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Field Measurements of the Erosion of Cohesive Sediments

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ABSTRACT

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Predictive modeling of estuarial fine sediment transport requires a description of the erosional properties of cohesive sediment beds. Available descriptions are commonly based upon flume experiments run on uniform beds. Field data pertaining to the erosion process are rather scarce.

A field experiment was undertaken at Mare Island Strait near Vallejo, California, to address the issue of surface erosion of a cohesive sediment bed. Suspended sediment concentration and water velocity data were collected in the bottom boundary layer of this muddy estuary. As a result, the critical shear stress of erosion initiation was found to be 1.44 dynes/cm^2 and the erosion rate coefficient was found to be 6.25 $\times 10^{-1}$ mg/cm^2-sec. These values compare favorably with results obtained in recent flume experiments.

ADDITIONAL INDEX WORDS: *Cohesive sediments, erosion, critical shear stress, Mare Island Strait, field measurement.*

INTRODUCTION

Modeling of the erosion of cohesive sediments has typically been described by the erosion rate expression given by KANDIAH (1974):

$$E = M((\tau_b - \tau_c)/\tau_c) \qquad (1)$$

where

E = the rate of surface erosion (mg/cm^2-sec)
M = the erosion rate coefficient (mg/cm^2-sec)
τ_b = the bed shear stress (dynes/cm^2)
τ_c = the critical shear stress (dynes/cm^2)

At present, little is known about the quantitative values of the critical shear stress and the erosion rate coefficient under field conditions. Estimates have been obtained from laboratory studies, but field verification has been limited (see GUST and MORRIS, 1989).

With this view in mind, a field experiment was undertaken to address the issues pertinent to predicting cohesive sediment transport within an estuary. The following discussion describes this field experiment and the associated data analysis.

FIELD EXPERIMENT

Experiment Site

The experiment was conducted in late September 1987 at Mare Island Strait near Vallejo, California. Mare Island Strait is a narrow, muddy estuarine tidal channel. Freshwater discharge and surface wave activity are negligible within the strait at this time of year and, thus, the tide-generated current is the predominant driving force for sediment motion. Annual dredging is required to maintain the 250-meter-wide channel and numerous shipyard berthing areas at 10.8 meters below the mean lower low water level. The experimental site was a flat portion of the artificially-deepened channel approximately 21 meters off the quay wall that forms the western boundary of the waterway (see Figure 1).

Instrumentation

An instrument support frame was constructed of steel. The frame consisted of two components: an outer support frame with large feet that allowed it to rest on the seabed, and a central staff where the instruments were mounted (Figure 2). The outer frame was constructed in such a manner that the flow measured by the instruments was not obstructed by the legs or support framework.

The following instruments were used:

- Two Marsh McBirney electromagnetic current meters (1½-inch ball) to measure horizontal velocities
- Five optical backscatterance sensors (OBS) to measure suspended sediment concentrations
- A Benthos plankton camera to measure floc siz-

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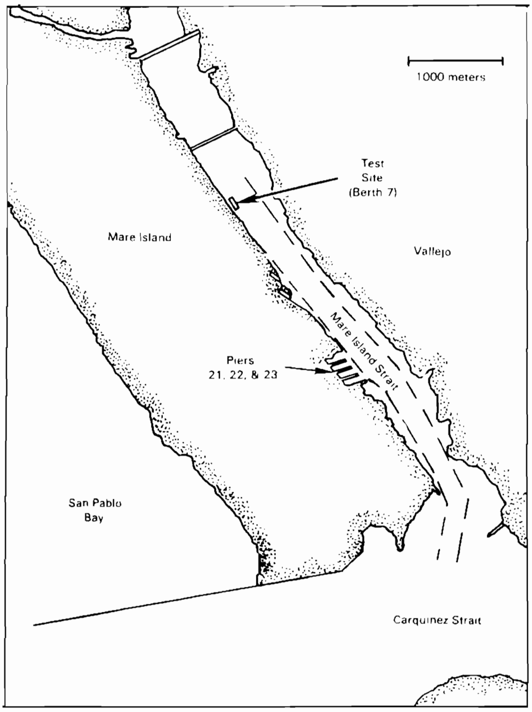

Figure 1. Location map of Mare Island Naval Shipyard and vicinity.

es (problems were encountered with the operation of the device, therefore no data were obtained)

- A bottom sensor, based on the design presented by KRONE (1972), to reference the other measurements to the location of the bottom
- A differential pressure transducer to measure the excursion of the instrument staff relative to its highest point of excursion (a strut on the framework)

Measurement Techniques

The central instrument support staff was not rigidly attached to the outer frame. Rather, the central staff was connected to a hydraulic cylinder which was mounted on the outer frame. By extending and retracting the rod of the hydraulic cylinder, the central staff could be moved in the vertical direction with respect to the frame, and therefore the seabed. The maximum range of motion for the central staff was 51 centimeters; a differential pressure transducer measured the position of the staff relative to the outer frame.

By moving the central staff, and thereby the instruments, in relation to the seabed, we were able to obtain a vertical profile of the water velocities and suspended sediment concentrations in the bottom boundary layer. A typical "profile" was taken in this manner: the staff is moved downward until the bottom sensor indicates that the seabed has been reached; the differential pressure sensor is zeroed and data are recorded from the lowest measurement station; the staff is moved upward 4 centimeters to the next measurement station and data are taken; the staff is again moved upward to the next station and more data are taken; this procedure continues through all of the stations; when the top of the range of movement is reached the procedure is reversed and data are taken at all of the stations as the staff is moved downward. Figure 3 documents the stations at which measurements were taken.

If steady-state conditions can be assumed, this manner of profiling permits the researcher to obtain a detailed data set with a small number of instruments. But, since each profile requires about 3 minutes, if conditions are not steady synopticity of data is sacrificed for detailed coverage. In all of the profiles that were taken there was no discernible difference between the data collected on the upstroke of the staff and that of the downstroke. This suggests that the assumption of a steady-state environment is valid.

Two techniques were used to collect data during this experiment. First, profiles were taken at half-hour intervals during the daylight hours. Second, stationary measurements, that is to say measurements taken without moving the central staff, were made at a single station (bottom sensor located at 5 centimeters above the seabed) every 10 minutes for the entire duration of the experiment, which consisted of five complete tidal cycles.

WATER VELOCITY DATA

Water velocity data were collected by two, two-axis electro-magnetic current meters mounted as shown in Figure 2. Threshold velocity of the instrument appeared to be roughly 3 centimeters per second, thus values obtained at slack currents that fall below this value are not likely to be accurate.

To eliminate the effects of small scale turbulence during the field experiment, each recorded value of water velocity was an average of ten measured values taken over an interval of 3 seconds. Using these averaged values, the horizontal ve-

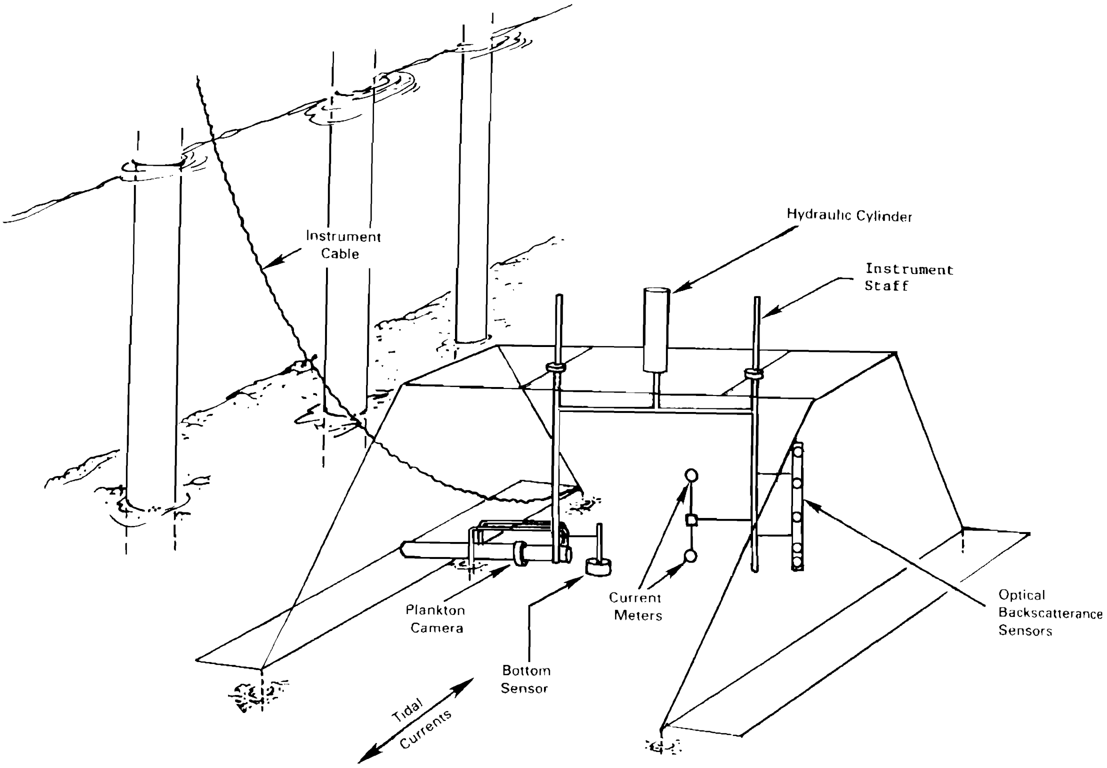

Figure 2. Seafloor landing frame with instrument staff.

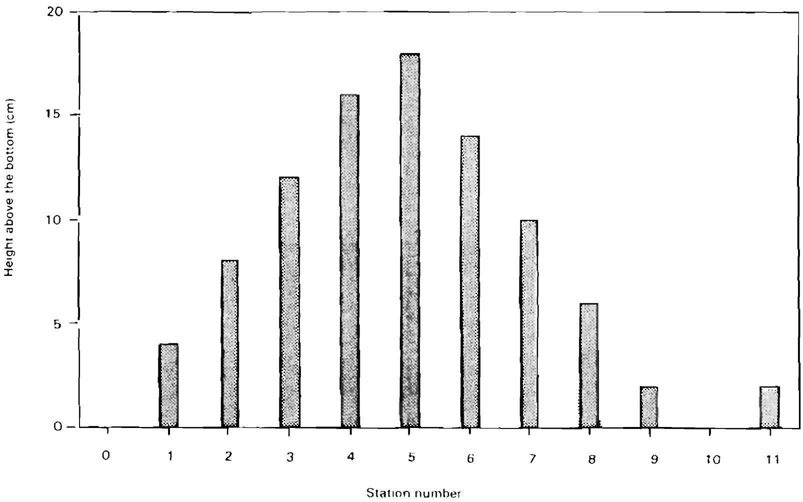

Figure 3. Stations of measurement during bottom boundary layer profiling as described by the position of the lowest instrument.

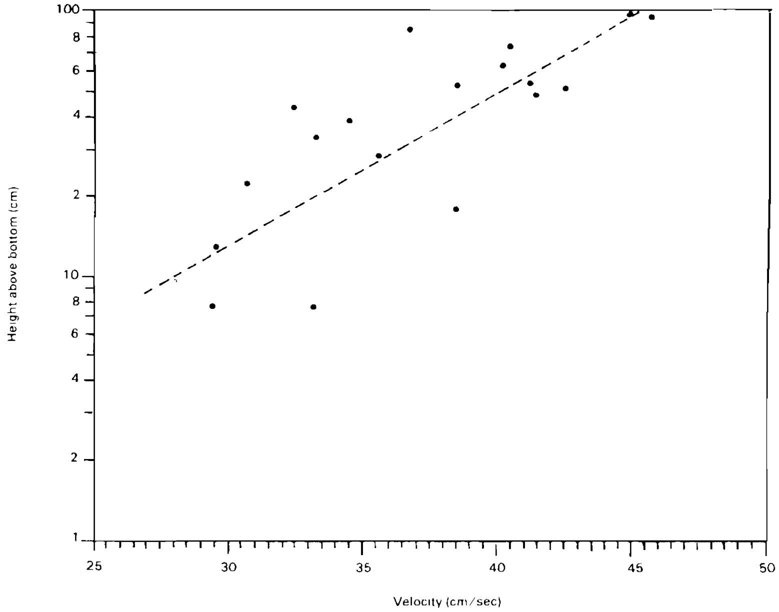

Figure 4. An example of the velocity data taken during bottom boundary layer profiling. Dotted line is the linear regression fit to the data.

locity vector for each position was calculated as follows:

$$\|U\| = (u^2 + v^2)^{1/2} \qquad (2)$$

where

$\|U\|$ = magnitude of the velocity vector (cm/sec)
u = current velocity along the channel axis (cm/sec)
v = current velocity perpendicular to the channel axis (cm/sec)

The friction velocity for each data set, both profile and stationary data, was found using the Kármán-Prandtl logarithmic expression:

$$U/U_* = k^{-1} \ln(z/z_0) \qquad (3)$$

where

U = the mean velocity at height, z, above the bed (cm/sec)
U_* = the friction velocity (cm/sec)
k = Kármán's constant
z = height above the sediment bed (cm)
z_0 = the roughness height (cm)

A least-squares linear regression curve was fit to the semilog plot of velocity versus the log of the height above the bed (see Figure 4). The slope of this line is U_*/k, and the intercept is z_0. The friction velocity was computed using a Kármán's constant of 0.4.

Based upon these friction velocity values, the bed shear stress was computed:

$$\tau_b = \rho U_*^2 \qquad (4)$$

where

τ_b = the bed shear stress (dynes/cm^2)
ρ = the fluid density (grams/cm^3)
U_* = the friction velocity (cm/sec)

SUSPENDED SEDIMENT CONCENTRATION DATA

Five optical backscatterance sensors were used to measure the suspended sediment concentration. These sensors determine the amount of backward scattering of infrared light caused by the fluid/sediment sample (Downing *et al.*, 1981), and relate it to the particulate concentration via instrument calibration. The sensors described herein were calibrated in the laboratory both be-

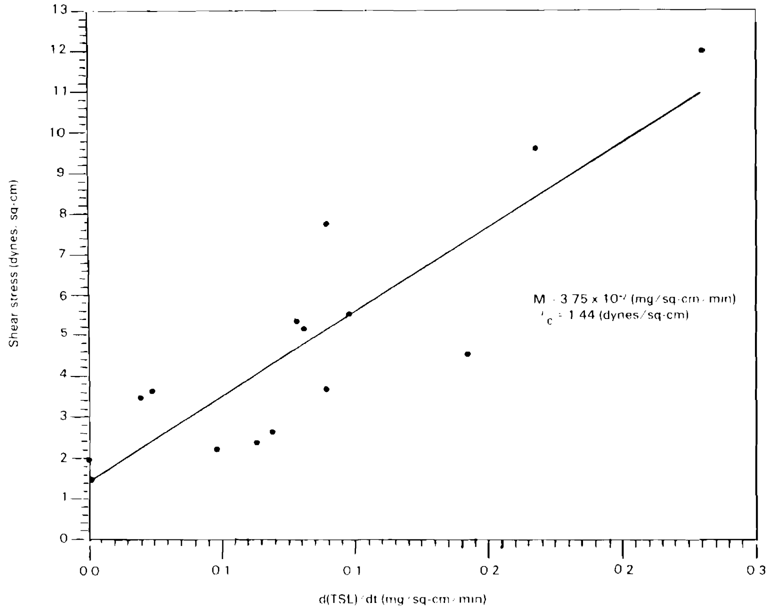

Figure 5. Shear stress plotted against the time derivative of the total suspended load including both the data points and a linear regression fit to the data.

fore and after the experiment using samples of sediment taken from the sediment/water interface of the experiment site. Solutions of known suspended sediment concentration were made and kept in suspension with a mixer. Each sensor sampled each solution at 3 Hz over a duration of 20 seconds. The average values were used to develop the calibration curves. The standard deviation of the measurements ranged from 0.6 to 1.8 percent error. The actual suspended sediment concentration of each solution was determined by gravimetric analysis.

In order to reduce the effect of small scale turbulence during the field experiment, each recorded data point was an average of ten measured points taken over 3 seconds. Using these averaged values, the total suspended sediment load for a given instant in time was calculated by integrating the suspended sediment concentration in the vertical dimension.

RESULTS

By continuity, the time derivative of the total suspended sediment load is equal to the rate of surface erosion. By substituting the time derivative of the total suspended load into Equation 1 and subsequently rearranging, an equation is obtained that relates the bed shear stress to the measured rate of surface erosion. That is:

$$\tau_b = (\tau_c/M)d(TSL)/dt + \tau_c \qquad (5)$$

where d(TSL)/dt is the time derivative of the total suspended load.

A least squares linear regression was fit to the plot of bed shear stress versus the time derivative of the total suspended load. The slope of the line is τ_c/M and the y-intercept is the critical shear stress, τ_c (see Figure 5). Solving for the y-intercept, the critical shear stress of the surface layer of sediment in Mare Island Strait is found to be 1.44 dynes/cm^2. Solving for the slope, the erosion rate constant, M, is given as 6.25×10^{-4} mg/cm^2-sec.

As a rough check on the calculated value, the critical shear stress was estimated in a second manner. Using the stationary measurements, the time series of the suspended sediment concentration was compared with that of the bed shear stress for the five measured erosion events. Due to both the concentration sensor position and the sampling rate used, it was assumed that the initiation of seabed erosion actually began a short time before the measurement (some time after the last reading that was taken 10 minutes prior). Therefore, the bed shear stresses at both the point of initiation and at the previous point were considered. The average value of bed shear stress at the measurement prior to erosion initiation was 0.8 dynes/cm^2; the average value at the measurement point just after erosion initiation was 4.4 dynes/cm^2. The value calculated using Equation 5 falls within this range.

The erosion rate constant is probably slightly underestimated. The reasoning for this statement stems from the integration method used in calculating the total suspended load. The flux of sediment into the water column above the highest measurement point was not taken into consideration in this calculation. The data suggest that this upward flux occurred as a gradual process through the later stages of the resuspension event. Therefore, the time derivative of the total suspended load, especially in the higher portions of the curve, is underestimated. An attempt has been made to estimate the magnitude of this error by using the Rouse equation (ROUSE, 1938) to extrapolate the sediment concentration data into this portion of the water column. These efforts suggest that the maximum error is approximately 15 percent of the stated value, thus offering a possible range of values from 5.8×10^{-4} to 6.7×10^{-4} mg/cm^2-sec for the erosion rate constant.

DISCUSSION

Removal of Flood Tide Data

Upon comparing the shear stress time series with that of the suspended sediment concentration time series, it was noted that positive correlations (as one might reasonably expect) were only observed for the ebb tide data. The unique flood tide concentration events, which included much larger suspended sediment concentration levels than did the ebb, did not correspond at all with the higher shear stresses as would be expected. Based upon past studies of the sedimentation mechanism at Mare Island, the following explanation is offered. Mare Island Strait is a small, deep channel that is appended to Carquinez Strait very near to its effluence into San Pablo Bay (see Figure 1). Carquinez Strait is a deep channel with extremely fast currents (in some areas it has scoured to a depth of 21 meters). San Pablo Bay is a shallow muddy embayment of substantial fetch. The waves generated by the typical onshore winds suspend mud in the flats near the mouth of the Strait. The combination of the intense mixing in Carquinez Strait and the wave-generated mud suspension in San Pablo Bay creates an ample source of suspended sediment that is washed into Mare Island Strait during the flood tide (KRONE, 1987).

Using this supposition, it is argued that the flood tide concentration events were caused by an advection of suspended sediment that was resuspended outside the zone of the assumed uniform flow and not, as we assumed in the erosion equations, resuspension events caused by local surface erosion. Based upon this justification, the flood tide data were removed from consideration in the analysis that was described above.

Critical Shear Stress

The critical shear stress is a rather nebulous term that addresses the strength properties of the sediment bed. PARCHURE and MEHTA (1985) have shown that this value increases with depth into the sediment bed. Based on laboratory tests, they suggest a three-zoned representation to describe this increase. Due to the complex nature of the bed shear stress function in the field, it was only possible to address the critical shear stress in the top zone of the seabed. This value, described as τ_{so} in PARCHURE and MEHTA, is the critical shear stress of erosion initiation. It is interesting to note that the value of τ_{so} measured at Mare Island Strait falls within the range of values PARCHURE and MEHTA obtained in the laboratory ($0.5 < \tau_{so} < 2.5$ dynes/cm^2).

Erosion Rate Coefficient

The erosion rate coefficient has remained, for the most part, merely a theoretical constant. This is due, in part, to the wide diversity of equations used to describe the erosion event (MEHTA *et al.*, 1972), but also it is due to the difficulty of measurement. Equation 1 is the most common form of the erosion equation. The erosion rate coefficient used therein has been quantified in a recent series of flume experiments by OCKENDEN and DELO (1988). They suggest that the erosion rate coefficient is a function of the sand fraction of the sediment. Values ranged from 3.6×10^{-1} for 0 percent sand to 6.0×10^{-2} for 11 percent sand. The value of the erosion rate coefficient measured at Mare Island, which has a sand fraction of 12 percent (MALLOY, 1980), shows reasonable agreement with the value for 11 percent sand fraction as reported by Ockenden and Delo.

SUMMARY AND CONCLUSIONS

A field experiment was performed with the purpose of quantifying the parameters of the most frequently used erosion rate equation. The critical shear stress of erosion initiation was estimated to be 1.44 ± 0.22 dynes/cm^2. The coefficient of the rate of surface erosion was estimated to be 6.25 $\times 10^{4} \pm 0.000042$ mg/cm^2-sec. These measured values appear to compare reasonably well to values recently obtained in careful laboratory experiments.

ACKNOWLEDGEMENT

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LITERATURE CITED

Downing, J.P.; Sternberg, R.W., and Lister, C.R.B., 1981. New instrumentation for the investigation of sediment suspension processes in the shallow marine environment. *Marine Geology,* 42, 19–34.

Gust, G. and Morris, M., 1989. Erosion thresholds and entrainment rates of undisturbed in situ sediments. *Journal of Coastal Research,* Special Issue No. 5, 87–99.

Kandiah, A., 1974. Fundamental aspects of surface erosion of cohesive soils. Ph.D. Thesis, University of California, Davis.

Krone, R.B., 1987. *Personal communication.*

Krone, R.B., 1972. A Field Study of Flocculation as a Factor in Estuarial Shoaling Processes. Committee on Tidal Hydraulics, USACOE, *Technical Bulletin No. 19.*

Malloy, R.J., 1980. U.S. Navy Harbor Maintenance Dredging Atlas. *Naval Civil Engineering Laboratory, Technical Note No. N-1597,* Port Hueneme, California.

Mehta, A.J.; Parchure, T.M.; Dixit, J.G., and Ariathurai, R., 1972. Resuspension potential of deposited cohesive sediment beds. *In: Estuarine Comparisons.* New York: Academic, pp. 591–609.

Ockenden, M.C. and Delo, E.A., 1988. Consolidation and Erosion of Estuarine Mud and Sand Mixtures. Hydraulics Research, Ltd., Wallingford, England, *Report No. SR 149.*

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

Rouse, H., 1938. Experiments on the mechanics of sediment suspensions. *Proceedings of the Fifth International Congress for Applied Mechanics* (Cambridge, Massachusetts).

□ RÉSUMÉ □

Les modèles de prédiction du transport des sédiments fins estuariens nécessite la description des propriétés d'érosion des lits sédimentaires cohésifs. La plupart des descriptions sont tirées d'expérimentations en cuve sur des lits uniformes. Les données de terrain relatives aux processus d'érosion sont assez rares. On a entrepris une expérimentation de terrain à Mare Island Strait, près de Vallejo, Californie, pour diriger l'issue d'une surface d'érosion dans un lit cohésif. La concentration des sédiments en suspension et les données de vitesse de l'eau ont été recueillies dans la couche voisine du fond de cet estuaire vaseux. On a trouvé une force de cisaillement critique de 1,44 dynes/cm^2 et un coefficient d'érosion de 6,25 $\times 10^{4}$ mg/cm^2/s. Ces valeurs sont très comparables aux résultats obtenus dans de récentes expériences en cuve.—*Catherine Bousquet-Bressolier, Géomorphologie EPHE, Montrouge, France.*

□ RESUMEN □

Los modelos predictivos de transporte de sedimentos finos de estuarios requieren una descripción de las propiedades erosivas de los lechos de sedimentos cohesivos.

Descripciones posibles están normalmente basadas en experimentos de flujo en lechos uniformes. Los datos de campo sobre procesos erosivos son más bien escasos.

Se emprendió un experimento de campo en Mare Island Strait, cerca de Vallejo, California, para obtener la pérdida de superficie erosionada del lecho de sedimentos cohesivos. La concentración de sedimentos en suspensión y la velocidad del agua fueron recogidos en la capa límite de fondo en este estuario lodoso. Como resultado, se encontró que la tensión crítica de inicio de erosión es de 1.44 dinas/cm^2.—*Department of Water Sciences, University of Cantabria, Santander, Spain.*