MEASURED AND COMPUTED COASTAL OCEAN BEDLOAD TRANSPORT

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ABSTRACT

A comparison is made between the measured infilling of two test pits off the coastline of San Francisco and predictions using a coastal bedload transport model. The model, based on the work of Madsen and Grant (1967), relates the bedload transport to the bottom shear stress through an empirical relationship based on laboratory experiments. The bottom shear stress is estimated from the bottom currents created by waves and low frequency currents. The model applies beyond the breaker zone in contrast to littoral transport.

The test pits, dredged as part of the Southwest Ocean Outfall Project for San Francisco, were located 1.6 km (1 mi) and 3.2 km (2 mi) offshore in 13 m (42 ft) and 16 m (53 ft) of water. The depth of the pits relative to the natural seabed was about 8.4 m (25 ft). The comparison was conducted for a period up to 2 months in the fall of 1978.

The paper discussed the quality and scope of available data required as input to the model and shows how regional wave data were transformed to augment local measurements. Uncertainties in model results stemming from limitations in the input data are presented. With suitable adjustment of the scale of the gravitational term in the expression for the Shields parameter, overall agreement between computed and measured bedload was accomplished within the limits of accuracy of the bathymetric surveys. A sensitivity analysis of selected input conditions and coefficients was also conducted.

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INTRODUCTION

Over the past two decades there has been a marked increase in construction of facilities in the coastal zone and continental shelf. In engineering such facilities, the effects of marine bedload sediment transport on the facility or, conversely, the effects the facility will have on bedload transport are often important. For example, where trenching of the sea floor is needed for installation of large outfalls, cooling water intakes, or other structures, it is often necessary to estimate the amount of overdredging and the time frame for construction as determined by the local rate of bedload transport and siltation. In other cases, it is important to estimate the probable effects on local shoaling or scour caused by large offshore structures such as artificial islands and breakwaters. Where new navigation channels are planned, it is advantageous to examine various geometries of the channel and associated turning basins to minimize future maintenance dredging requirements. In light of these needs, various methods have evolved to evaluate marine bedload transport and siltation during the engineering phases of projects.

The purpose of this study to evaluate computed siltation rates, due to marine bedload transport, through comparison with measured data. The data available was typical of the quality available for engineering studies, and, as such, was not of optimum quality. Thus, this is a practical test of the present state-of-the-art for computing siltation rates.

The field data for this study was collected as part of the Southwest Ocean Outfall Project (hereafter SWOOP). The SWOOP project is part of a series of projects comprising the Clean Water Program of the City and County of San Francisco, California. The objective of the Program is to provide an efficient means for collecting and disposing both sanitary and storm wastewater flows resulting from the present and future needs of San Francisco. The Southwest Ocean Outfall will disperse these wastewaters at diffuser sections located well offshore in the Pacific Ocean. The outfall, a single conduit with an inside diameter of 3.7 m (12 ft), will be embedded throughout its length in a trench excavated as much as 8.4 m (25 ft) below the existing sea floor.

In order to evaluate some of the marine soil behavior, monitor marine siltation, and judge the effectiveness of floating marine equipment in the wave and current environment of the site, a Test Pit Program was conducted. Two test pits were excavated by a derrick barge to depths of approximately 8.4 m (25 ft) below the existing sea floor at locations 150 m (500 ft) south of the proposed outfall centerline. Test pit numbers 1 and 2 were located approximately 1.6 km (1 mi) and 3.2 km (2 mi) offshore in water depths of about 13 m (42 ft) and 16 m (53 ft) below mean lower low water (MLLW), respectively. Detailed bathymetric surveys were conducted on an approximately bi-weekly interval. Waves and near bottom currents were continuously measured in-situ. Figure 1 shows the location map of the project, and Figure 2 is a more detailed project map showing the test pits and oceanographic monitoring stations.

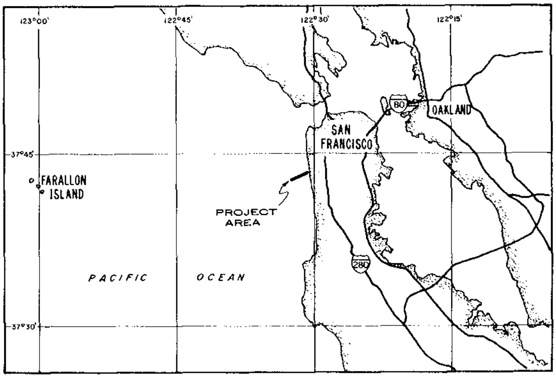


FIGURE 1

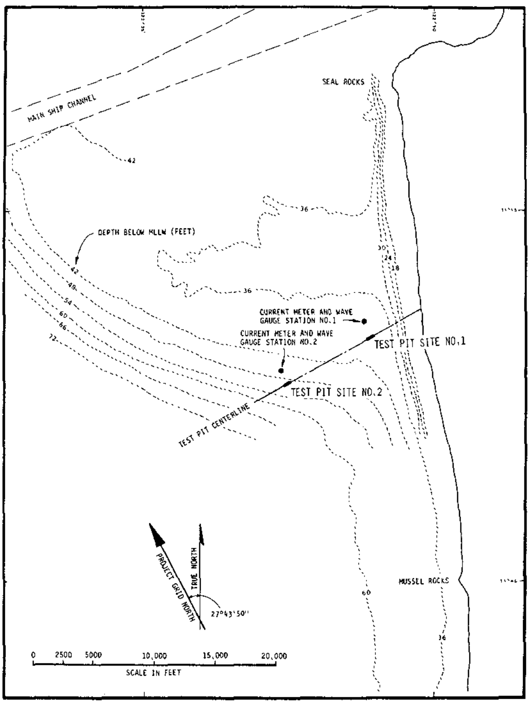


FIGURE 2

The original intent of the test pit program was to relate the measured siltation rates to the wave and current conditions in an empirical manner. However, the availability of this rather unique data set was an incentive to test a deterministic methodology to calculated siltation rates. The method developed by Madsen and Grant (1976) was selected as the basis for a computer program to calculate marine bedload transport and siltation within the test pits from the wave, current, and sediment data available from the SWOOP test pit program.

MEASUREMENTS

The measurements conducted during the SWOOP test pit program included waves, bottom currents, and sea floor sediment samples in addition to detailed bathymetric surveying. The methods, equipment, and techniques employed to make these measurements are discussed below.

Bathymetric surveying was conducted from the 20 m (60 ft) survey vessel POLARIS, using Raytheon Model DE719 survey fathometer with a hull-mounted, narrow-beam transducer. Horizontal positioning was accomplished with a Motorola Mini-Ranger III navigation system coupled to a data processor, terminal printer, and ship track plotter. Detailed surveys of the test pits were run using a grid with line spacing of about 24 m providing both primary and tie-lines. Tide height corrections were initially based on data collected visually from a shore station. Later, predicted tide levels for San Francisco was used as the two were well correlated. Considering all factors, such as position fixing, sea and swell, tides and variations in seawater sound velocity, the absolute accuracy in resolving depth was approximately ±0.3 m (±1.0 ft). Greater accuracy was obtained for differential depths between successive surveys, e.g., accuracy in resolving cut and fill at each test pit was approximately ±0.15 m (±0.5 ft) (Murphy, et al., 1979).

Bathymetric surveys were conducted at approximately two-week intervals from 4 September to 16 November 1978. The results of surveys conducted on 15 September, 4, 19 and 31 October and 16 November were used in the present study.

Seventy-seven sediment samples were obtained from the dredge clamshell, and 15 directly from within the test pits by SCUBA divers. SCUBA dives were made on September 5, September 20, and November 15, 1978. Thirty-nine of the 77 samples collected aboard the derrick barge and all of the diver-collected samples were seived to determine grain size distribution.

Two in-situ oceanographic instrument moorings were placed approximately 305 m (1,000 ft) north of the test pits at water depths of 13 m (41 ft) and 16 m (52 ft) below MLLW. An ENDECO Model 105 recording current meter was located 3 m (10 ft) above the sea floor on each mooring, and set to monitor at 30-minute intervals. Interocean Model WG/100 analog recording pressure transducers were incorporated in each mooring to measure waves. These operated only intermittently, and their data were of limited use to this study.

The current meters and wave gauges were initially installed on 15 August 1978, serviced on 20 September and 28 October and recovered on 15 November 1978, yielding a continuous record of currents for a period of 93 days. Due to numerous electrical and mechanical failures, only 21 days of data from one of the wave gauges was useful.

The lack of measured onsite wave data was partially offset by obtaining NOAA visual wave observations from Southeast Farallon Island, approximately 40 km (25 mi) offshore of the site (Figure 1). These observations consisted of swell height, period and direction, sea height and direction, and wind speed and direction, thrice daily. The steep offshore slopes around this island and its position well seaward of the project location made these visual observations reasonable estimates of the general sea and wind conditions.

DATA ANALYSIS

The data collected were analyzed both for engineering results and for the specific research aims of the present study, as discussed below.

The bathymetric records were reduced and corrected for tidal height by hand, and plotted according to the navigation data. In preparing successive bathymetric charts of each test pit, it was observed that the sea floor depths and morphologies beyond the edge of the test pits did not change significantly. Therefore, only changes in the shape and depth within the test pits were noted on subsequent charts. Examples of these charts are shown in Figures 3 and 4.

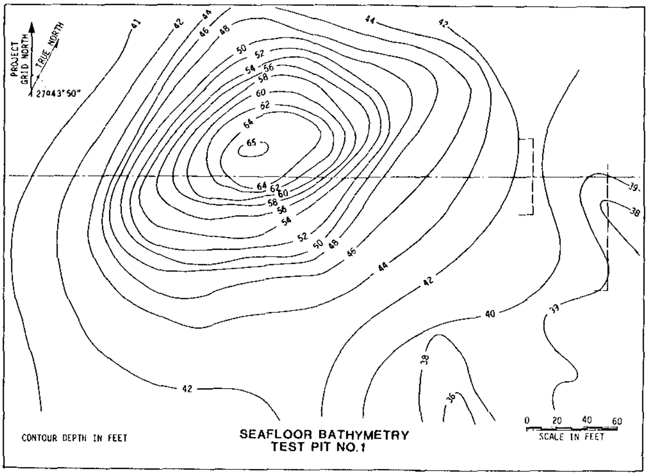


FIGURE 3

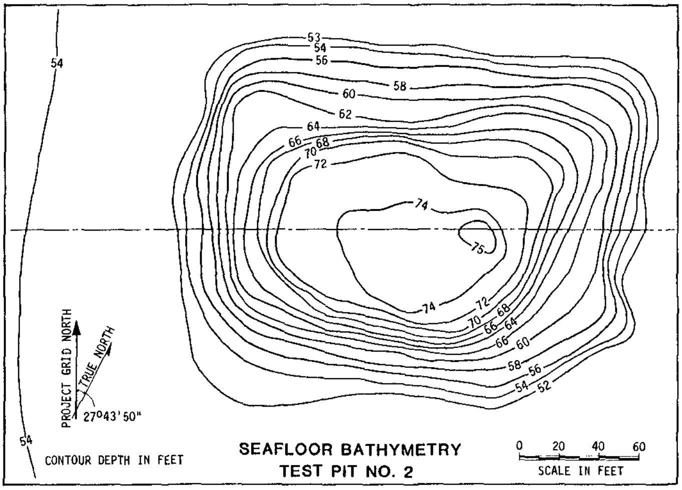


FIGURE 4

Sediment samples were analyzed using standard seiving procedures. The range of results are shown on Figure 5. Two shadings are used on this figure. One defines a band of gradation curves for the dredged sediments, and the other, gradation curves for sediments recovered by divers during the monitoring program, representing material recently deposited within the test pit. In general, both were very similar.

The film records from the current meters were processed to produce digital time series of speed and direction. Figure 6 shows a progressive vector diagram of currents at Test Pit No. 2 from the period 28 October through 15 November 1978. The figure shows net northeasterly drift with tidal oscillations.

As the field experiments were not planned to support a detailed sediment transport study, data on the vertical structure of the benthic boundary layer were not collected. For the purposes of the calculations, it was assumed that the current meters measured flow near the top of the benthic boundary layer. Data from other more detailed studies (Niedoroda, 1980; Niedoroda and Swift, 1981) suggest that 3 m is a reasonable estimate of the average boundary layer thickness at these distances from the shore. The method for computing marine bedload transport, described later, requires the depth averaged flow velocity over the thickness of the benthic boundary layer. In the absence of more detailed data, this was taken to be 80 percent of the measured values.

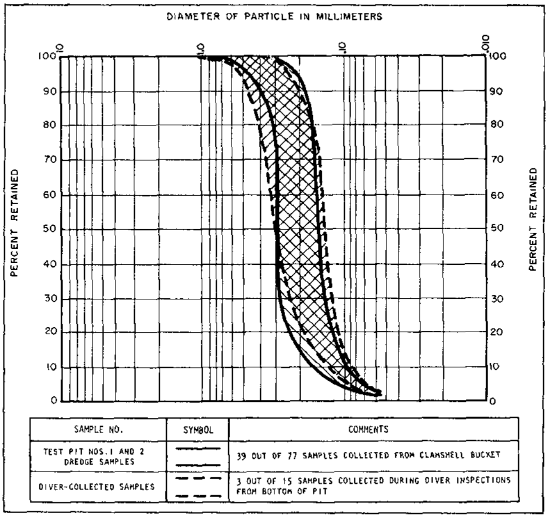
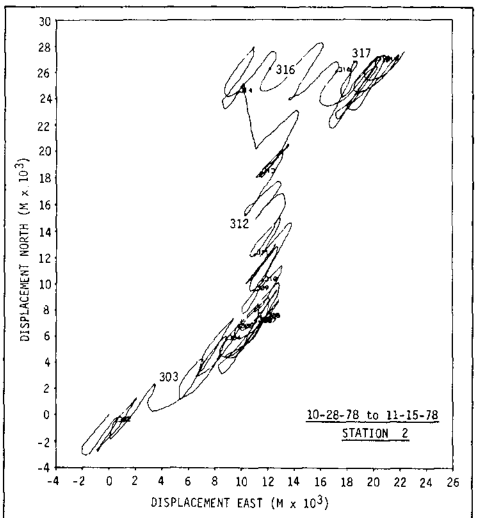


FIGURE 5



PROGRESSIVE VECTOR DIAGRAM OF CURRENT SPEED AND DIRECTION

FIGURE 6

The primary wave data used in this study came from the NOAA visual observations recorded at Southeast Farallon Island, 31 km (19.5 mi) south of Pt. Reyes and 42 km (26 mi) west of San Francisco; near the edge of the continental shelf. Refraction drawings show essentially no modification of wave heights of open ocean waves arriving there. The other Farallon Islands to the NNW are too small and distant to affect the waves from that direction. With care, it should be possible to make valid incident wave observations from Southeast Farallon.

The data from South Farallon Island were transferred to the test pit sites by the following procedure. As part of the previous coastal engineering investigation, a series of refraction drawings using 10 and 12 second wave periods had been generated, and used to evaluate the propagation of directional components of waves from 10 severe storms to the outfall site. Because of the dominance of the partial sheltering influence of Pt. Reyes, the storm waves were divided into directional components. For each storm, the incident height and direction, and the refracted height and direction at the site were found, and the "response curves" of Figure 7 generated. For varying incident wave direction, these curves give both the reduction in wave height and the change in wave direction due to refraction.

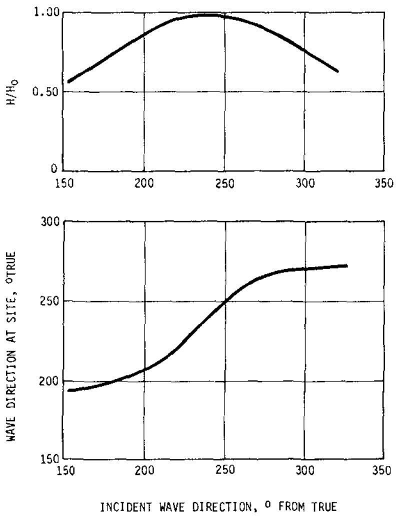


FIGURE 7

The actual location of the site referred to above is about 2.4 km (1.5 mi) west of the offshore test pit (No. 2); corresponding to the location of the outfall diffuser. Results of the wave spreading and refraction analysis at this site were considered representative because wave heights and directions measured at pits 1 and 2 showed smaller differences than the uncertainty in both the raw data and the refraction analysis.

The response or transfer curves of Figure 7 were applied to both sea and swell. Strictly speaking, this is not correct for the swell, because the curves were generated using a directionally spread wave typical of sea, not the more narrowly spread swell. In this case it was believed important to include the effect of directional spreading, even if slightly overestimated for swell, due to the importance of Pt. Reyes in providing partial sheltering from the predominant NW and NNW sea and swell.

The sediment transport analysis considers the combined effect of currents and one wave train. As both sea and swell were generally present and recorded separately, it was necessary to combine the two. Adding wave energy densities gives the following relationship for the equivalent wave height (H_e).

$$H_e = (H_w{}^2 + H_s{}^2)^{1/2}$$

where H_w and H_s are the height of the sea and swell, respectively.

This relationship ignores the effect of wave and swell directional differences on the near-bottom kinematics, but most of the time, the waves and swell were nearly from the same direction (i.e., NNW and NW).

In summary, the quality of the raw wave data, although poor by some standards, was better than that often available for engineering projects. A comparison of the significant wave heights computed by this method from the Southeast Farallon data with data measured at Test Pit No. 1 is given in Figure 8. When the significant wave height

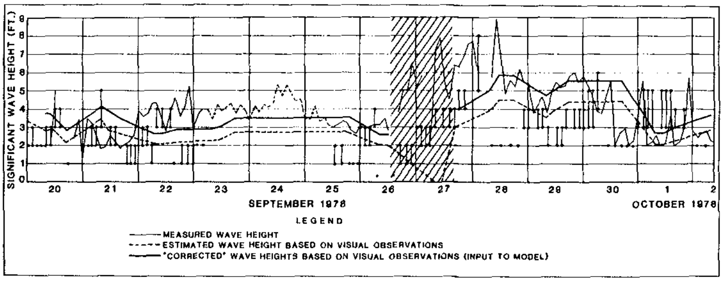


FIGURE 8

as measured (thin, irregular line) was compared to that from the corrected visual observations (heavy, dashed line), it was found that a 30 percent difference existed. This comparison excluded the period from the evening of 26 September to the evening of the 27 September, where the visual wave heights reported are suspect. The visual wave height estimates were thus corrected by a factor of 30 percent and are shown on this figure as a solid, heavy line.

MARINE BEDLOAD TRANSPORT CALCULATIONS

Several methods are available for computing marine bedload transport due to the combined effect of waves and current. The method selected for this study is given by Madsen and Grant (1976). This method was selected because: it incorporated the experimental work done by Jonsson (1966), Kalkanis (1964), Abou-Seida (1965), and several other researchers; the method is relatively straightforward to apply; and the input parameters were available from the field measurements.

The Madsen and Grant (1976) method uses the Einstein-Brown relationship to compute instantaneous bedload transport when the critical Shields parameter for sand entrainment is exceeded. The bottom shear stress formulation is the quadratic stress law where the instantaneous current is the vector sum of the near bottom wave orbital and the depth-mean benthic boundary layer velocities. The drag coefficient is in the form of Jonsson's combined wave-current friction factor.

A computer model was written to apply the method. The computer model used a two-dimensional 20 x 20 grid with 4.6 m (15 ft) spacing between grid points (the square defined by the grid points are referred to as elements) upon which the depths and local wave orbital velocities and near bottom depth-mean currents were specified. The orbital velocities were computed using Airy (linear) wave theory. The magnitude of the bottom boundary layer currents varied with depth to satisfy continuity. It was assumed that the structure of the near bottom flow is large in comparison to the size of the test pits and that no significant flow perturbations (e.g., large scale eddies) developed within the pits. A uniform mean sediment diameter of 0.22 mm was used throughout. A constant bedload flux boundary condition was imposed to eliminate erosion or deposition near the grid boundaries.

The bedload transport calculation was accomplished according to the following scheme. Wave and current data were entered at two-hour intervals. The instantaneous near bottom wave orbital and benthic boundary layer velocities were computed at each grid point for 17 sub-time intervals over a wave period (the near bottom current magnitude was also adjusted for the local depth). During each of the 17 sub-time intervals, the bottom stress (and in its nondimensional form, the Shields parameter) was computed from the resultant current. If the computed Shields parameter exceeded the critical Shields parameter, the instantaneous bedload transport was computed through the Einstein-Brown relationship. Otherwise the transport was set to zero for that sub-time interval.

Once the sediment transport flux at each grid point, for each of the individual sub-time intervals, was computed they were summed over the wave period, then divided by the wave period to determine the time-averaged rate of bedload transport. The calculation was done for all 400 grid points. The sediment continuity equation was then applied to each element to compute the net change in depth over the 2-hour time step. The program then read the wave and current data for the next two-hour interval and the above sequence was repeated.

It is important to note that gravitational effects were included in the Shields parameter in a bottom slope term (see Madsen and Grant, 1976, Appendix I). Madsen and Grant suggest a value of 0.07 for the coefficient in the term, while Fredsoe (1979) suggests a value of approximately 0.1 but points out that its actual value is poorly known. Evaluation of this coefficient was an important outcome of the present study.

In applying the results of the above-described program to the project data a problem arose with respect to defining an undisturbed seabed to serve as the datum for measuring siltation. The computer program showed small but significant erosion around the test pit lips; however, the data from the bathymetric surveys did not indicate any change in sea floor elevation outside of the pit. Therefore, computed erosion of the sea floor outside of the test pits was neglected when comparing the computed and measured values of siltation.

RESULTS

Prior to discussing results, it is important to review sources of error and uncertainty. The successive bathymetric surveys claimed accuracy in differential depth measurements of approximately ±0.3 m, corresponding to a volume difference over the area of siltation in the test pits of approximately 125 m^3 or a total error of approximately 250 m^3 (±) in estimating siltation from successive bathmetric surveys. The time history of infilling rates and associated error bars are shown in Figure 9. Inaccuracies in the wave data have been noted previously. The only complete time series of wave data is the transformed NOAA visual data. When these transformed data were used in raw form, they are identified as Wave Data 1. Where the wave heights have been increased by 30 percent (Figure 7) as previously discussed, they are referred to as Wave Data 2. Furthermore, in some numerical experiments the measured currents were used; whereas in others, depth mean bottom boundary layer current velocity was estimated as 0.8 times the measured current.

Measured and computed siltation rates for Test Pit No. 1 are shown on Figure 9 (the measured values with corresponding error bars). The dashed curve shows computed siltation rates using Wave Data Set 1 and the full value of the measured currents. The dash-and-single-dot curve shows the siltation rate computed using Wave Data Set 2 and the the measured currents. The dash-and-3-dot-curve shows the siltation rates using Wave Data Set 2 and the estimated depth mean value of the near bottom currents. In computing each of these curves, the value of the gravitational constant in the Shields parameter equation was 0.1. From the data shown on this figure it was concluded that Wave Data

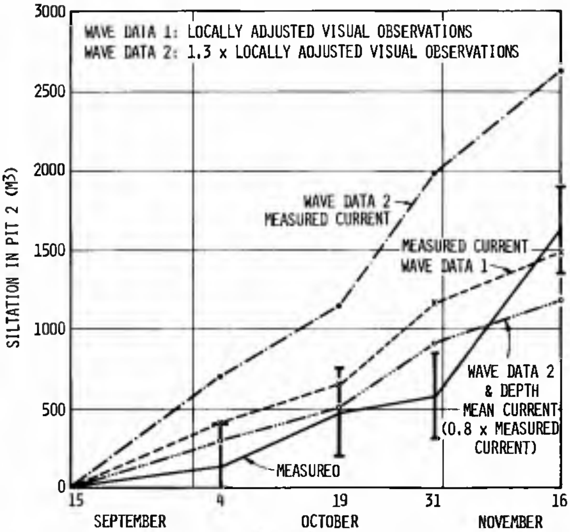


FIGURE 9

Set 2 and the depth mean value of the near bottom currents was most appropriate. Each of these curves could be adjusted by changing the value of the gravitational constant in the Shields parameter equation.

A series of numerical experiments were conducted to evaluate the gravitational constant (c_s) in the equation for the Shields parameter. Perfect overall agreement could be accomplished for measured and computed siltation at Test Pit No. 1 using the value of c_s of 0.123, as shown in Figure 10. It should be noted that computed

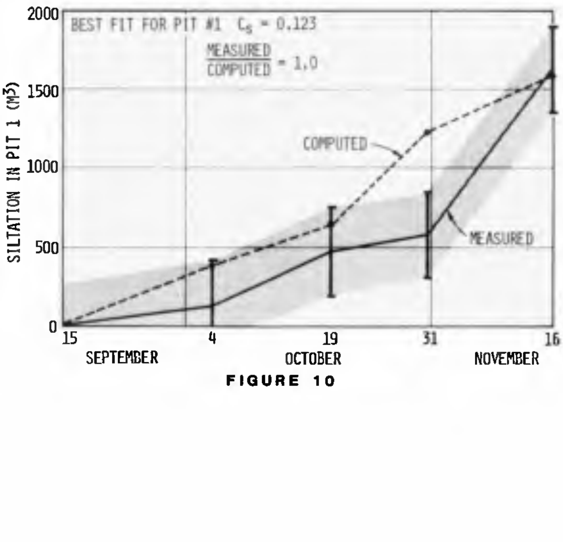


FIGURE 10

values of siltation are higher than those measured at the intermediate surveying dates. However, at two of these three points, the computed values lie within the range of error in the surveyed values. When this value of the gravitational constant in the Shields parameter equation is applied to data from Test Pit No. 2, the amount of siltation was underestimated (Figure 11). In order to accomplish perfect agreement in the overall measured and computed siltation for Test Pit No. 2 a value of c_s of 0.193 was required. In this case, the projected siltation for the intermediate survey data is less than the measured value. Nevertheless, the computed value is within the measurement error.

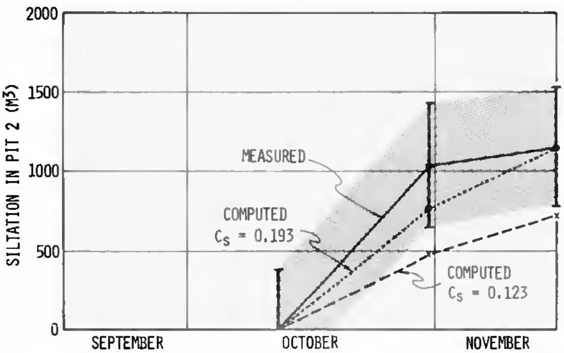


FIGURE 11

Figure 12 shows corresponding data for both Test Pit No. 1 and Test No. Pit 2. A value of c_s of 0.14 yields the best qualitative agreement for the data from both test pits. The difference between measured and computed siltation values is about 14 percent for Test Pit No. 1 and 28 percent for Test Pit No. 2. The value of the coefficient was selected to fit the data at Test Pit No. 1 better than that at Test Pit No. 2 because of the larger number of surveys and longer duration of measurements at Test No. Pit 1. Considering the rather large uncertainties in all of the measurements in this study, as well as those typical of marine engineering studies, the agreement between measured and computed siltation rates is reasonably good.

The computed siltation rates have been shown to depend on wave heights, wave periods, near bottom currents, and the gravitational constant in the equation for the Shields parameter (c_s). A series of numerical experiments were conducted to reveal the sensitivity of the computed siltation rates to variations in these parameters. Figures 13, 14, 15, and 16 show the sensitivity of siltation to variations in wave height, wave period, depth mean near bottom currents, and c_s, respectively. Figure 13 shows that siltation calculations are extremely sensitive to wave height and therefore errors in measurement of wave height significantly affect the reliability of projections. Figure 14 shows a more complex relationship to variations of wave period. If wave periods are higher than their true

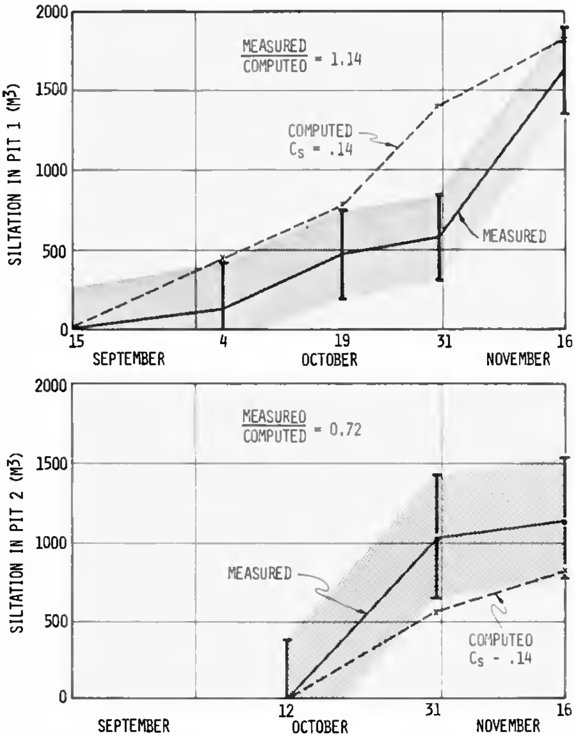


FIGURE 12

value the computed siltation rate decreases because the increase in wave period results in lower wave orbital valocities. If the wave period is decreased from its true value, the computed rate of siltation first increases and then dramatically decreases. This trend illustrates that given the depths of the test pits there is a narrow band of shorter wave periods for which near bottom orbital velocities are increased. Waves with even shorter periods produce lower near-bottom wave orbital velocities due to the depth-decay in orbital velocities. Figure 15 shows that computed siltation rates are less sensitive to variations in the magnitude of depth averaged near bottom currents than they are to waves. Figure 16 shows a linear relationship between the siltation rate and the constant in the gravitational term of the Shields parameter equation.

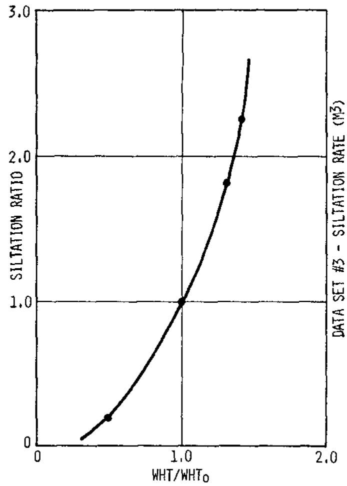


FIGURE 13

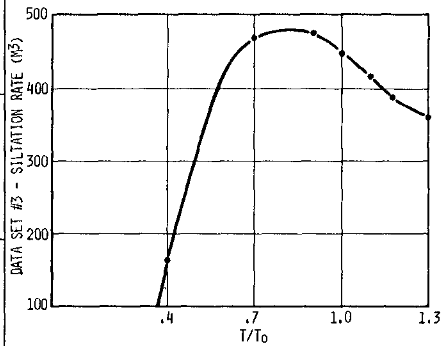


FIGURE 14

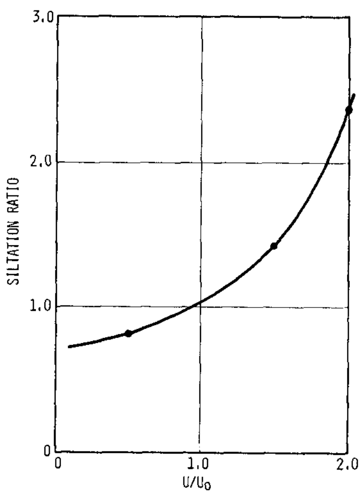


FIGURE 15

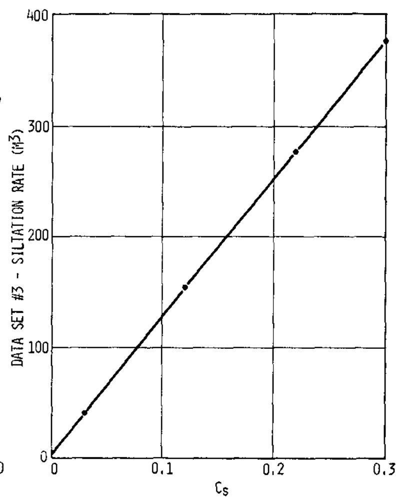


FIGURE 16

CONCLUSIONS

The Madsen and Grant analysis, based in part on laboratory experiments, appears to provide a sound basis for estimating bedload transport caused by the interaction of waves and currents beyond the breaker zone. Input data required of the analysis are commonly collected for coastal engineering projects or developed from other data sources as illustrated herein for the wave data.

The effect of bottom slope was important in this study and was varied (by varying the multiplicative coefficient in the term) to achieve better agreement between the predicted and measured siltation. The value of the coefficient for best fit for net sedimentation in each test pit was 0.12 for Test Pit No. 1 and 0.19 for Test Pit No. 2. The value of the coefficient for best fit for net sedimentation in both pits was 0.14. This value resulted in a maximum difficiency between measured and predicted sedimentation of about 25 percent.

The accuracy of predictions of marine bedload transport and corresponding erosion or siltation is controlled by the accuracy of input parameters in the following order: wave height, current speed and direction, bathymetry, sediment diameter, and wave period.

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