

The Contribution of Ballistic Momentum Flux to the Erosion of Cohesive Beds by Flowing Water

C.L. Amos, M.Z. Li, and T.F. Sutherland

Geological Survey of Canada
P.O. Box 1006, Dartmouth
Nova Scotia, B2Y 4A2 Canada

ABSTRACT

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An adaptation of Bagnold's (1936) method of estimating solid-transmitted shear stresses has been used to define the ballistic momentum flux of aggregates saltating over a cohesive bed. Results from *in situ* observations of these aggregates show that up to 7% of the mass transport of sediment was in saltation (under type II erosion), and took place in the form of irregular shaped aggregates that were up to 6.8 mm in diameter. The total momentum flux/unit area/unit time (shear stress) was $O(10^{-1}\%)$ of the fluid-transmitted bed shear stress. Nevertheless, observations showed that corrosion of the aggregates took place, with "sediment splashes" observed during aggregate impacts with the bed. This led us to believe that the impact forces (the impulse) beneath the aggregates was higher than the erosion threshold of the bed material (1.5-2.0 Pa) and aggregate strength. By normalising the ballistic momentum flux by the estimated area of impact, shear stresses up to 9.5 Pa were determined which were sufficiently high to explain the observed erosional behaviour. These stresses were applied over an impact area of $0.009 \text{ m}^2/\text{m}^2$. The estimated effect on the net resuspension from the bed is small but significant (3%). Thus, it appears that saltating aggregates can contribute to the erosion threshold and erosion rate of cohesive beds in the Bay of Fundy at high current speeds ($> 0.35 \text{ m/s}$).

ADDITIONAL INDEX WORDS: Solid-transmitted stresses, erosion, mudflat.

INTRODUCTION AND BACKGROUND

W. Kamphius (*personal communication*) noted erosion and transport of compacted cohesive sediment that comprised the shoreface of the Great Lakes even though the apparent fluid stresses were much lower than those required to cause erosion. Kamphius speculated that erosion took place by abrasion of mobile sand, shells and other aggregates that moved over the cohesive substrate under waves. The same phenomenon appeared to be eroding the cohesive bluffs of Lake Winnipeg (Forbes, *personal communication*, 1996) and glaciomarine fine-grained sediment beneath mobile sand waves in the Bay of Fundy (DABORN *et al.* 1996). Is this a reasonable mechanism for cohesive bed erosion and how generally can it be applied?

The erosion of cohesive beds is largely considered to be a continuous process of particle release into suspension when the shear stress (τ_o) is above some threshold stress (τ_c), and erosion rate (E) is defined as: $E = M (\tau_o - \tau_c)$. MEHTA and PARTHENIADES (1982) showed that this is a simplification of reality, and that two types of erosion prevail in laboratory experiments: type I erosion—the release of flocs into suspension under low Reynolds numbers; and type II erosion—the quantum release of rip-up clasts to form aggregates moving as surface creep and in saltation. In the first case, erosion decreases with time and no bedload population exists. For a

well-mixed case, sediment discharge (Q_s) may be defined as the product of suspended sediment concentration (C) and the integration of velocity (U) with height (z) above the bed:

$$Q_s = C \int_0^d U dz$$

where d is flow depth. As type I erosion is usually associated with the early stages of resuspension and hence lower sediment concentrations, the bed shear stress (leading to erosion) is imparted by fluid shear under Newtonian flow. Sediment mass transport due to type II erosion is complicated by the addition of a saltation load (M_g) and a traction load (M_b) (AMOS, DABORN *et al.*, 1992):

$$Q_s = \int_{h_b}^d (CU) dh + U_g M_g + U_b M_b$$

The concentration cannot be assumed to be constant with height above the bed, and a bedload layer exists of height h_b . The second term in the equation ($U_g M_g$), the mass flux, is also the total momentum associated with the saltation load, which may be used to determine the ballistic momentum flux to the bed if we know the nature of the saltation and the impact of aggregates with the bed. If we regard the traction flux ($U_b M_b$) as negligible for the present purposes, then sediment mass transport reduces to the suspended flux and the momentum of the saltating grains. The question we address

in this study is how important is the second term in cohesive sediment transport.

Type II erosion is continuous and takes place through the spontaneous ejection into the flow of rip-up clasts and large aggregates that move as bedload (surface creep and saltation). If ballistic momentum flux is important to erosion, it will be so only for this type of erosion. Furthermore, the incorporation of shell fragments as well as organic and inorganic detritus under high flows fuels the process of saltation (REINECK and SINGH, 1975).

Applying Newton's Second Law, the sum of all changes in momentum (p) of saltating grains over a given time ($t_2 - t_1$) is equal to the sum of the forces (F) exerted on the grains:

$$\Delta p = \int_{t_1}^{t_2} F \delta t$$

The formula expresses the *impulse-momentum theorem*, and the right hand side of it defines the impulse of an object. The concept of impulse is particularly useful for brief, rapidly varying forces (ZIFRATOS, 1976), such as those imparted by saltating grains. If we assume that the time interval $t_2 - t_1$ is small enough to be considered instantaneous, then the momentum flux may be equated with the peak force of impact. As the bed shear stress is the force at the bed divided by area, the peak shear stress imparted by saltating grains (T) may be determined provided we can determine the momentum transmitted from the saltating grains to the bed in unit area and unit time.

The transfer of energy to the bed from saltating grains (the solid-transmitted shear stress) has been defined by BAGNOLD (1936) (working on aeolian sand) as: $T = M_g (U_g - U_c) / l$, where M_g is the total mass of saltating grains per unit time and unit width, U_g is the terminal velocity of saltating grains, U_c is the ejection velocity which is assumed to be negligible, and l is the mean saltation length. LEEDER (1979) has re-defined this formula in quadratic form which expresses the mean (time-averaged) "living stress" of an object:

$$T = M_g U_g^2 / l$$

where M_g has units of mass/unit area. Note that the stress is not applied evenly across the bed but has been normalised by the saltation length. According to ABBOTT and FRANCIS (1977), the transfer of momentum by saltating grains to the bed is a function of impact angle (α). The momentum remaining in the grains is manifested by forward rolling before they are launched on the next saltation. Only the vertical component ($U_g M_g \cos \alpha$) of the momentum flux is delivered to the bed, while the horizontal part ($U_g M_g \sin \alpha$) maintains the forward motion of the saltating aggregates (Figure 1).

The tangential component of the momentum flux is derived from the flow itself (U_r) and so the flow must decelerate within the saltation layer; the vertical component is due to the force of gravity acting on the saltating particles. Thus the saltating grains absorb momentum from the flow (with a reduction in the flow velocity and increase in apparent bed roughness, WIBERG and RUBIN, 1989) and subsequently provide an efficient transfer of momentum to the bed. Could Bagnold's mechanism for the maintenance of saltation on desert

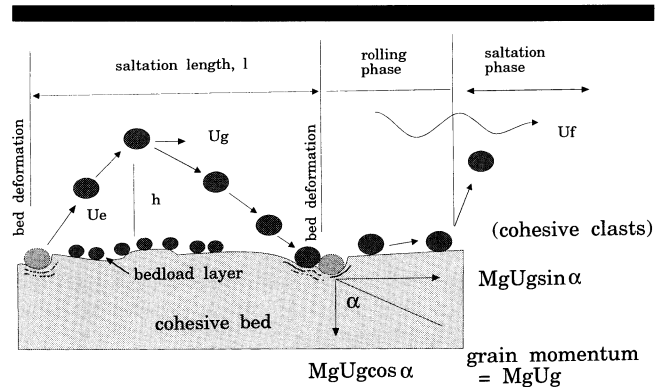


Figure 1. A schematic diagram of the saltation process and the ballistic momentum flux to the bed of the saltating aggregates. The illustration depicts bed erosion and deformation resulting from the impacts of saltating material, and illustrates that the particle motion may be broken down into a saltation phase and a rolling phase.

dunes be applicable to the erosion of natural cohesive beds within the marine environment? Furthermore, could the action of saltation provide a general mechanism for the continuous erosion of cohesive material into suspension and the traction of eroded aggregates that typify type II (chronic) erosion? These questions were examined through the analysis of video observations as well as through detailed measures of the erosion of a cohesive seabed in Annapolis Basin, Bay of Fundy using the benthic flume—Sea Carousel.

THE DATABASE AND METHODS

The data for this study came from two deployments of the benthic flume Sea Carousel in Annapolis Basin, Bay of Fundy. These deployments have been described by AMOS, DABORN *et al.* (1992). The physical characteristics of Sea Carousel, as well as the operational procedures and calibrations are given in AMOS, GRANT *et al.* (1992). The erosion tests were carried out through *in situ* deployments. The velocity inside the flume was increased in increments and the subsequent erosion was observed by two optical backscatter sensors and in high-resolution video recordings of the eroding bed. Mean current speed (U_{18}) was determined from lid rotational speed (U_r): ($U_{18} = 0.574U_r$ m/s) and also with a Marsh-McBirney EM current meter situated mid-stream at a height of 18 cm above the bed. The clear-water fluid-transmitted shear stress (τ_o) was estimated from an empirically-derived relationship: $U_* = 0.097U_{18}$ m/s, and $\tau_o = \rho U_*^2$. The turbidity-reduced bed shear stress ($\tau_s = \rho U_{*s}^2$) was determined from hot-film probe experiments reported in AMOS, GRANT *et al.* (1992) and AMOS *et al.* (in press), and took the form: $U_{*s} = [U_* - (0.2267 \log_{10}(C)) * (U_*/6.35)]$ cm/s.

The video records were freeze-framed and the number, size, velocities, and trajectories of saltating grains were recorded at each speed increment. Aggregate velocity (U_g) was determined by counting the number of $1/30$ second frames for the aggregates to travel between 2 calibration marks (10 cm apart) in the field of view. The mean aggregate velocity was

found from the average of 10 successive measures. The bulk density of the eroded aggregates (ρ_s) was equated with that of the eroded bed which was 1800 kg/m^3 . The buoyant mass of each aggregate was determined by measuring the diameter ($D = 2r$) and assuming sphericity ($\frac{4}{3}\pi r^3[\rho_s - \rho]$), where ρ is the fluid density (taken as 1000 kg/m^3). The saltation length could not be determined accurately because of the small field of view, but could be inferred from the ratio of saltation height:length ≈ 0.1 (ABBOTT and FRANCIS, 1973). As the saltation height was around 5 cm, the saltation length has been assumed to be 50 cm. The angle of impact (α) was taken as 25° from WIBERG and SMITH (1985).

RESULTS AND DISCUSSION

The Sea Carousel Results

In situ observations of the erosion process of natural cohesive beds were made using the benthic flume Sea Carousel. Results from this flume clearly showed the presence of type I erosion at low current speeds, giving way to type II erosion at higher speeds. Video observations made concurrently in the Sea Carousel showed that under type II erosion, rip-up clasts were entrained by the flow. These clasts were up to 6.8 mm in diameter (Figure 2; Table 1). The aggregate buoyant mass (M_g) varied up to $1.70 \times 10^{-3} \text{ kg}$, which comprised up to 7% of the total mass in transport. The video imagery showed a clear traction population, as well as the impact of the saltating grains with the bed with subsequent corrosion (reduction in aggregate size due to shearing) at $U_{18} > 0.35 \text{ m/s}$.

The number (#/min), diameter (diam), and speed (U_g) of saltating aggregates are listed in Table 1 for each current speed increment of the two deployments (stations 6 and 7). Also given are the suspended sediment concentrations (C), index azimuthal current speed (U_{18}), estimated turbidity-reduced fluid bed shear stress (τ_s) and three estimates of the solid-transmitted shear stress (BAG—BAGNOLD, 1966; LEED—LEEDER, 1979; and herein). The saltation mass generally increased with current speed. The aggregate momentum ($M_g U_g$) peaked at $1.06 \times 10^{-4} \text{ kg/s}^2$ and was also greatest at highest speeds. BAGNOLD'S (1936) solid-transmitted stresses due to saltating grains was $O(10^{-4} \text{ Pa})$ and peaked at the middle or late stages of each deployment. LEEDER'S (1979) relationship (which gives an average stress) was marginally lower, but indicated the same order of stresses as Bagnold. These values were well below the erosion threshold for this material (1.5–2.0 Pa; AMOS, DABORN *et al.*, 1992) and well below the fluid-transmitted shear stresses. Yet we measured the reduction in aggregate size through corrosion (Figure 2B). This observation led us to believe that the stress on the grains (and hence on the bed) during impact exceeded the strength of the material (which is equal or greater than the erosion threshold of the bed). How can we reconcile these two apparent contradictory results?

The impulse forces of the saltating grains were not delivered evenly across the bed (as is assumed for a fluid) but took place over the sum of the aggregate cross-sectional areas (A; up to 0.09 m^2). By normalising the total momentum flux by this area (instead of by the saltation length and flume width)

and redefining impact mass in terms of total mass per unit time, the stress beneath the aggregates on impact was derived. The stress so imposed varied up to 0.48 Pa, which was still less than the critical values for erosion. If the momentum was delivered over only 5% of the cross-sectional area (a reasonable area for spherical aggregates) then the stress under the impacting aggregates would be up to 9.5 Pa, which is sufficient to explain the corrosion of the aggregates and also to advance the process of bed erosion. These stresses are given in Table 1 ($T = U_g M_g / 0.5A$) and plotted in Figure 3 with the turbidity-reduced, fluid-transmitted bed shear stresses. The solid-transmitted stresses for the two deployments generally increased with current speed. In the early stages of each experiment they were below the fluid-transmitted stresses, but they increased rapidly above $U_{18} > 0.35 \text{ m/s}$. This was equated with rough turbulent flow as the grain Reynolds number Re_g was 132 ($Re_g = U_g d / \nu$; where U_g is the friction velocity and ν is the kinematic viscosity = 0.00000131 kg/ms). Under such conditions it is reasonable to assume that turbulent pressure fluctuations due to bed irregularities could contribute to the ejection of aggregates into the flow and so feed the process of saltation.

The Ratio of Solid and Fluid Transmitted Bed Stresses

According to BAGNOLD (1966), the total shear stress in a flow (τ_t) may be decomposed into the solid-transmitted stress (T) and the fluid transmitted shear (τ_o): $\tau_t = T + \tau_o$. The solid-transmitted shear stress is caused by grain-to-grain interactions and so it is present in the saltation region but is dominant in the traction layer (Figure 4). LEEDER (1979) has found that the transfer of momentum from saltating sand grains in water can balance the movement of the traction load i.e. saltating grain impacts provide a large component of the bed shear stress.

In the present case, we propose that the grain-to-grain transfer of energy may be equated with the grain-to-bed momentum flux, given the relatively low value of M_b on cohesive beds. When considering unit area of the bed, this represents only a fraction of the fluid-derived momentum (0.1%). This indicates that flow deceleration in the saltation layer due to acceleration of the saltating grains is small and may be ignored in the calculation of the fluid-transmitted stress.

The Effect of Aggregate Shape

The influence of saltating grains on the erosion of cohesive beds is apparent only at the point of impact of the saltating aggregates. In this study it was a maximum of 0.009 m^2 (the sum of aggregate cross-sectional areas). If the aggregates were spherical, then the area of impact would be of the order of 5–10% of the projected area. Pellets and ovoids might impact across 5% of their area, while shell fragment edges and rods would likely impact across 1% of the cross-sectional area (shell edges and end faces). As the stress is inversely proportional to the area of impact, the shape of an aggregate and how it impacts the bed has a profound influence on the solid-transmitted stress. For example, we saw that shells were transported with their long axis parallel to the flow, and they

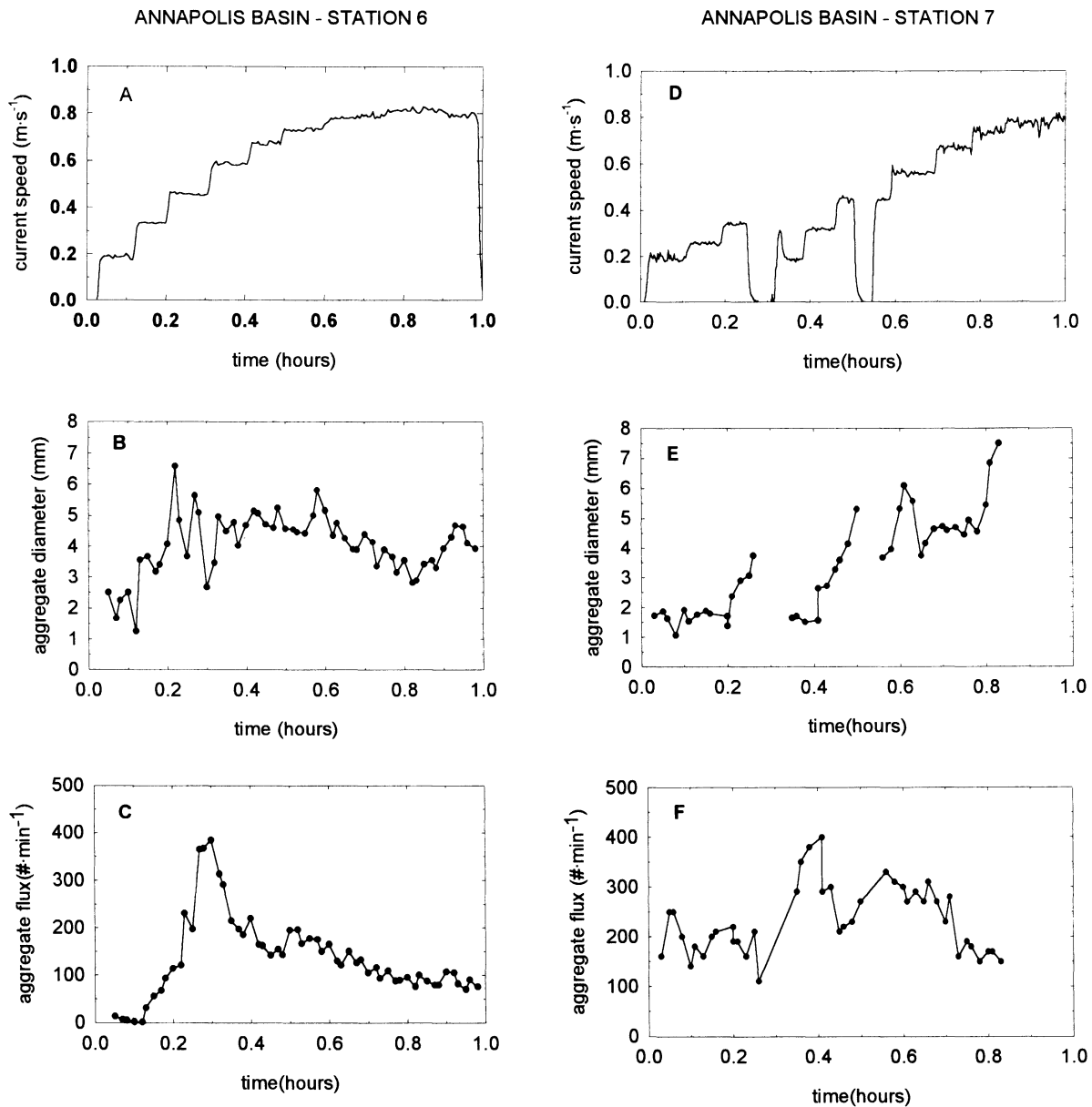


Figure 2. Time-series of the results from Sea Carousel stations 6 and 7, Annapolis Basin, Bay of Fundy: (a,d) current speed; (b,e) aggregate diameter. Notice that the peak aggregate diameter for station 6 occurred at the mid stages of erosion and then decreased due to corrosion; and (c,f) aggregate flux (determined from video observations). At station 7, there was a steady increase in aggregate diameter with current speed (e).

made contact with the bed along the shell sharp edges. The effect of this was to cut the bed in a tilling action. Rods and pellets appeared to saltate through end-to-end impacts with the bed creating prod marks, bounce marks, brush marks, skip and roll marks or chevron marks (REINECK and SINGH 1975).

The significance of these observations is that spheres will likely influence the erosion process of cohesive beds by corrosion and plastic deformation, whereas irregular objects such as shells and rods could enhance the erosion process through cutting, pitting, and reptation.

The Contribution of Saltating Aggregates to Resuspension

We may estimate the proportion of the suspended load due to saltating grains by use of the following equation, which was developed specifically for Bay of Fundy, cohesive sediments (AMOS, DABORN *et al.*, 1992):

$$\ln(E/5.1 \times 10^{-5}) = 1.62 [\tau_s - \tau_c]^{0.5}$$

We have simplified the time-series for erosion to mean, constant stresses during the erosion period and have as-

Table 1. A summary of the observations and calculations made at the two Sea Carousel deployments comprising this study. The two estimates of the solid-transmitted shear stress are also given (BAG—Bagnold, 1936; LEED—Leeder, 1979) and the ballistic momentum flux (herein).

U_{18} (m/s)	U_g (m/s)	Diam (mm)	Aggreg Flux (#/min)	C (mg/L)	τ_s (Pa)	BAG. (Pa)	LEED. (Pa)	Herein (Pa)
Station 6								
0.19	0.20	2.25	5	25	0.97	1.59e-5	3.18e-6	1.20
0.33	0.27	3.67	56	51	1.75	1.04e-3	2.82e-4	2.64
0.46	0.55	6.58	121	268	2.41	0.026	0.014	2.63
0.58	0.61	3.47	313	646	3.15	0.011	6.79e-3	5.64
0.66	0.76	4.71	142	679	3.84	0.016	0.012	9.55
0.73	0.62	4.57	195	551	4.60	0.016	9.98e-3	7.56
0.78	0.69	4.76	121	307	5.40	0.013	8.67e-3	8.76
0.78	0.76	4.39	105	271	5.46	9.43e-3	7.16e-3	8.90
0.81	0.79	3.89	109	234	5.89	7.08e-3	5.59e-4	8.19
0.79	0.82	3.54	95	225	5.67	4.83e-3	3.96e-3	7.74
Station 7								
0.19	0.17	1.87	250	106	0.86	3.88e-4	6.47e-4	0.85
0.25	0.29	1.53	180	129	1.15	2.61e-4	4.35e-4	1.18
0.34	0.39	1.70	220	170	1.65	5.89e-4	9.81e-4	1.77
0.18	0.27	1.64	290	170	0.78	4.82e-4	8.04e-4	1.18
0.32	0.38	1.56	400	165	1.52	8.06e-4	1.34e-3	1.58
0.45	0.34	4.13	230	189	2.41	7.69e-3	0.013	3.74
0.55	0.42	5.31	300	304	3.11	0.026	0.044	5.95
0.67	0.52	4.59	280	341	4.18	0.020	0.033	6.36
0.72	0.42	6.84	170	465	4.56	0.032	0.053	7.66

sumed a constant erosion threshold: for station 6, $\tau_s = 5$ Pa; $T = 7$ Pa; $\tau_c = 1.5$ Pa; the eroded bed area for fluid-transmitted stresses = 0.873 m^2 (the base of the Sea Carousel); the eroded bed area for solid-transmitted stresses = $(0.873 \times 0.009) \text{ m}^2$; and the erosion time interval = 0.72 hours; for station 7, $\tau_s = 5$ Pa; and $T = 4$ Pa; all other parameters were the same as station 6. We estimated that 0.035 kg of material would be eroded by the impacts of saltating aggregates dur-

ing deployment 6 while the fluid-induced net erosion would be 1.02 kg. Thus 3.5% of the resulting eroded mass would be derived from the process of saltation. The results from deployment 7 showed that 0.009 kg would be eroded by saltation, while 0.77 kg would be eroded by the fluid itself. In this case, 1.1% of the mobilized load would be derived from the saltation process. In both cases, the contribution is a small but not an insignificant portion of the eroded mass and suggests that the contribution of the ballistic momentum flux to the erosion of cohesive beds should not be ignored in those cases where type II erosion and saltation is expected. The ballistic momentum flux may contribute up to 50% of the

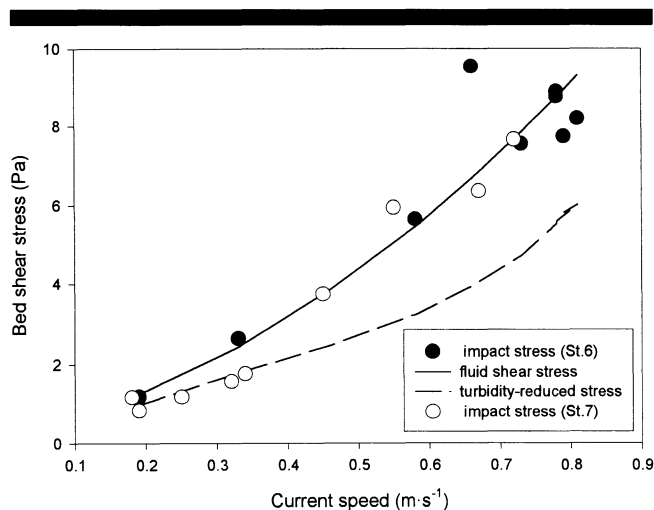


Figure 3. The calculated ballistic momentum flux ($T = U_g M_g / 0.05A$), the fluid-transmitted stresses, and the turbidity-reduced fluid-transmitted shear stresses plotted against azimuthal current speed for the two Sea Carousel deployments reported in this paper. Notice that the estimated solid-transmitted shear stresses were greater than the turbidity-reduced fluid-transmitted shear stress under type II erosion ($U_{18} > 0.35$ m/s).

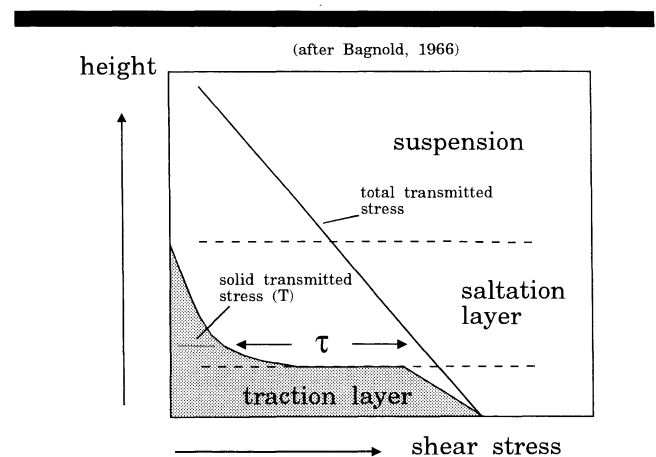


Figure 4. The partitioning of shear stresses into the solid and fluid-transmitted parts. According to Bagnold (1966) the saltation layer (immediately above the traction layer) has a significant solid-transmitted component (T).

grains in saltation (7% of the total load), the remainder must therefore be derived by the fluid-transmitted shear stresses.

CONCLUSIONS

This study was undertaken to determine if aggregates saltating over a cohesive bed could induce erosion through the solid-transmitted bed shear stress. An initial evaluation was made of video records, collected during two deployment of Sea Carousel in Annapolis Basin, Bay of Fundy. The conclusions of this study are as follows:

- (1) saltating grains formed a significant portion (7%) of the transported load at flows in excess of 0.35 m/s;
- (2) saltating aggregates were up to 6.8 mm in diameter, and suffered corrasion during the transport process;
- (3) the solid-transmitted shear stress (per unit bed area) due to saltating aggregates formed only a small portion (order $10^{-1}\%$) of the total transmitted stresses even at high saltation rates;
- (4) the solid-transmitted shear stresses under the impacting aggregates were estimated to be up to 9.5 Pa, which was enough to cause bed erosion and aggregate corrasion. The shape of the aggregates was thus important to the contribution of saltating aggregates in the erosion process. This was particularly relevant to the transport of shell debris, which was largely transported through bed contacts along the shell edges; and
- (5) the erosion of the bed due to saltating aggregates appeared to contribute up to 3.5% of the total load in transport. This was a small but significant portion of the total load and

suggested that it should be considered in those regions where saltation is expected.

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