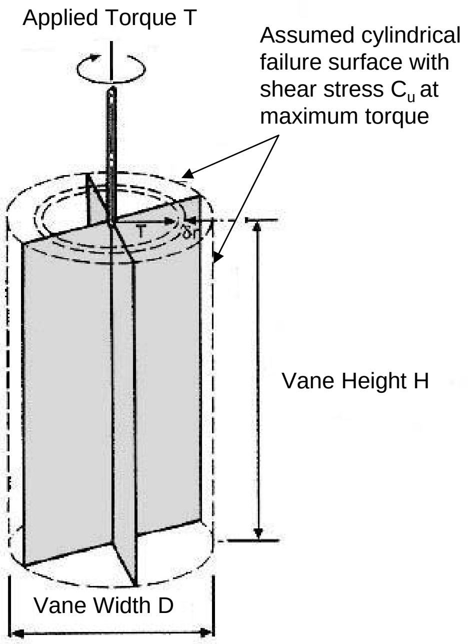


Fig.1 Standard Vane tester with varying dimension of vane height (H) and vane diameter (D).

objectives in Japan. They described the erosion process in the cohesive mixed sediments due to simulated rainfall as well as proposed an erosion rate formula considering factors like cohesion content, shear velocity etc.

The present study focused on the analysis of direct and indirect role of cohesion on the river channels and its associated phenomena. Series of experiments were conducted to measure the flood-plain strength i.e. resistance against erosion with the variation of parameters as cohesion content and discharge fluctuations.

2. Experiments

Fig. 1 shows the schematic diagram of the Vane tester[14] used for all experimental cases. Vanes with different dimension i.e. diameter and height were used. The Vane fitted with conveyor belt is driven by the motor to produce the torque. The torque is measured by the electronic device at a distance called arm length from the Vane (see appendix). The maximum torque is related with the failure stress on the cylindrical surface at the outer perimeter as shown in Fig.1. The precision of the apparatus used in the present work was 1gm/cm^2 for strength measurement.

Two different types of test were performed i.e. indirect (off-site) and direct (on-site) measurements of the shear failure stress. The conditions for both cases are defined in Table 1 and Table 2. The samples for the indirect shear failure were prepared separately outside the flume in double layers to represent the natural meandering flood-plain[15]. The fully saturated sand (d_{50}=0.28mm) is laid in the bottom layer of a paper sample box.

Table 1: Indirect (off-site) shear failure measurements

S.N.	Cohesion content (%)	Time of experiment (hr)
1	5 to 50	About 12 hour

Table 2: Direct (On site) shear failure measurements

Run	Flow condition	Channel condition	Experiment duration (hr)	Clay content
Run I	Intermittent	Straight	58	20 %
Run II	Intermittent	Straight	127	20 %
Run III	Depth fluctuation	Straight	127.5	$<$5 %
Run IV	Depth fluctuation	Meandering	131.5	$<$5 %

The top layer is composed of mixture of white Kaolinte varying from 5 to 50% and the remaining portion of fine sand (d_{50}=0.11mm) in the mixtures. The Kaolinite had a powder form consistency with 5-44 micrometer in average size and 0.26 of bulk density. The mixtures were well mixed, massaged and formed uniform before laying in the top layer. The samples were kept for about 12 hours to ensure good drainage on the paper tray. The Vane is driven on the prepared samples and the torque is applied with small motor and the values for the failure were noted. The failure stress is calculated with the formula given in appendix for the failure condition[14].

For the direct shear failure test, same vane apparatus was used to measure the failure stress directly in the main flume. The detail about the experimental flume is described elsewhere[10]. The first two runs conducted with cohesion content of 20% in mixture of fine sand of mean diameter d_{50}=0.11mm in the layered flood plain while the later two runs were conducted in the mixture of single layer of mean diameter d_{50}=0.64mm and cohesion content of less then 5%. The cohesion content on the last two runs were reduced to decrease the water holding effect of cohesive sediments due to higher water content on running flumes. The flow conditions were defined as intermittent for the case with consideration of flow running and termination repeatedly. Further, two more cases were observed for the straight and meandering channel with the flow depth fluctuations. The consideration of bankfull flow and normal flow cases were to represent the year round actual discharge fluctuation in most of the natural rivers. The summary of the test condition is presented in Table. 2.

3. Results

The shear failure experiment in the indirect measurement was conducted for the samples varying from 5 to 50% cohesive sediments and remaining non cohesive sediments in the mixture

Table 3: Measured failure stress in each case after 4 hours

S.N.	Time in seconds	Failure stress for different cohesion content (gm/cm^2)					
		5	10	20	30	40	50
1	10	5.66	6.47	7.68	14.15	12.13	11.32
2	20	8.89	14.15	14.96	27.89	17.78	16.98
3	30	13.34	21.83	22.23	37.59	22.64	21.83
4	40	18.59	28.70	26.68	45.67	26.68	25.46
5	50	23.04	32.74	30.32	52.55	29.91	28.70
6	60	25.87	36.78	33.95	59.82	32.34	31.53
7	70	29.51	40.42	37.19	66.29	33.95	33.95
8	80	32.34	42.85	40.42	71.95	36.38	35.97
9	90	35.17	45.27	42.44	77.61	37.19	37.59
10	100	37.19	46.48	44.46	82.05	38.40	39.21
11	110	38.40	46.89	46.08	86.50	39.21	40.02
12	120	39.61	45.67	47.29	90.54	39.21	40.42
13	130	39.21	41.23	48.10	94.18	38.40	41.63
14	140	38.00	40.42	48.50	97.41	37.59	41.63
15	150	36.38	39.61	48.91	99.03	37.59	40.42
16	160	35.17	36.78	48.10	100.24	35.97	39.61
17	170	34.36	35.57	47.70	100.65	35.97	38.40
18	180	33.55	35.17	46.48	101.05	34.76	37.59
19	190	32.34	33.95	46.08	100.65	33.95	36.78
20	200	31.93	33.95	44.46	100.24	33.14	36.38
21	210	32.34	32.74	44.46	99.84	32.74	34.76
22	220	31.53	32.74	43.65	99.84	33.14	34.76
23	230	31.53	32.34	42.44	100.24	32.34	34.36
24	240	31.53	32.34	42.44	99.43	32.74	33.55
25	250	31.12	32.34	42.04	99.84	31.93	32.34
26	260	30.72	32.34	41.63	99.84	31.12	32.34
27	270	30.72	31.12	40.82	99.84	30.32	31.93
28	280	30.72	31.12	40.02	100.65	31.12	31.53
29	290	29.51	30.72	40.02	100.24	31.53	31.12
30	300	29.51	30.72	40.02	100.24	31.12	31.12

Table 4: Failure stress for each cohesion content measured at different time since start of measurement

Cohesion content	Failure stress with every failure (gm/cm^2)					
	After 0 hr	After 2 hr	After 4 hr	After 6 hr	After 8 hr	After 10 hr
5	19.8	23.8	39.6	71.1	103.5	
10	25.9	30.7	46.9	77.6	98.2	
20	21.4	42.4	54.0	83.0	102.0	
30	46.9	59.0	101.1	124.9	130.2	
40	29.5	34.0	39.2	48.9	67.5	99.0
50	17.8	36.0	41.6	48.1	64.3	79.2

of upper layer. As the vane inserted in the sample and starts rotation, the stress goes increasing and reached the maximum values and decrease or stays constant for the measured duration. The measurement with 10 seconds interval showed the breaking strength or failure strength with highest values in Table 3. The observed maximum values in the standard vane tester are the failure stress or breaking stress for that sample at that instant. The result after 4 hour for all cases of cohesion content is presented in Fig. 2. and Table 3. There was increasing trend for increasing cohesion up to 30% and reduces for more increase in cohesion in the samples. The general observation shows that there was temporal increase in failure stresses for the samples in each cohesion content categories. But the failure stress variation compared with the cohesion content for every subsequent failure after about 2 hours shows increase in strength reaches maximum at about 30%. Further increase in cohesion in the samples shows decrease in failure stresses in the samples. Thus the decreasing behavior continues and the final

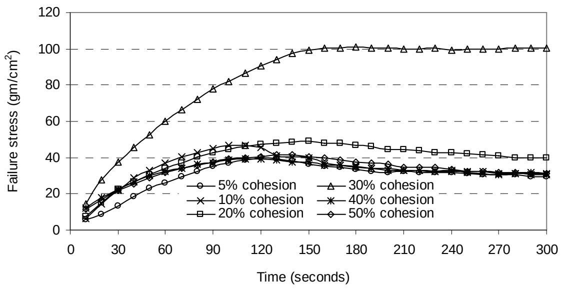


Fig. 2 Evolution of failure stress during measurements after 4 hours for each case of cohesion. The highest point in the curve represents the breaking stress.

strength of maximum cohesion content samples reaches nearly same values for the initial cohesion content of 5% in the mixture. The experimental data are presented in Table 3 and Table 4 as well as in Fig 2 and Fig 3 respectively.

Similarly, the observations during the direct measurement of failure stress on the experimental flood-plain shows good sensitivity against the flow condition in the channel at the centre of flume. The intermittent flow condition as well as depth fluctuation of the flow caused to vary the failure stresses on the flood-plain. The intermittent condition of discharge i.e. active (with flow) and inactive flume (no flow) cases shows the direct effect on the resulting failure stresses due to pore water pressure and consolidations due to cohesion content on the floodplains. There is substantial increase in the failure stress after the flow was terminated in the flume and reduction of the stresses appeared when resumption of the flow in the same flume. Thus the flood-plain increased its strength against erosion after the discharge termination in the flume and act vice-versa for the discharge flowing case. The discharge fluctuation between bankfull case and low flow case has also significant reactions on the resulting bank stresses. The flow depth variation from 80% to 20% of the total depth shows fluctuation of failure stress more then 50%. Further, the meandering flood-plain reacted in the same way for water depth fluctuations. The results for the direct measurement are presented in Fig. 5.

4. Discussion

4.1. Cohesion variation

The failure stress variation from 1.5 to 3 times as of cohesion variation as shown in Fig. 3 in the present experiments are similar with earlier observations[13), 16), 17)]. One observation[16)] was very similar with the present case having much higher increase of critical shear stress for 30% mud with sand mixtures then 50% mud with sand mixtures. Also the second observation reported[17)] even up to 90% increase in stress due to addition of clay in sand mixtures. The present nature of the experimental result of decreasing failure stress after 30% cohesion is reported for first time. The cohesion behavior as electrochemical and inter-particle forces with high clay content causes for the binding of the material and holding water for longer durations. The maximum failure stress observed at around 30% of cohesion might have some unique relations indicated earlier[18)]. It explained that the individual sand particles are in contact with each other till the mud content reach 30% where the governing criteria works with submerged weight of sediment by internal angle of friction. With more than 30% mud content the individual sand particles are no longer in contact and the erosion is controlled mainly by the resistance of clay friction. Sekine et. al[13)] also observed similar nature of lower strength and higher erosion rate during his experiment of low cohesion content on the samples.

4.2 Time dependent consolidation

The increase in resistance to erosion weather in indirect measurements or direct measurements as shown in Fig. 2, Fig 3 and Fig 5 was due to consolidation of the cohesion contents on the sediment mixtures. The present results with increasing and asymptotic nature is similar with earlier observations[19)] about the temporal variation of mean bed density as well as critical stress. The faster consolidation is due to the mixture of cohesionless which accelerate faster drainage and reduces the water content in mixtures with the present experiments. But with the higher cohesion content experiments, the water holding capacity causes low drainage rate and ultimately differs the consolidation behavior of the samples. This is the case with cohesion content of more than 30% in the present experiments.

The increase in stress from 3 to 5 times was observed during the observation of about 12 hours for all the cohesion content variations in the indirect measurements. The consolidation time in the present experiment is the time since preparation of the samples, while Zriek et. al[20)] defined it as the time between end of deposition and start of erosion, which basically replicate the cases of the natural depositions. The results observed for the indirect measurements were after 12 hours since preparation of samples. The significant increase in the failure stresses practically signifies the process of consolidation takes a period ranging from few days to a week as explained before[21)].

The separate measurement for the bulk density and water content in the indirect measurement shows increase up to 10% of bulk density during the measured duration of 36 hours while there is sharp reduction of water content and the void ratio of the samples on the same durations. The result for the bulk density and void ratio are presented in Fig. 4. The self drainage cause to reduce antecedent (actual) moisture content in the samples which ultimately affects the consolidation characteristics. This behavior is thus reflected in the measurement of bulk density and failure stress with the vane measurement.

4.3 Discharge Fluctuation

The two intermittent discharge fluctuation cases presented in

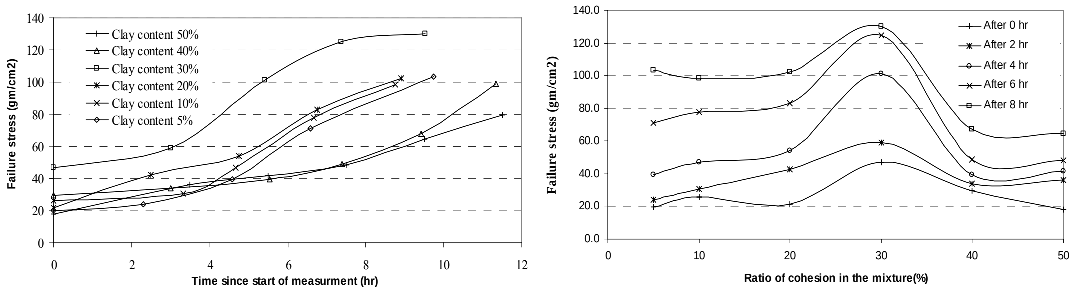


Fig. 3 Failure stress variation in the layered sediments (a) Stress rises with the time durations. (b) Rises with the cohesion content up to certain extent then decreases.

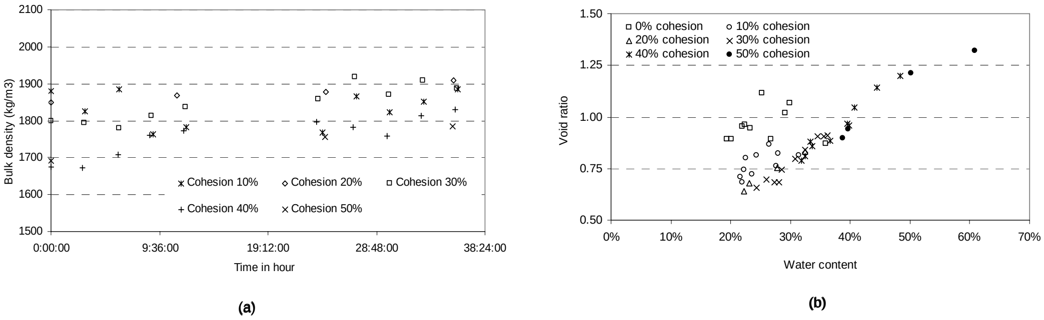


Fig. 4 Evolution of various parameters like (a) Bulk density during indirect measurements (b) Antecedent moisture content with the void ratio during indirect measurements.

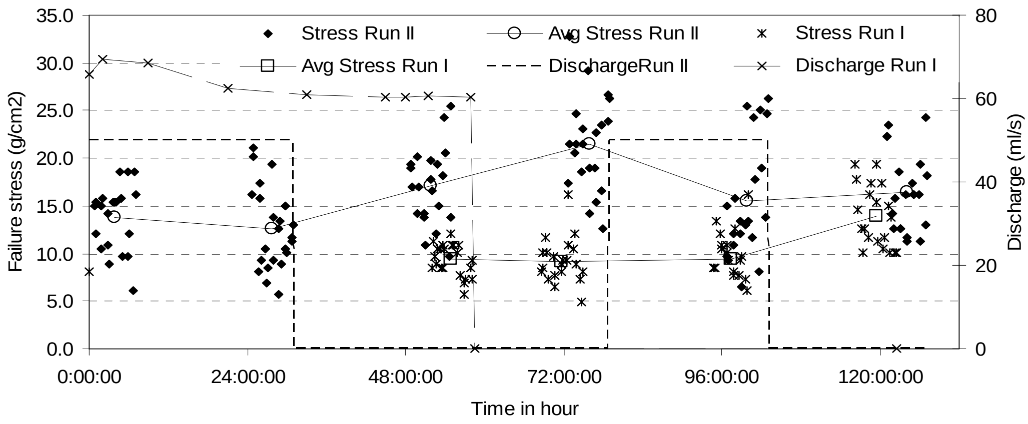
Fig. 5(a) shows direct variation of bank strength with the discharge condition in the flume. Results from Run I depicts slow evolution in the strength after termination of the flow. The response towards the drainage, due to higher cohesion content of 20%, results very negligible effect in the beginning of inactive case. The result presented for Run I did not show as much consolidation evidently due to pore pressure and higher water content due to water diffusion of the sediment. Water percolates up to the surface of the sediment and the layer of water prevents increase in shear stress to the testing vane. On the other hand results for 36 and 58 hours brought 20% to 50% increase from its initial values. More clear observation was found in Run II with the increased flume slope which helps faster drainage. The termination of the discharge leads to the increase up to 100% of the shear stresses whereas the continuation of the flow decreases the stress up to 75%. However during inactive case significant increase in shear failure observed as the water from the sample drains slowly. The complete termination of the flow in the channel shows sharp increase due to consolidation and drainage.

The experiment run with flow depth fluctuation replicates the real river discharge fluctuations for most of the rivers in nature. The cohesion content was adjusted to less then 5% and the bank was prepared with mixture sediment to reduce water holding effect of cohesive particles during continuous flow in the channel. The responses on the failure stress due to flow depth fluctuation between 20 to 80% had about 30 to 50%. The drawdown of 48 hours during Run III with straight flume case and alternate drawdown of 24 hours with meandering flume case has noticeable stress variations (Fig. 5b).

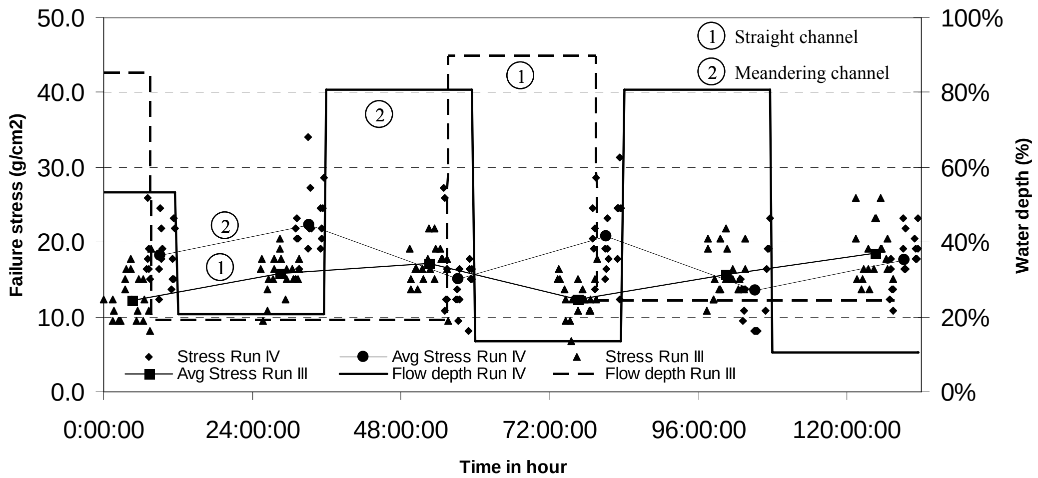
The decrease in flow conditions leads towards the strengthening of the bank and thus increases the failure strengths whereas the next increase of water level again softens the bank which produces less failure strength with the vane tester. The cycles of discharge fluctuation on the natural conditions leads with this effect of changing the shear resistance of the bank and caused more failures during bank full flow compared with low discharge. The minor effect of strength increment is further acceralated in the natural cases due to new vegetation grown in the flood-plain during low flow cycles[7]. A very similar phenomena observed by Pizzuto[22] during the long term observations of the bank erosion and migrations in the Powder River with changing discharges.

5. Hysteresis

The hysteresis phenomena were observed both in indirect and direct measurement of failures strengths. The hysteresis with the cohesion variation was found at around 30% (Fig. 3b) of the cohesion content on the samples, which shows change in behavior for strength against erosion. The temporal increase for the failure strength shows increasing trend upto 30% only which is due to earlier explanation[18] of bonding between sand and clay particles in 30%. There is more clear observation of the hysteresis process in the direct bank strength measurements. The obtained results of the hysteresis during the direct shear failure measurements are presented in Fig. 6 and Fig. 7. A

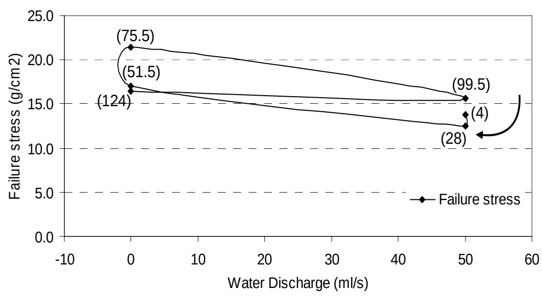


(a)

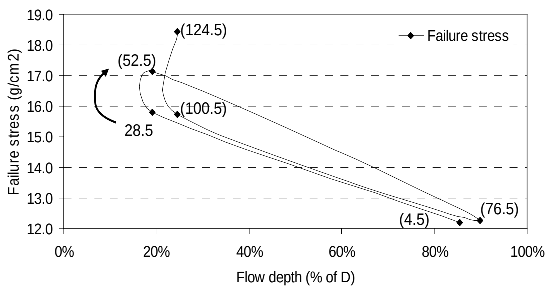


(b)

Fig.5 Variation of failure stress with active and non active cases (a) Intermittent discharge flow condition (b) Fluctuation of flow depth with two flume cases.



(a)



(b)

Fig.6 Hysteresis behavior for the failure stress during the test with (a) Discharge fluctuation (b) Depth fluctuation. Values in parenthesis indicate the time of measurement since start of experiment.

noticeable clockwise movement of hysteresis is observed for the strength evolution of the flood-plain in both cases (Fig. 6a and 6b) of intermittent discharge condition as well as the flow depth fluctuations. The longer duration of flow termination in

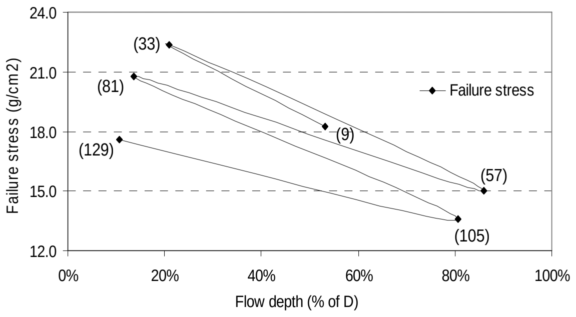


Fig.7 Hysteresis behavior observed in the meandering channel due to flow depth fluctuation. Values on parenthesis indicate time of measurement.

Run II and drawdown in Run III are noticed in the figures with increasing values of the stresses in same ordinates. This behavior replicates similar with the natural condition with discharge fluctuations. The cyclic variation of discharge and flow depth leads to the consolidation of the bank as well as softening by increasing antecedent moisture content. Similarly, the hysteresis observed in Run IV for the meandering channel is presented in Fig. 7. Due to variation of input hydrograph having alternate high and low flow depth of equal time duration; the nature of hysteresis seems different compared with Run III. There is not any noticeable direction of movement though there is fluctuation between higher and lower values with flow depth variations between bankfull flow and normal flow. Also the strength observed between two banks i.e. inner and outer banks shows minor variations. More number of data observed in the inner bank shows higher values of the failure strength for the same instant measurement in the outer banks. The general hysteresis phenomenon considering various sediment processes with cohesion in the river channel evolutions is summarized in Fig.8. The interrelationship among the basic cohesive sediment transport processes as settling and deposition, consolidation, erosion and transport, which is basically in action due to the inclusion of cohesion on the bank sediments.

The diagram illustrates the hysteresis effect with regard to the sediment processes of channel evolutions. As has been observed and described in the experiments[6], the magnitude of shear stress needed to erode a cohesive deposit (τ_{c1}) is significantly greater than the shear stress needed to transport and deposit loose sediments (τ_{c2}). Over time the new deposit consolidates and becomes more resistant to erosion as compaction and deposition of suspended clay begin to stick the sediment grains of the deposit together. In natural settings the growth of plant roots also has a very strong effect on consolidation.

Hysteresis due to erosion and deposition cycle of alluvium, which is likely an extension of natural scale streams and hysteresis due to alluvium in the meandering is of two types i.e.

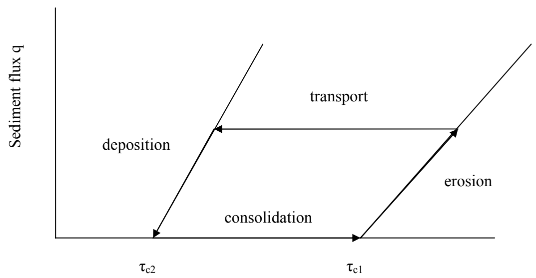


Fig.8 General hysteresis phenomena with consideration of cohesive sediments.

bedload and suspended load. Bedload has steep erosion curve due to easily erodible material so that added shear would generate more sediment flow. Bank material is significantly more resistant to the force of the water flow. Its erosion threshold is much higher then bedload so the erosion curve is less steep due to internal cohesion (Fig 8).

6. Conclusion

Bank strength is found to be proportional with the consolidation resulting from the cohesion content of the sediment mixtures. The shear strength fluctuation is observed in the experiments with the parameter variability as cohesion content, discharge fluctuation as well as the water depth fluctuations. There is clear indication of hysteresis on the bank strength development with the external effects of flow characteristics and bank sediment compositions. Similarly the individual hystersis behavior on the bank strength with discharge and depth fluctuation might help to understand the general hystersis behavior to some extent.

The result presented here based on the recently conducted experiments brings some important possibility of real variation of bank strength due to responses with various factors. It suggested that the cohesion might be equally important as of hydraulic parameters on the evolutions of river channels. This can help for the researcher to deal the evolution process considering bank sediment compositions. Though the quantity of the present work is not sufficient to proof all the effects of cohesion on the flood-plain evolutions, but can give some information to understand the phenomena. On the other hand this experimental works needs some validation with the real measurement from the rivers with the similar aspect.

Appendix

The shear strength, C_u is obtained by equating the applied torque, T, to the shear force moment.[14]

$$C_u = \frac{6\,T}{7\,\pi\,D^3}$$

$$T = P \times l$$

Notations

C_u - Shear stress or Failure stress

T - Applied torque

D - Vane width

P - Measured load by electronic device

l - Arm length for the measured load

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References

1) Schumm, S.A.: The shape of alluvial channels in relation to sediment type, Geological Survey Professional paper, 352(B), pp.17-30, 1960

2) Schumm, S.A.: The effect of sediment type on the shape and stratification of some modern alluvial deposits, American Journal of Science, 258, pp.177-184, 1960

3) Schumm, S.A.: Sinuosity of alluvial rivers on the great plains, Geological Society of America, Bulletin., v.74, pp.1089-1100, 1963

4) Schumm S.A. and Khan, H. R.: Experimental Study of Channel Patterns, Geological Society of America.., Bulletin, 83, pp. 1755-1770, 1972

5) Jin, D. and Schumm, S.A.: "A new technique for modeling river morphology," in K.S. Richards, Ed., Proc. First International Geomorphology Conference, Wiley, Chichester, Part I, pp. 681-690, 1986.

6) Smith, C.E.: Modeling high sinuosity meanders in a small flume, Geomorphology, 25, pp. 19-30, 1998

7) Schumm, S.A., Mosley, M.P. and Weaver, W.E.: Experimental Fluvial Geomorphology, JOHN WILEY & SONS, 1987

8) Emmanuel Partheniades.: Erosion and Deposition of cohesive soils., Journal of Hydraulic Engineering, 91(1),pp. 105-139, 1965

9) Mehta, A.J., Hayter, E.J., Parker, R. Krone, R.B. and Teeter, A.M.: Cohesive sediment transport. I: Process description, Journal of Hydraulic Engineering, 115(8), pp. 1076-1093, 1989.

10) Dulal, K.P. and Shimizu, Y.: Experimental simulation of river planforms in cohesion mixed flood-plain, Annual Journal of Hydraulic Engineering, JSCE, Vol 53, pp133-138, 2009.

11) Kothyari, U.C. and Jain, R.K.: Influence of cohesion on incipent motion of sediment mixtures, Water resources research, vol.44, W04410, doi.1029/2007WR006326, 2008

12) Sekine, M, Nagahama M., and Nishimori K.: Study on the surface erosion of bare slope with cohesive sediment due to an artificial rainfall. Annual Journal of Hydraulic Engineering, JSCE,Vol. 50, pp.1045-1050, 2006(Japanese)

13) Sekine M., Nishimori, K., Fujio K. and Katagiri, Y.: Erosion process of cohesive sediment and erosion rate formula, Journal of Hydroscience and Hydraulic Engineering, JSCE, Vol. 22, No 1, pp. 63-70, 2004.

14) Terzaghi, K., Peck, R.B. and Mesri, G.: Soil Mechanics in Engineering Practice, JOHN WILEY & SONS, 3rd edition, 1987.

15) Kobayashi K., Dulal KP., Shimizu Y. and Parker G.: Numerical computation of free meandering process of rivers considering the effect of slump block in outer bank region. River flow 2008, Turkey, pp. 1289-1296, 2008

16) Mitchener, H. and Torfs, H.: Erosion of mud/sand mixtures, Coastal Engineering, 29, pp. 1-25, 1996

17) Panagiotopoulos, I., Voulgaris, G. and Collins, M.B.: The influence of clay on the threshold of movement of fine sandy beds, Coastal Engineering, 32, pp.19-43, 1997

18) Wiberg, P.L. and Smith, J.D.: Calculations of the critical shear stress for motion of uniform and heterogeneous sediments, Water Resource research, 23(8), pp1481-1493, 1987.

19) Nicholson, J and O'Connor, B.A.: Cohesive sediment transport model, Journal of Hydraulic Engineering, pp. 621-639, 1986.

20) Diana, A. Zreik., Bommanna, G. Krishnappan., John T. Germaine, Ole S. Madsen., and Charles C. Ladd.: Erosional and Mechanical strength of deposited cohesive sediments., Journal of Hydraulic Engineering, 124(11),pp. 1076-1085, 1988.

21) Parchure, T.M. and Mehta, A.J. : Erosion of soft cohesive sediment deposits, Journal of Hydraulic Engineering, 111(10), pp. 1308-1326, 1985.

22) Pizzuto, J.E.: Channel adjustments to the changing discharges, Power River, Montana, Geological Society of America, Bulletin, 106, pp. 1494-1501, 1994.

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