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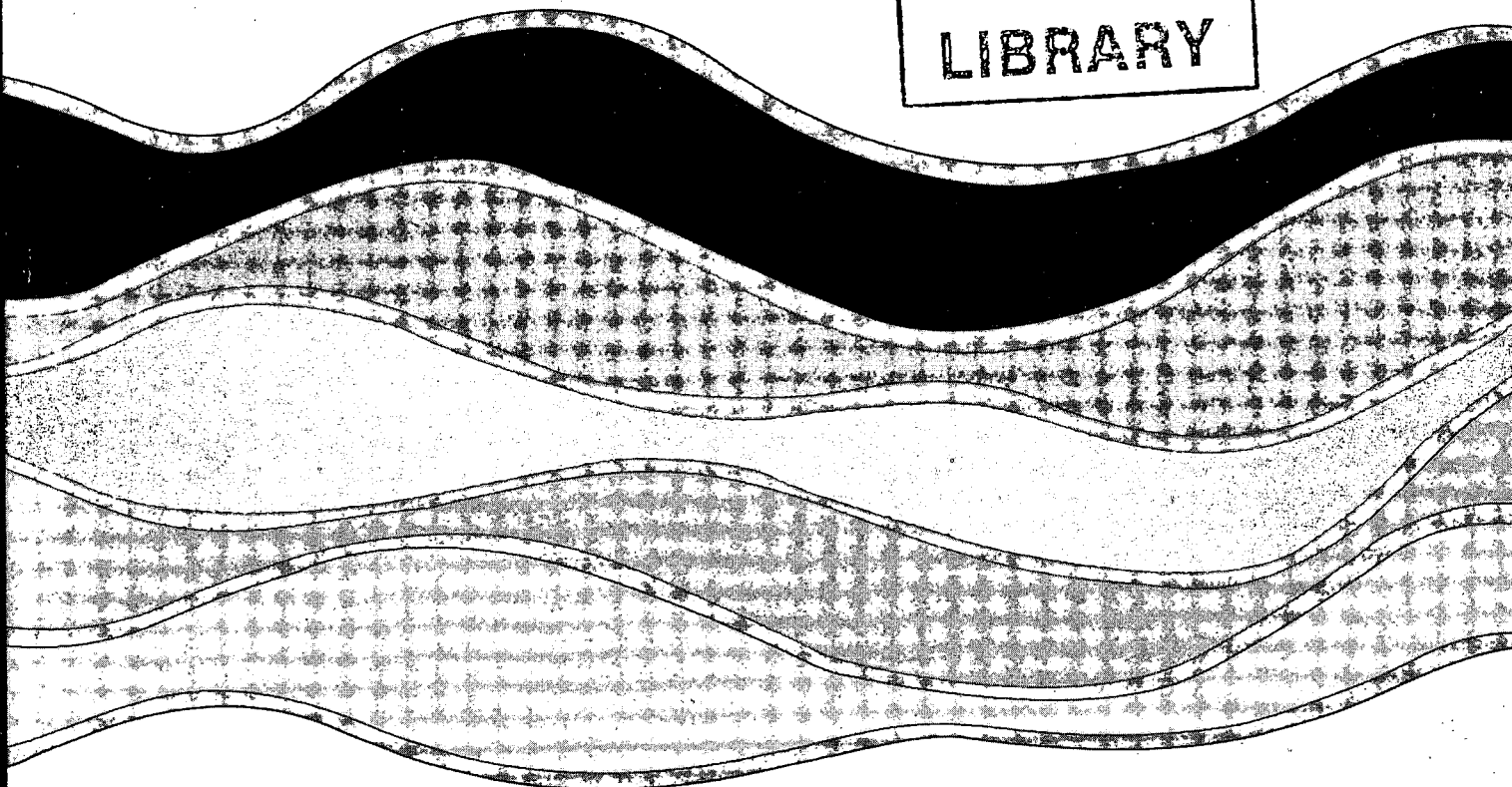RESEARCH
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CRITICAL SHEAR STRESSES FOR EROSION AND DEPOSITION OF FINE SUSPENDED SEDIMENTS IN THE FRASER RIVER

B.G. Krishnappan and P. Engel

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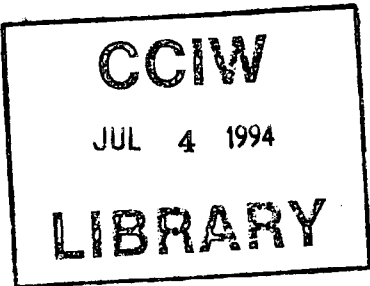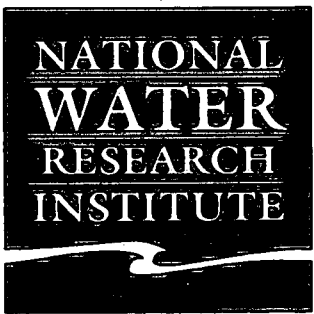
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CRITICAL SHEAR STRESSES FOR EROSION AND DEPOSITION OF FINE SUSPENDED SEDIMENTS IN THE FRASER RIVER

by

B.G. Krishnappan and P. Engel

MANAGEMENT PERSPECTIVE

Models of cohesive sediment transport require parameters describing the erosion and deposition rate functions which, at present, can only be obtained by measurements in laboratory flumes using site specific sediments. Conventional straight flumes are not suitable for cohesive sediment studies because the transport processes are time dependent with time scales ranging from hours to days and would require excessively long flumes. Previous studies have shown that an alternative approach is to use circular flumes and to generate the flow by moving the flow boundaries rather than the fluid. Such a rotating, circular flume was designed and built in 1992 at the National Water Research Institute in Burlington, Ontario, Canada.

Tests on cohesive sediment suspensions, from the Fraser River and its tributary the Nechako River near their confluence, were conducted using this rotating flume. Sediment concentration, size distribution of suspended sediment flocs as a function of time, and critical shear stresses for deposition and erosion were measured. Some tests were repeated with known concentrations of the pulp mill effluent added to the water-sediment mixture in the flume to examine the effluent effect on the deposition and erosion processes. The results of these tests are presented in this paper.

SOMMAIRE À L'INTENTION DE LA DIRECTION

Les modèles de transport des sédiments cohésifs ont besoin de paramètres décrivant les fonctions des vitesses d'érosion et de dépôt qui, présentement, ne peuvent être obtenues que par des mesures dans des canaux de laboratoire, pour des sédiments provenant d'un endroit particulier. Les canaux de laboratoire droits habituels ne sont pas adaptés aux études de sédiments cohésifs parce que les processus de transport dépendent du temps, ayant des échelles temporelles comprises entre quelques heures ou quelques jours, et que leur études nécessiterait des canaux excessivement longs. Des études antérieures ont démontré qu'il était possible d'utiliser une autre approche, soit l'utilisation de canaux circulaires, et de créer un écoulement en déplaçant les limites de l'écoulement plutôt que le liquide même. Un canal circulaire rotatif de ce type a été conçu et construit en 1992 à l'Institut national de recherche sur les eaux à Burlington, Ontario, Canada.

On a effectué des essais dans ce canal rotatif avec des suspensions de sédiments cohésifs provenant du fleuve Fraser et de son affluent, la rivière Nechako, prélevés près de leur point de confluence. On a mesuré la concentration des sédiments, la distribution granulométrique des flocs des sédiments en suspension en fonction du temps, ainsi que les contraintes critiques de cisaillement pour le dépôt et l'érosion. Certains essais ont été répétés avec des concentrations connues d'effluents d'usines de pâte ajoutés au mélange eau-sédiment dans le canal, afin d'étudier l'effet de l'effluent sur les processus de dépôt et d'érosion. Les résultats de ces essais sont présentés dans cette publication.

ABSTRACT

Depositional and erosional characteristics of the Fraser River sediment were studied in a new rotating circular flume. The influence of pulp mill effluent on these processes was also examined. It was shown that the sediment exhibits transport characteristics peculiar to cohesive sediments and that the pulp mill effluent enhanced deposition and inhibited erosion. The implications for field conditions are discussed.

RÉSUMÉ

Les caractéristiques de dépôt et d'érosion de sédiments du fleuve Fraser ont été étudiées dans un nouveau canal circulaire rotatif. On a aussi examiné l'influence des effluents d'usines de pâte sur ces processus. Il a été démontré que les sédiments présentent des caractéristiques de transport propres aux sédiments cohésifs et que les effluents d'usines de pâte augmentaient la vitesse de dépôt et inhibaient l'érosion. On examine les implications de ces résultats pour des conditions sur le terrain.

TABLE OF CONTENTS

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INTRODUCTION

Models of cohesive sediment transport require parameters describing the erosion and deposition rate functions which, at present, can only be obtained by measurements in laboratory flumes using site specific sediments. Conventional straight flumes are not suitable for cohesive sediment studies because the transport processes are time dependent with time scales ranging from hours to days and would require excessively long flumes. Previous studies have shown that an alternative approach is to use circular flumes and to generate the flow by moving the flow boundaries rather than the fluid (Partheniades and Kennedy, 1967; Mehta and Partheniades, 1973; Kuijper et al, 1989; Petersen and Krishnappan, 1994; Krishnappan et al, 1994b). Such a rotating, circular flume was designed and built at the National Water Research Institute in Burlington, Ontario, Canada (Krishnappan, 1993).

Tests on cohesive sediment suspensions, from the Fraser River and its tributary the Nechako River near their confluence, were conducted using this rotating flume. A site specific sediment-water sample of about 800 ℓ was obtained for testing. In addition, a separate container of effluent from two pulp mills discharging into the Fraser River was obtained. Sediment concentration, size distribution of suspended sediment flocs as a function of time, and critical shear stresses for deposition and erosion were measured. Some tests were repeated after known concentrations of the pulp mill effluent were added to the water-sediment mixture in the flume to examine the effluent effect on the deposition and erosion processes. The results of these tests are presented in this paper.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

The Flume

The flume is 5.0 m in mean diameter, 0.30 m in width, 0.30 m in depth and rests on a rotating platform. A counter rotating top cover, called the ring, fits inside the flume and makes contact with the surface of the sediment-water mixture in the flume. By rotating the platform and the ring assembly in opposite directions, it is possible to generate turbulent shear flows and to study the behaviour of fine sediments under different flow conditions. The flume and the ring can each be rotated up to a maximum rate of three revolutions per minute. A sectional view of the flume is shown in Figure 1.

Instrumentation

The flume is instrumented with a Laser Doppler Anemometer (LDA) to measure the flow field, a Preston tube to measure the bed shear stress, a Malvern Particle Size Analyzer (MPSA) to measure the in situ particle size distribution in the flow and an optical turbidity sensor (OSLIM) from Delft

1

Hydraulics to measure sediment concentration in the flow. The instrumentation activated for the present experiments were the Preston tube, the MPSA and the OSLIM sensor.

The Preston tube entered the flume at one location through a water tight sleeve attached to the outside flume wall. The difference between the dynamic and static pressures was measured with a Valedyne model DP-45 pressure transducer with a diaphragm having a pressure capacity equivalent to 25.4 millimeters of water. The calibration proposed by Patel (1965) was adopted to compute the shear velocities from the pressure difference measured with the pressure transducer.

The MPSA operates on the light diffraction principle (Fraunhoffer diffraction). Complete details of the method can be found in Weiner (1984). Continuous in situ measurements of the floc sizes were made by mounting the MPSA on the rotating platform below the flume so that the flow-through sensor was located directly below the centre-line of the flume cross-section. The sediment suspension was drawn continuously from the flume by gravity through a 5 mm tube, located on the centre-line of the cross-section, having its intake above the bed at approximately one half of the flow depth, through the sensor and into a reservoir from where it was pumped back into the flume. The end of the tube was bent at a right angle, similar to a Pitot tube, so that the intake would face directly into the flow on the centerline of the cross-section. The length of the withdrawal tube was kept to a minimum to avoid flocs disruption and the withdrawal rate was just large enough to avoid deposition of sediment in the tubes.

The measuring principle of the OSLIM sensor is based on the attenuation of a light beam, caused by light absorption and reflection by the sediment particles. The light source used by this instrument is an infra red light emmiting diode (LED). The light absorption is dependent on the particle size distribution but by pumping the suspension through a short, small diameter tube just ahead of the sensor and allowing the shear in the tube to break up the flocs, the error caused by varying size distributions was kept to a minimum. The sediment suspension was pumped continuously from the flume through a 5 mm tube which entered the flume horizontally through the flume wall at approximately a height of about half the flow depth above the flume bed. Once again the tube was bent at a right angle so that the intake would face directly into the flow. The suspension was pumped from the withdrawal tube through the OSLIM sensor and back into the flume downstream of the withdrawal point at a rate just large enough to prevent deposition of sediment in the pumping circuit.

Measurement of Shear Stress

The Preston tube cannot be used in flows with suspended sediment because the presence of the sediment particles inhibits its functioning. Therefore, a relationship between the bed shear stress and the rotational speed of the flume was established using clear, distilled water prior to the tests with suspended sediment. For the chosen water depth of 12 cm, the ratio of rotational ring speed to rotational flume speed was determined to be 1.167. This gave the best two dimensional cross-sectional shear stress distribution for this flow depth. Details of the shear stress experiments are described in Krishnappan et al (1994b). For a given linear relative flow velocity, computed from the rates of rotation of the flume and ring, the bed shear stress can be obtained from the curve in Figure 2.

Collection and Preparation of River Water Sample

River water samples were collected on the Fraser and Nechako rivers upstream of two pulp mills. A pumping system, similar to that used for cleaning swimming pools, was used to vacuum

the sediment deposited on the gravel bed and pump river water into 100 ℓ plastic containers which could be sealed tightly for shipping. Four such containers were filled at each river site for a total of 800 ℓ. Care was taken to obtain representative samples of the entire cross-section at each site. To determine the effect of pulp mill effluent on the deposition and erosion rates, about 50 ℓ of effluent was collected from the discharge wells of the pulp mills and put into a suitable container for shipping.

All containers were kept in refrigerated storage for a sufficient length of time to allow the sediment to settle. The supernatant was then drawn off the sediment and 500ℓ were placed in the flume and the remainder put into separate containers and returned to refrigerated storage. The remaining sediment slurry was combined into one container. The concentration of the slurry was determined so it could be added to the water in the flume resulting in water-sediment mixtures of known initial concentrations.

Deposition and Erosion Tests

Before beginning a deposition test, the water-sediment suspension was thoroughly mixed in the flume with a mechanical mixer to break up existing flocs. The ring was then lowered to the desired position resulting in a water depth below the ring surface of 12 cm. The ring penetrated the water surface by about 3 mm to ensure proper contact between the ring and the water surface. The MPSA and the OSLIM sensor were then checked to ensure that they were operating properly. Having completed all preparations, the flume and ring were set in motion to run at $N_f = 2$ rpm and $N_r = 2.5$ rpm respectively to obtain a suspended sediment concentration in excess of that sustainable by the flow at the chosen test speeds. After twenty minutes, the flume and ring were slowed down to their respective test speeds in accordance with the established ratio $\frac{N_r}{N_f} = 1.167$ for the water depth of 12 cm. Samples were withdrawn from the flume at intervals of 5 minutes during the first hour of the test and every ten minutes thereafter until completion of the test. Each time a sample was drawn, the volume removed was replaced by clear river water. A test was considered to be complete after the suspended sediment concentration remained virtually constant for at least 1 hour. The samples were taken at mid-depth as tests had shown that the concentration was virtually uniform over the depth. The concentration of each sample was determined by filtration, drying and weighing. Simultaneously, with the manual sampling, sediment concentration was determined with the OSLIM sensor to evaluate its performance under operating conditions. Its main contribution was the ability to obtain real time concentrations which permitted accurate observations of the rates of change in concentration as deposition took place. The size distribution of the suspension was measured at regular intervals with the MPSA and recorded on a disc file and computer print-out. This way the formation of flocs and changes in the size distribution of the flocs with time could be monitored. Once a test was completed, the procedure was repeated for other flume speeds.

Before beginning an erosion test, the water-sediment mixture in the flume was left undisturbed for a chosen length of time to allow the sediment to settle and consolidate on the flume bed. Care was taken to ensure that the water depth was 12 cm, that the ring penetrated the water surface sufficiently and that the MPSA and the OSLIM instruments were operating properly. Having completed all preparations, the flume and ring were set in motion beginning with the lowest flume speed. As before, samples were withdrawn from the flume and the change in concentration monitored with the OSLIM at intervals of 5 to 10 minutes until the sediment concentration became virtually constant. When this stage was reached, the flume and ring were set to the next speed. This sequence was repeated until the largest desired flume speed was reached. The size distributions

3

of the suspended sediment were again measured at regular intervals with the MPSA and recorded on a disc file and computer print-out.

RESULTS AND DISCUSSION

Altogether, sixteen tests were carried out for the Fraser River sediment. A summary of the experimental conditions is given in Table 1.

Deposition Tests

Deposition experiments were carried out for two different initial concentrations and four different bed shear stresses. The influence of the effluent was examined in the tests with the higher initial concentration. The time variation of concentration is shown in Figure 3 for the first four tests. In this figure, the 20 minutes period during which the flume and the ring were rotated at high speeds for initial mixing was also included. It can be seen from this figure that, after the initial period, the concentration decreases gradually and reaches a steady state value for all the runs. For the lowest bed shear stress (i.e. 0.0563 N/m^2), the drop in the concentration is the biggest; the steady state concentration is only about 1/20th of the initial concentration. A slightly lower shear stress would have produced a nil concentration of sediment in suspension and would correspond to the critical shear stress for deposition for this sediment. As the bed shear stress increases more and more sediment stays in suspension during the steady state.

Figure 4 shows the depositional characteristics of the sediment under constant bed shear stress but with different initial concentrations. It can be seen that the steady state concentration is a function of the initial concentration and the ratio of the two is a fixed value for a particular bed shear stress. For these tests the ratio is about 0.50. Such behaviour is typical of cohesive sediments and conforms to earlier studies by a number of investigators such as Partheniades and Kennedy (1967), Mehta and Partheniades (1973) and Lick (1982). In a recent study, Lau and Krishnappan (1994) had shown that during cohesive sediment settling, there is no simultaneous erosion and settling of the sediment near the bed and provided support for the concept that the sediment settles in a flocculated form and only those flocs which are strong enough to settle through the region of high shear near the bed can deposit on the bed. Weaker flocs are broken up at the region of high shear and are brought back into suspension. As there can only be a certain fraction of sediment in the mixture that can form stronger flocs, the amount remaining in suspension becomes a function of the amount in the initial suspension.

Flocculation of the sediment during deposition can be inferred from the size distribution data shown in Figure 5. In this figure, the size distribution of the sediment suspension as measured with the MPSA at different times during deposition for Test No. 4 are shown. During the initial mixing period, the weaker flocs are broken up and the suspension contains sediment flocs with a median size of about 74 microns. As the deposition begins, weaker flocs are reformed and the median size of the flocs increases and attains a steady state value of around 110 microns. This trend is common to all of the deposition tests except the ones with the lowest bed shear stress. For these tests, the deposition of sediment continues without the formation of larger sediment flocs. This may be due to lower concentration of sediment in suspension and decreased turbulence level. The size distribution pattern for Test No. 1 is shown in Figure 6. Similar distributions were obtained for all the tests with the lowest bed shear stress of 0.0563 N/m^2, which is closer to the critical shear stress for deposition.

4

When extrapolating the laboratory data on deposition of sediment to field conditions, it is important to consider the similarity in maximum velocity gradient rather than the similarity in bed shear stress. In laboratory channels with smooth bed, where the viscous sublayer thickness could be several times larger than the particle size, the sediment flocs could be subjected to much larger velocity gradients within the viscous sublayer in comparison to a flow in the field where the bed roughness elements are likely to protrude through the viscous sublayer. A scale relationship for the bed shear stress, that will satisfy similarity of maximum velocity gradient inside and outside of the viscous sublayer can be derived by assuming a linear velocity profile within the sublayer and a logarithmic profile outside. Such a relationship is given as

$$\lambda = \frac{1.0}{11.6\kappa} \tag{1}$$

where λ stands for the ratio of model value of a property to the prototype value of the same property and κ is the Von Karman constant. If one assumes a value of 0.4 for κ, then the bed shear stress obtained from flume tests has to be multiplied by a factor of about five to obtain the bed shear stress in the field that would produce the same maximum velocity gradient. This implies that the bed shear stress in the field has to be five times larger than that in the flume to produce similar depositional characteristics for the sediment.

The effect of pulp mill effluent on the depositional characteristics of the sediment is shown in Figures 7 and 8. From these figures, it can be seen that the pulp mill effluent does effect the depositional behaviour and increases the deposition rate of the sediment. A possible explanation for this behaviour is that the pulp mill effluent has enhanced the flocculation of the sediment and thereby increased the settling velocity and the deposition rate. A field study carried out in the Athabasca River downstream of a pulp mill at Hinton, Alberta, Canada (Krishnappan et al, 1994a) also showed evidence of increased deposition rate of the ambient sediment.

Erosion Tests

The experimental conditions for the erosion tests are given in Table 1. Two different ages of sediment deposit and the influence of the pulp mill effluent on the erosional behaviour were tested. A typical result of an erosion test is shown in Figure 9 for Test No. 14 corresponding to a deposit age of 164 hours. In this figure, the shear stress steps and the corresponding concentration profiles are shown. The sediment deposit is fully stable until the bed shear stress step of 0.1210 N/m^2 is established. After initiation, the sediment concentration in suspension gradually increases and attains a steady state value for each shear stress step. For the maximum shear stress (0.4620 N/m^2) tested, not all the deposited sediment was resuspended. The maximum concentration reached was only about sixty percent of the total concentration that would have resulted from complete resuspension.

The effect of the age of the deposit and the pulp mill effluent are shown in Figures 10 and 11 respectively. In these figures, the steady state concentration for each shear stress step is plotted against the shear stress. It can be seen from Figure 10 that the age of deposit does have an effect at least during the initial stages of erosion. When the age of deposit is higher, the erosional resistance of the sediment is higher and hence less sediment is resuspended. A similar effect is noticed with the pulp mill effluent. The presence of pulp mill effluent makes the deposited sediment more stable also during the initial stages of erosion.

5

The size distribution of the resuspended sediment measured during the erosion tests with the MPSA sheds some further light on the erosional process. From the size distribution data shown in Figure 12, which corresponds to Test No. 14, it appears that the sediment bed is peeled off during the erosion process and the resuspension contains a large percentage of larger sized flocs. As the bed shear stress is increased, these larger flocs break up and attain a distribution similar to that obtained during the initial stage of the deposition tests.

SUMMARY AND CONCLUSIONS

Depositional and erosional characteristics of the Fraser River sediment were studied in a rotating circular flume. The influence of the pulp mill effluent on these processes was also examined. The laboratory measurements show that the sediment exhibits transport characteristics peculiar to cohesive sediments. The depositional process is dominated by the flocculation of the sediment and the pulp mill effluent further enhanced the flocculation mechanism. The erosion process of the deposited sediment is characterized by a peeling off of the top layer of the sediment bed rather than by the mobilization of individual particles normally encountered in cohesionless sediment. The pulp mill effluent inhibits erosion of the Fraser River sediment and this effect increases with the age of the sediment deposits.

ACKNOWLEDGMENT

REFERENCES

Kuijper, C., J.M. Cornelisse and J.C. Winterwerp, 1989: Research on Erosive Properties of Cohesive Sediments. J. Geophysical Res. 95(C10), 14341-14350.

Krishnappan, B.G., 1993: Rotating Circular Flume. J. Hydraul. Engrg. ASCE 119(6), 758-767.

Krishnappan, B.G., R. Stephens, J.A. Kraft and B.H. Moore, 1994a: Size Distribution and Transport of Suspended Particles in the Athabasca River Near Hinton. NWRI Contribution 94-112, National Water Research Institute, Burlington, Ontario, Canada, 33 pp.

Krishnappan, B.G., P. Engel and R. Stephens, 1994b: Shear Velocity Distribution in a Rotating Flume. NWRI Contribution 94-102, National Water Research Institute, Burlington, Ontario, Canada, 23 pp.

Lau, Y.L. and B.G. Krishnappan, 1994: Does Reentrainment Occur During Cohesive Sediment Settling ?. J. Hydraul. Engrg. ASCE 120(2), 236-244.

Lick, W., 1982: Entrainment, Deposition and Transport of Fine Grained Sediments in Lakes. Hydrobiologia (91), 31-40.

Mehta, A.J. and E. Partheniades, 1973: Depositional Behaviour of Cohesive Sediments. UFL/COEL-TR/016, Coastal and Oceanographic Engineering Department, University of Florida, Gainesville, Florida, 297 pp.

Partheniades, E. and J.F. Kennedy, 1967: Depositional Behaviour of Fine Sediment in a Turbulent Fluid Motion. Proc. 10th Conf. on Coastal Engineering, Tokyo, Japan **2**, 707-729.

Patel, V.C., 1965: Calibration of the Preston Tube and Limitations on its Use in Pressure Gradients. J. Fluid Mech. **23**(1), 185-208.

Petersen, O. and B.G. Krishnappan, 1994: Measurement and Analysis of Flow Characteristics in a Rotating Circular Flume. Submitted for publication J. Hydraul. Res., IAHR.

Weiner, B.B., 1984: Particle and Droplet Sizing Using Fraunhofer Diffraction. Modern Methods of Particle Size Analysis, H.G. Barth, ed., John Wiley and Sons, New York, N.Y., 135-172.

NOTATION

The following symbols are used in this paper

N_r = the rate of rotation of the ring;
N_f = the rate of rotation of the flume;
u_* = the shear velocity;
V = tangential velocity of the flow;

α = the ratio of ring speed to flume speed;
κ = the Von Karman constant;
λ = the ratio of model value of a property to the prototype value of the same property;

TABLE 1. SUMMARY OF EXPERIMENTAL CONDITIONS:

Test No.	Experiment Type	Shear stress N/m²	Initial Conc. mg/l	Age of deposit in hr	Effluent Conc in % by vol.
1	Deposition	0.0563	200	n/a	0
2	Deposition	0.121	200	n/a	0
3	Deposition	0.169	200	n/a	0
4	Deposition	0.213	200	n/a	0
5	Deposition	0.0563	250	n/a	0
6	Deposition	0.121	250	n/a	0
7	Deposition	0.169	250	n/a	0
8	Deposition	0.213	250	n/a	0
9	Deposition	0.0563	250	n/a	3
10	Deposition	0.121	250	n/a	3
11	Deposition	0.169	250	n/a	3
12	Deposition	0.213	250	n/a	3
13	Erosion	n/a	n/a	114	0
14	Erosion	n/a	n/a	164	0
15	Erosion	n/a	n/a	40	2
16	Erosion	n/a	n/a	114	2
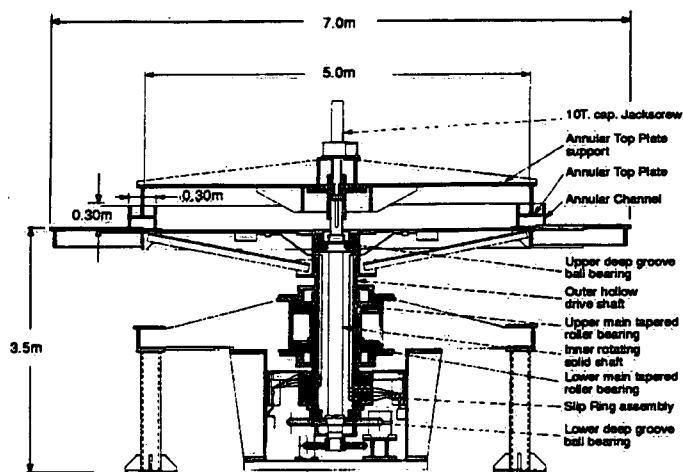
Figure 1. Sectional view of the rotating flume assembly
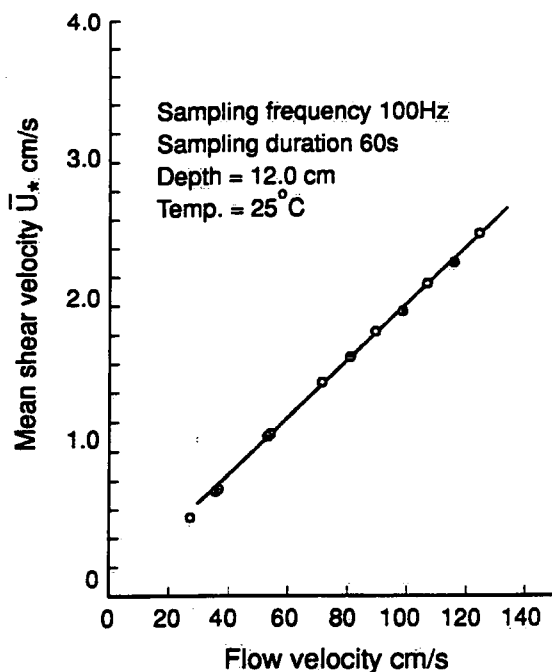
Figure 2. Two dimensional flow shear velocity as a function of flow velocity.
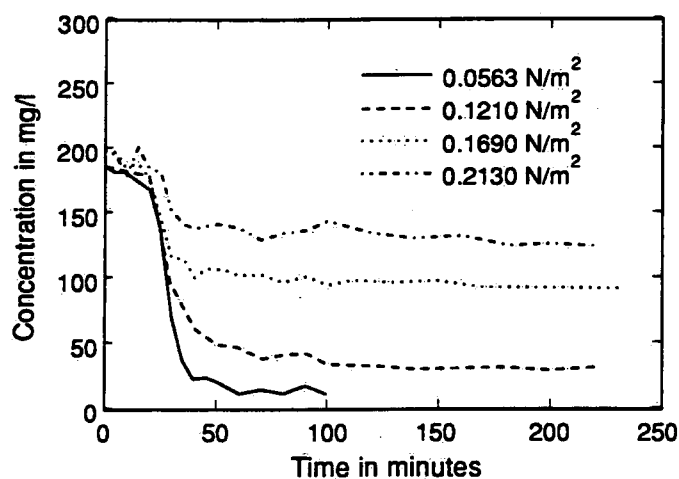
Figure 3. Variation of concentration for different shear stress

Figure 4. Variation of concentration for different initial concentrations

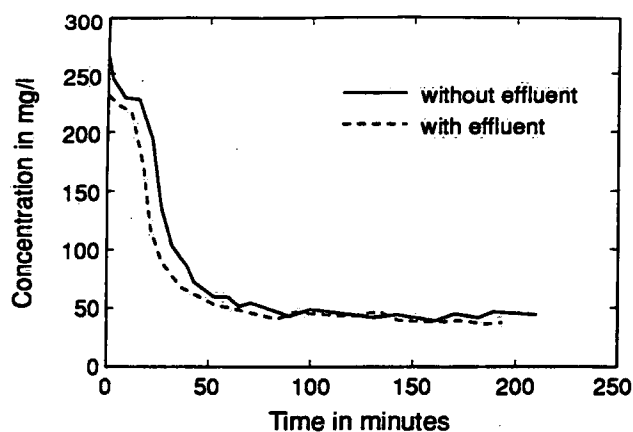Figure 5. Size distribution of suspended sediment in Test No. 4
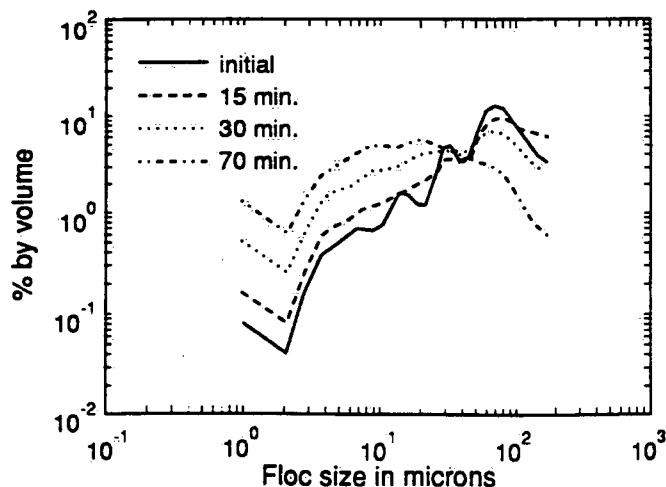
Figure 6. Size distribution of suspended sediment in Test No. 1

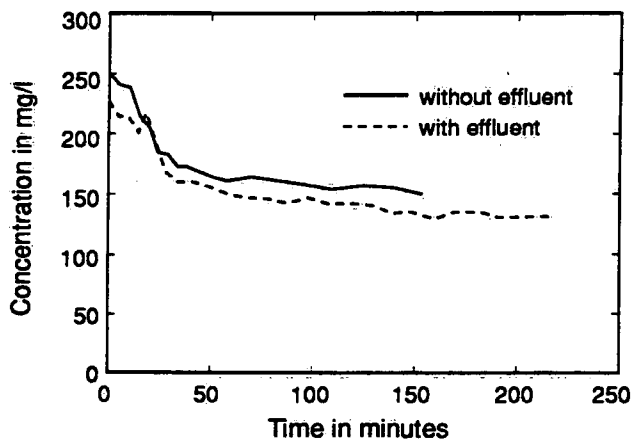Figure 7. Effect of pulp mill effluent during deposition - shear stress = 0.121N/m²

Figure 8. Effect of pulp mill effluent during deposition - shear stress = 0.213N/m²
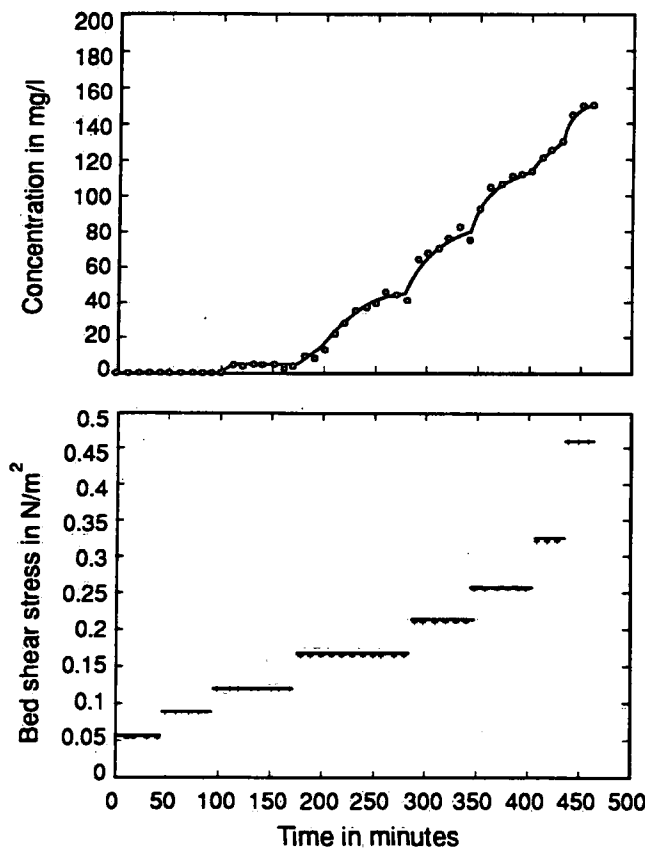
Figure 9. Erosion of Fraser River sediment - Age of deposit: 164 hours
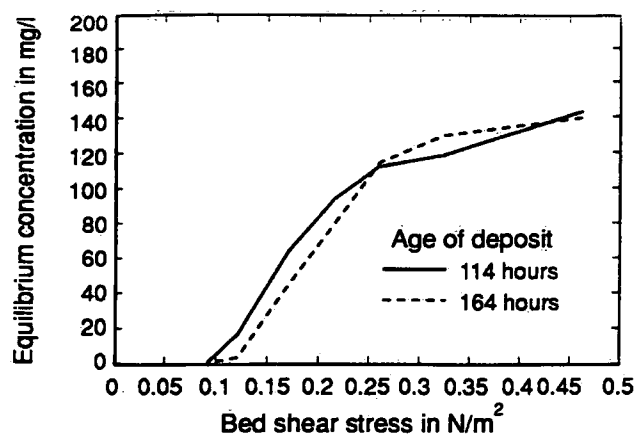
Figure 10. Effect of age of deposition on erosion
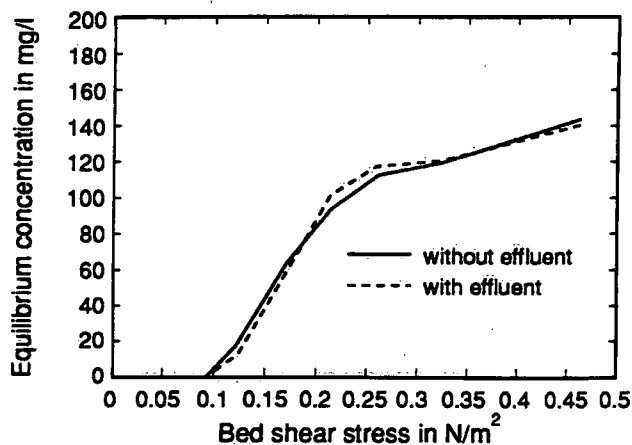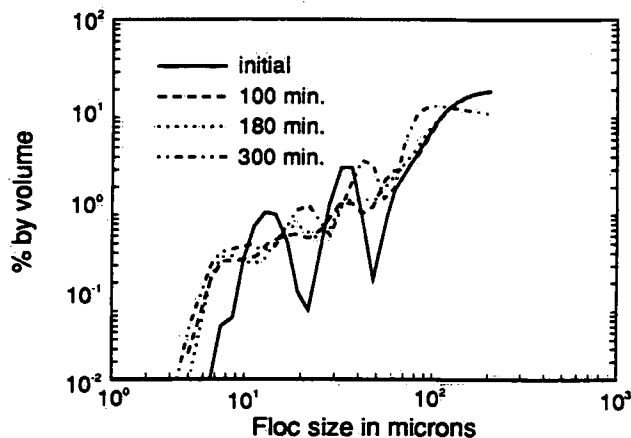

Figure 11. Effect of pulp mill effluent on erosion

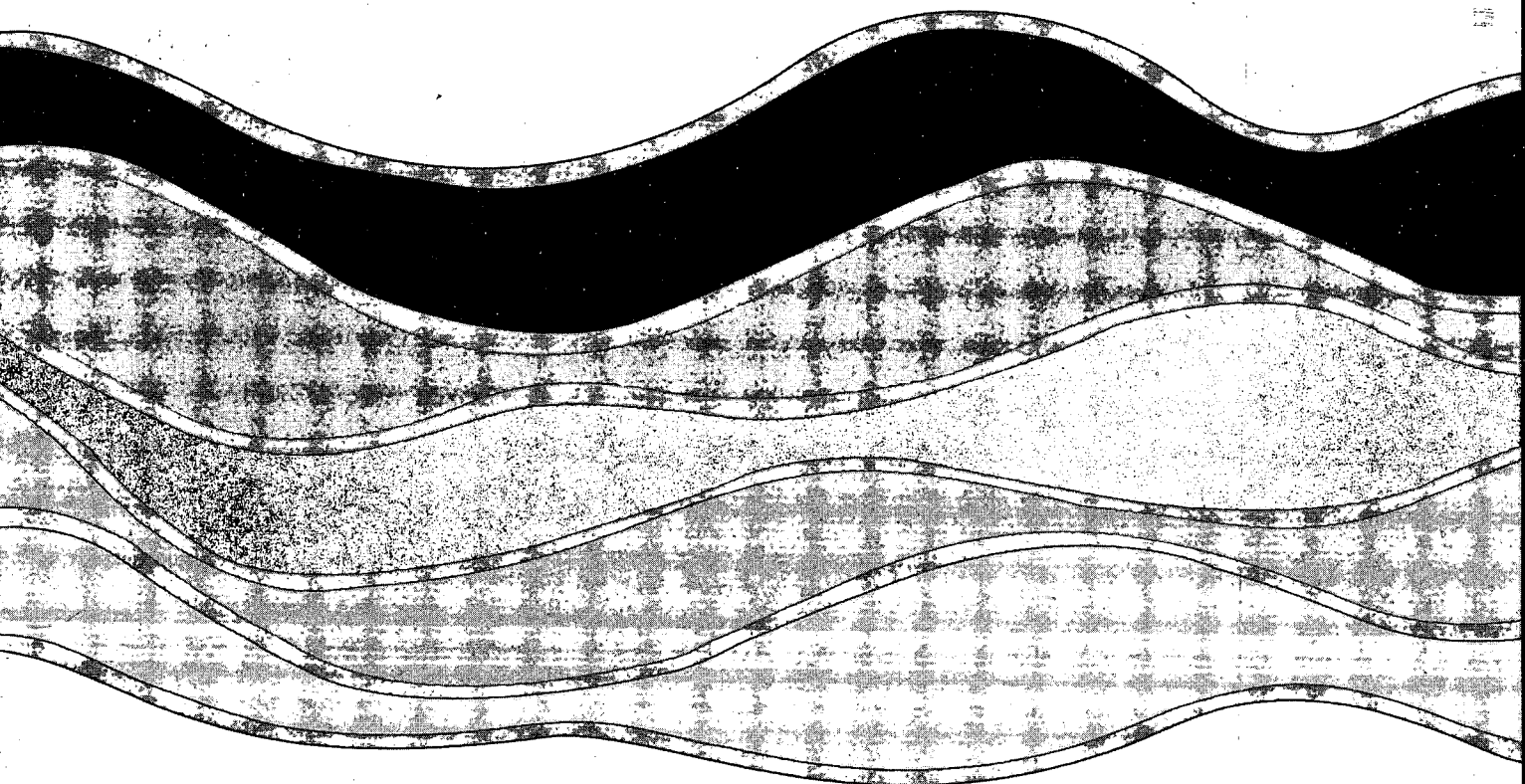Figure 12. Size distribution of suspended sediment in Test No. 14

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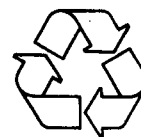Environment Environnement
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