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PHOTOGRAMMETRIC EXPERIMENTS ON NEARSHORE MIXING AND DIFFUSION

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ABSTRACT

Aerial multispectral photography and fixed point metering were used in the study of coastal currents at two sites in California. The system combining current meters, low-altitude photography and photodensitometric analysis of the suspended matter or tracer dyes is well suited to the study of both advective and diffusive processes in the ocean. Experiments were carried out in the vicinity of marine structures for the purpose of understanding their influence on coastal circulation.

INTRODUCTION

Sėlecting the site of a marine structure on an open coast is usually preceeded by comprehensive surveys on nearshore bathymetry, local wave regime, wind and frequency of storms, coastal currents and resulting littoral transport. The structure, when completed, will alter the flow circulation patterns in its vicinity and the magnitude of this change is difficult to predict. Unexpected and unwanted accumulations or erosion of sand, currents of excessive velocity, appearance of breaking waves in areas of navigation are commonly considered design failures, when in fact their prediction from open-coast processes is not possible on account of the complexities of nearshore environment.

To understand some of these processes, and to relate them to engineering use, we have initiated a program for the study of coastal currents about various structures used in shore protection and navigation. One phase of this program consists of measuring currents in situ and surveying the shore-normal distribution of currents with meters mounted on a sea-sled (Fig. 1). In experiments of the past two years data collected with four ducted-impeller current meters have been stored as analog records on board the sled (Fig. 2). During the next field experiment all data will be telemetered to shore, digitized and recorded on tape.

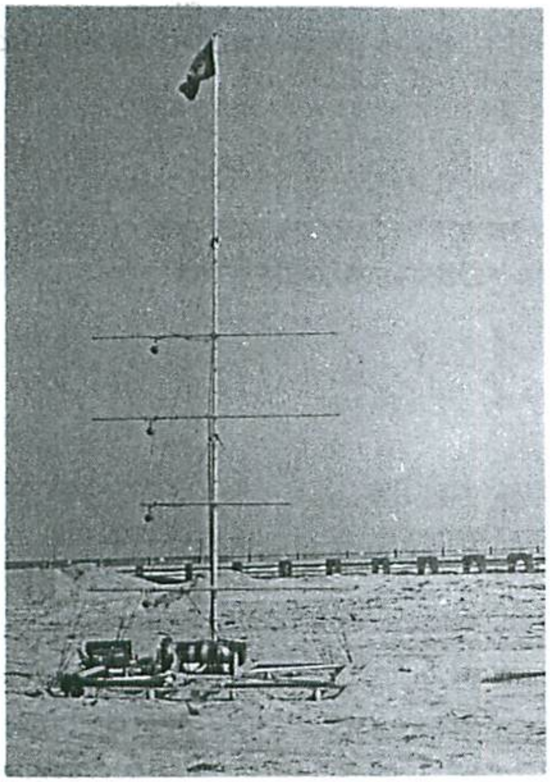

Figure 1. The sea-sled instrumented with current meters at Pt. Mugu, California. The cross-members are adjustable vertically and horizontally and so is the position of each metering device. The sled, towed by an amphibious vehicle, can operate both shoreward and seaward of the surf zone.

In the early stages of development there was a certain shortcoming to this system, owing to the spatial and temporal variability of currents near the shore. To paraphrase Neumann (1), ocean currents can only be described correctly with the concurrent applications of Eulerian and Lagrangian methods. The sled-mounted meters enabled collecting the former of these two types of data. To obtain the Lagrangian information the well-known technique of tracing with dyes, injected into the ocean as point or continuous sources, and recording them by means of aerial photography had to be utilized.

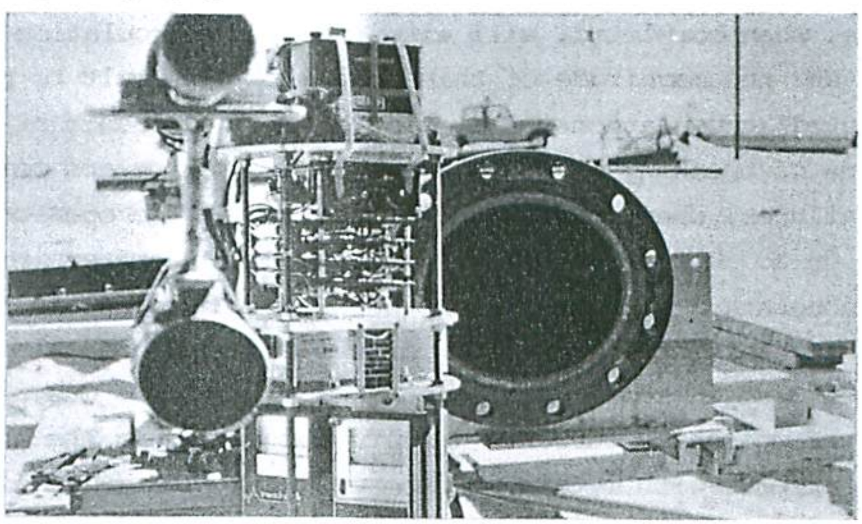

Figure 2. Close-up of the duct and five-bladed impeller of the current meter. To the right is the analog data collection unit which is housed in a water-proof cylinder and rides on the sled.

This paper summarizes efforts to this date for the identification and tracing of water masses in the vicinity of marine (engineering) structures, using both metering and low-altitude photography of dye dispersion, with the emphasis placed on certain photogrammetric procedures used for the extraction of information from the collected imagery. All field studies were conducted for the purpose of understanding what influence engineering structures (such as groynes and breakwaters) have on coastal currents (and specifically on their shore-normal distribution at the surface and the bottom) and how this is related to sand transport. Tracing with dyes is not only suitable to the study of these advective processes, but also to the study of oceanic mixing (2), waste disposal in marine and estuarine environments (3, 4) and for the identification of areas of biological productivity (5).

SOME THEORETICAL CONSIDERATIONS

When photographing the coastal zone, one will frequently notice eddies of various dimensions. Their presence does not explicitly signify that the associated flow is turbulent. It does indicate, however, that mixing is taking place. Mixing can be regarded as a diffusive process which tends to produce uniformities in the properties of the flow (2). Molecular diffusion, which contributes to mixing, is a process through which the transfer of a given property takes place always from higher to lower concentrations. This is not a requirement of turbulent diffusion. When there is spatial variation in the mean fluid velocity (as in nearshore waters), molecular and turbulent diffusion cannot be considered to be identical to the mechanism of mixing, although both induce it.

In addition to experiencing diffusion, water masses are also advected, due to, e.g. a gradient of the ocean surface. One of the best methods for studying advection and diffusion in coastal waters is to inject known quantities of a tracing substance, such as fluorescent dye, which then assumes the main characteristics of the flow itself. Although not every water soluble dye is stable either chemically (6) or spectrally (7), we assume that the tracer remains a conservative substance for the duration of study and write the diffusion equation as:

$$\text{(1)} \qquad \frac{dc}{dt} = \frac{\partial}{\partial x}\left(k_x \frac{\partial c}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial c}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial c}{\partial z}\right)$$

where c is the diffusing quantity, t is time and k_x, k_y, k_z are the diffusion coefficients in Cartesian coordinates. In the presence of an advective mechanism equation 1 becomes:

$$\text{(2)} \qquad \frac{dc}{dt} = u\frac{\partial c}{\partial x} + v\frac{\partial c}{\partial y} + w\frac{\partial c}{\partial z}$$

where u, v and w are components of a current in the coastal zone.

Introducing turbulence: $u = \overline{u} + u'$ etc., eddy diffusivity: $\overline{u'c'} = -e_x\, \partial c/\partial x$ etc. and combining equation 1 and 2, we get

$$(3) \quad \frac{\partial c}{\partial t} + \bar{u}\frac{\partial \bar{c}}{\partial x} + \bar{v}\frac{\partial \bar{c}}{\partial y} + \bar{w}\frac{\partial \bar{c}}{\partial x} = (k_x + e_x)\frac{\partial^2 \bar{c}}{\partial x} + (k_y + e_y)\frac{\partial^2 \bar{c}}{\partial y} + (k_z + e_z)\frac{\partial^2 \bar{c}}{\partial z}$$

which is averaged with respect to time. According to (8) we can rewrite the convective terms on the left hand side of equation 3 as:

$$(4) \qquad (\alpha_x + \frac{h-\eta}{2}y)\frac{\partial \bar{c}}{\partial x} = \bar{u}\frac{\partial \bar{c}}{\partial x} \text{ etc.}$$

so that the principal mechanisms of vorticity ($\eta \equiv \partial\bar{v}/\partial x - \partial\bar{u}/\partial y$), stretching deformation ($\alpha \equiv \partial\bar{u}/\partial x = -\partial\bar{v}/\partial y$) and shearing ($h \equiv \partial\bar{v}/\partial x + \partial\bar{u}/\partial y$) become explicit.

Equation 3 describes both advective and diffusive mechanisms for the transport of dye in turbulent flow. Its solution depends on the mode of dye injection and such factors as whether the flow is meandering. Its use for engineering purposes also depends on the correctness of estimates obtained for e_x, e_y and e_z often computed from $e_x = d(\sigma_x^2)/2dt$ etc. Although most experimenters confirm that Richardson's "4/3-law" applies in deep oceanic waters, according to the Allan Hancock Foundation studies (5), the mean square dispersion along the x-axis, σ_x^2 in coastal waters is not linearly related to diffusion time t unless the turbulent eddies are smaller than the dye patch (i.e. mixing is thorough). That is, (assuming constant energy dissipation) when the eddies are larger than the dye patch (as in the beginning of an experiment when mixing is light) $\sigma_x^2 \propto t^2$, and when eddies and the dye plume are comparable in size $\sigma^2 \propto t^3$ and mixing is accelerated.

The significance of this is in the interpretation of sequential photographs of the dye. Shortly after releasing the tracer the interfacial area between the dye and the surrounding waters is small, only molecular diffusion is active, and the spread of the dye from its source is slow. Continuous penetration of the plume by turbulent eddies increases the areal extent of the interface as a direct function of time, and gradually mixing begins to dominate diffusion resulting in an accelerated dispersion of the tracer. Consequently, photographic records of dye displacement in the early stages will underestimate the true surface current velocity, because dye dispersion is slow.

FIELD EXPERIMENTS

Since 1971 several field experiments have been conducted with the combined sled-aerial photography system, concurrently with radioisotopic sediment tracing tests (9) for the purpose of recording water velocities and mapping circulation patterns in the vicinity of engineering structures. Two of these experiments are described herein, the first of which was at the site of the CERC experimental groyne at Pt. Mugu, California; the second at Oceanside Harbor, California.

In the April 16, 1972 field study fluorescent dyes were released near-simultaneously at depths of -4.7, -17, and -27 feet (-1.43, -5.18 and -8.23 m) on a line normal to shore (Fig. 3). In the inner-and outer most injections Uranine B dye (Fig. 4) was used, in the center Rhodamine B. The sea-sled was

Figure 3. Dye streak at Pt. Mugu on April 16, 1972 at 15:18. Current is moving southward.

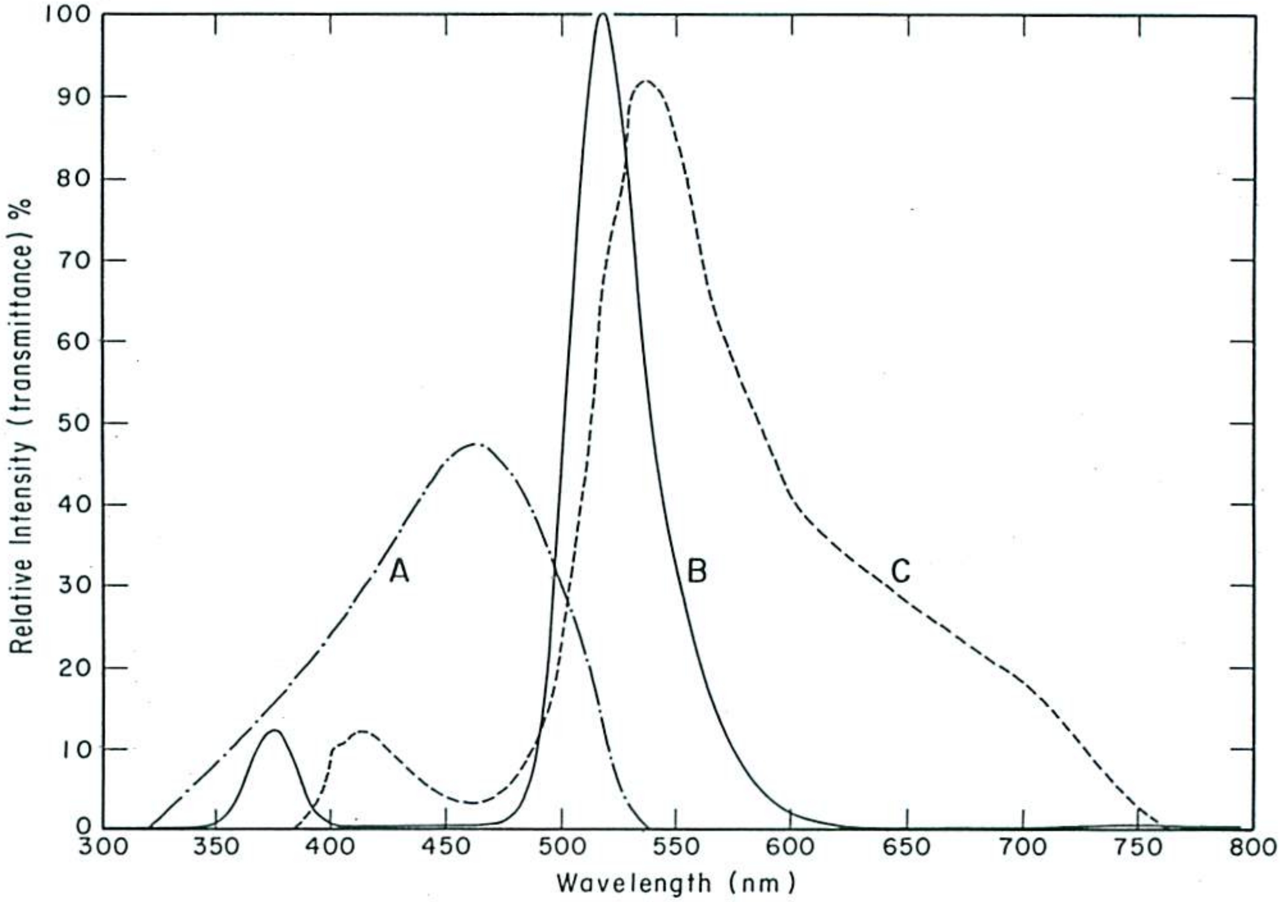

Figure 4. Spectral response of Uranine B dye in the visible region; "A" is the absorption curve indicating maximum emission is reached near 550 nm, "B" is the fluorometric record for a solute concentration of 2×10^{-11} in sea water and the excitation peak of 366 nm and "C" is the reflectance curve of the dye on an ocean surface simulated in outdoor tank tests.

towed to the point of release for the Rhodamine B dye and current speeds were recorded at 1.14, 2.29, 3.43 and 4.57 m above the bottom with the meters oriented in the shore-parallel direction.

Aerial photography of the propagation of the dye patches commenced at the time of injections. A cluster of four 35-mm format Yashica cameras with 52 mm focal lengths were used. Images were recorded simultaneously on four types of films: Agfachrome, Kodak High Speed Ektachrome, Kodak Color Infrared and GAF (experimental) minus-blue film (10).

Sequential photography of ocean currents is a well-known and much practiced technique (11, 12, 13). Vertically oriented cameras are used generally, although Burgess and James (4) prefer oblique photography to eliminate direct sunlight reflection from the rough sea surface. In the Pt. Mugu experiments images were also recorded obliquely, but not with a fixed tilt. As a result each frame had to be rectified independently using the principles outlined in Fig. 5, for a four-point reconstruction on a Zoom Transfer Scope (this instrument also enables matching the scales of photographs and the base map).

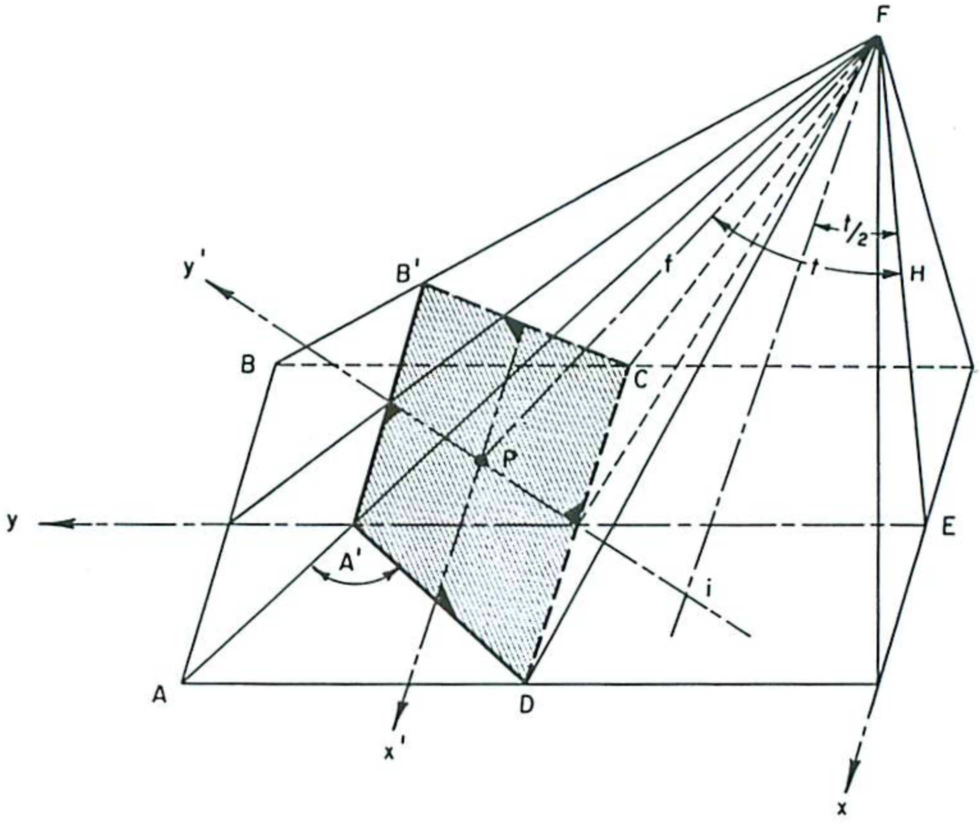

Figure 5. Scale distortion diagram for oblique aerial photography (after Bondarenko and others, 1972). ABCD represents the area photographed on the ocean surface, A'B'CD is its image recorded on film. The optical axis (f) between the focal point (F) and the principle point of the photograph (P) is displaced from the vertical by the angle of tilt (t). The intersection of the tilt axis with the principal plane determines the isocenter (i). Flight altitude is H and the direction of flight is along the x-axis.

Of the three dye injections, the one nearest the shore diffused rapidly across the adjacent breaker zone and could not be traced. Rhodamine B dye released at the intermediate point on the line was not visible nor could it be recorded on film. The outermost dye was recorded for the duration of one hour as it was advected south past the groyne.

In the second experiment, conducted at Oceanside, California in February 1973, dyes were again used to study the circulation patterns (Fig. 6) in connection with a study on shoaling and sand by-passing in the harbor. In addition to data collected on dyes, rather severe wave conditions generated a series of sediment plumes near the breakwater which were sequentially photographed. Using optical rectification described earlier, individual sediment vortices were traced from their origin at the outer dog-leg of the structure to some distance past the harbor entrance. The phenomenon observed resembled Karman vortices appearing behind obstacles in fluid flow, except that only one half of the vortex-street was present.

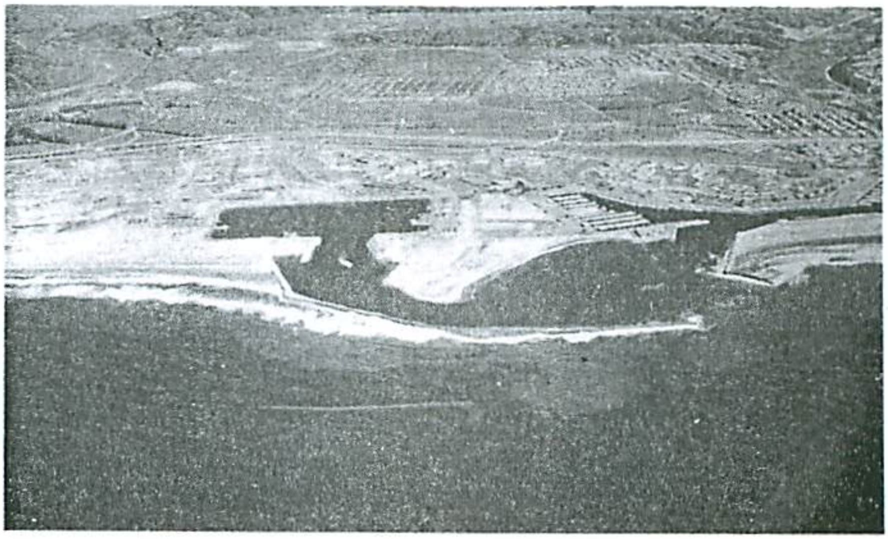

Figure 6. Dye streak near the breakwater at Oceanside harbor, California, on 26 January 1973 at 13:16. Current is moving toward the south.

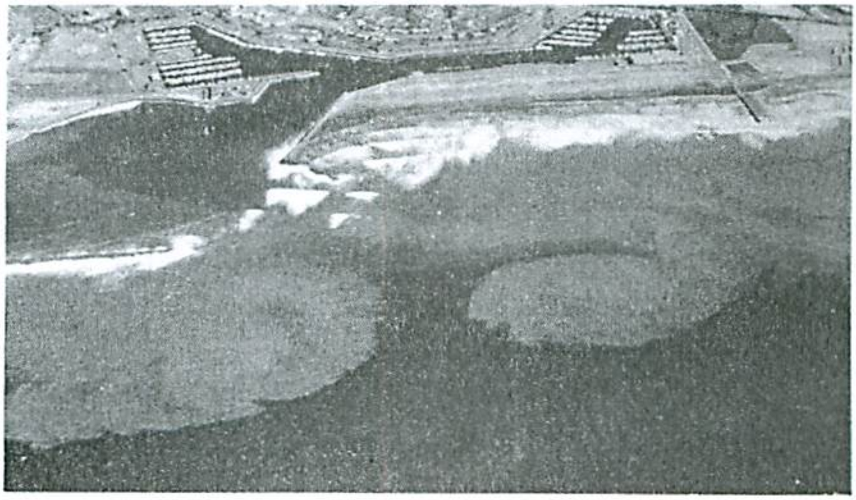

Figure 7. Sediment suspended in an eddy which was generated at the dog-leg of the breakwater (to the left) is undergoing dispersion and possibly deposition at the harbor entrance.

Each vortex, and especially its centroid, can be viewed as a tracer of the water mass and as an indicator of the turbulent eddy structure in nearshore waters (Fig. 7). To determine where the center of the mass of suspended matter was at a given time and what the relative concentration gradients were, images can be densitometrically analyzed (Fig. 8).

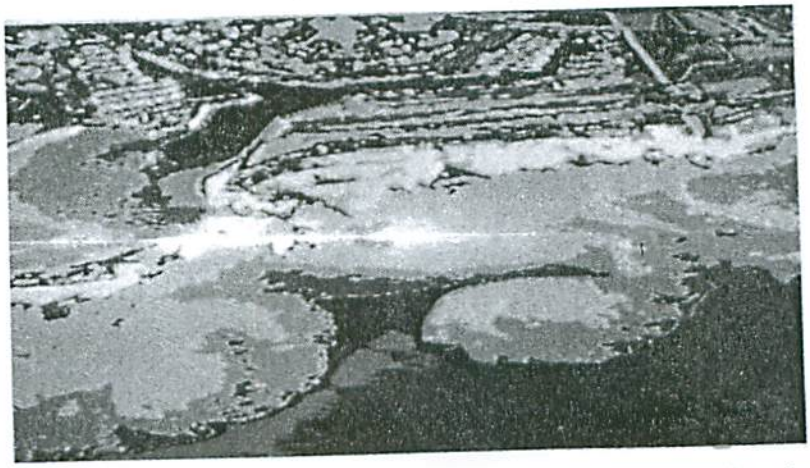

Figure 8. Densitometric slicing of preceding photograph in 14 steps shows that the clockwise motion of sediment generates steep density gradients near the edge of the vortex.

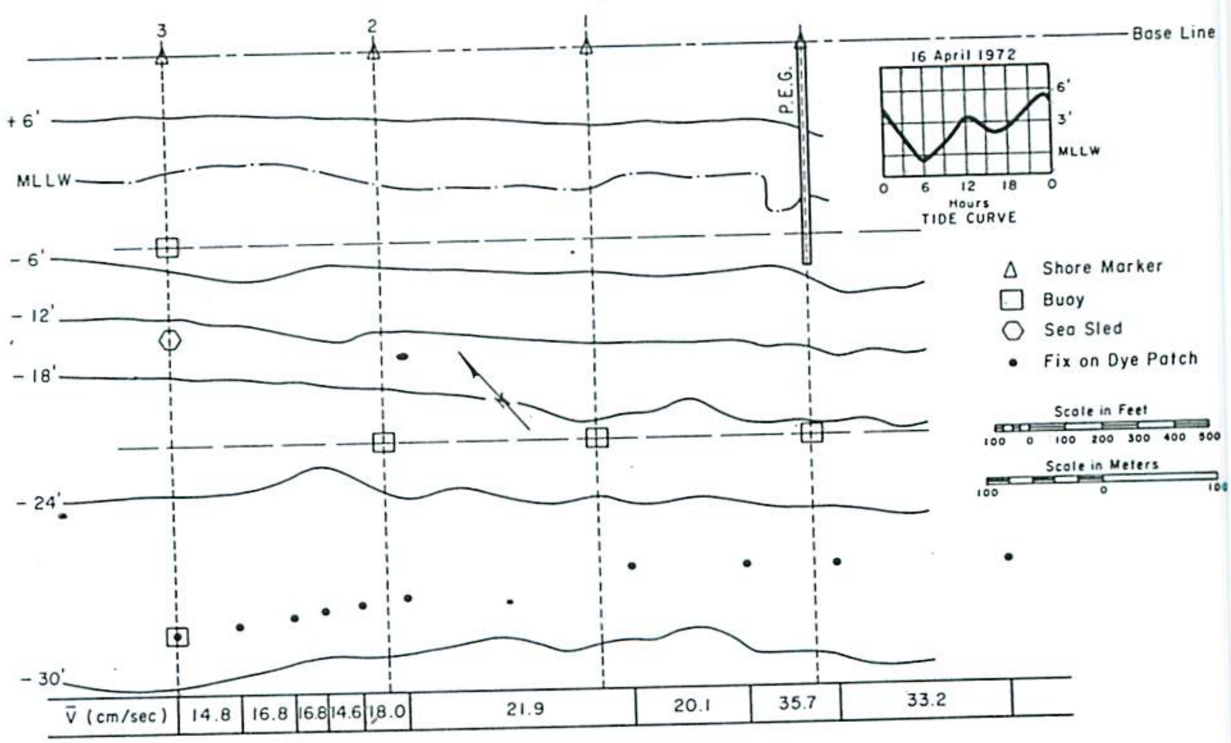

Figure 9. Surface current velocities above the -27 ft (8.23m) depth contour at Pt. Mugu, California on April 16, 1972 calculated with the time-of-travel principle. Dye propagation shown is the outer most of three continuous-source releases. Buoys and shore markers serve as ground targets for the rectification of oblique images.

DATA ANALYSIS

In the Pt. Mugu experiments surface current velocities were calculated from the displacement of the leading edge of the dye plume between two consecutive frames (Fig. 9). As expected from diffusion theory, initial transport from the injection point was slow because at the outset the variance of diffusion is a function of diffusion time squared. True surface velocities may have been attained by the dye patch when it reached the vicinity of the groyne (shown in Fig. 9) or approximately 1600 feet from the source.

Current velocities obtained from photography of the seaward most dye source are compared in Table 1 to records obtained from the current meters situated at four elevations in 5.2 meters of water. Information from the four meters is represented as one-minute averages of 25 data points in the time interval indicated.

TABLE 1

Comparison of Current Velocities
from Dye Travel and Current Meters

Time (hr:sec)	Dye Transport (cm/sec)	Average current speed 4.57m	3.43m above bottom (cm/sec)	2.29m	1.14m
14:37 - 14:40.5	14.8	26.28	18.71	19.01	14.81
- 14:45	16.8	23.35	18.41	18.09	12.17
- 14:48	16.8	24.63	20.90	18.13	13.32
- 14:51.5	14.6	27.77	21.9	20.65	16.19
- 14:55	18.0	24.50	19.69	23.04	16.33
- 15:10	21.9	28.50	22.44	26.20	20.16
- 15:18	20.1	30.78	25.68	17.28	12.11
- 15:21.5	35.7	29.08	25.97	15.69	10.85
- 15:29	33.2	24.15	23.58	20.48	14.63

Data from the meters represent summary amplitudes, i.e. tidal, wind, wave or geostrophic components have not been subtracted. Although dye and metered data were obtained in different water depths, the amplitudes of current speed are of the same order of magnitude as the rate of dye transport.

A pilot estimate of the frequency distribution (14) of metered current speed near the surface (Fig. 10) shows that most of the record is in the low frequency region of the spectrum. When results of both the dye study and the histogram are considered, it is seen that the non-uniform shore-parallel flow is quasi-steady.

Current speed from the dye plume was calculated to be 33.2 cm/sec between 15:21 and 15:29 (hours) or approximately 9 cm/sec faster than the value recorded at the sled 30 cm below the sea surface (adjusted for tide). The difference is response to the presence of flow convergence in the horizontal plane near the groyne, commonly observed when dye sources are located closer to shore. In convergent flow, mass transfer is accelerated and shearing occurs in the

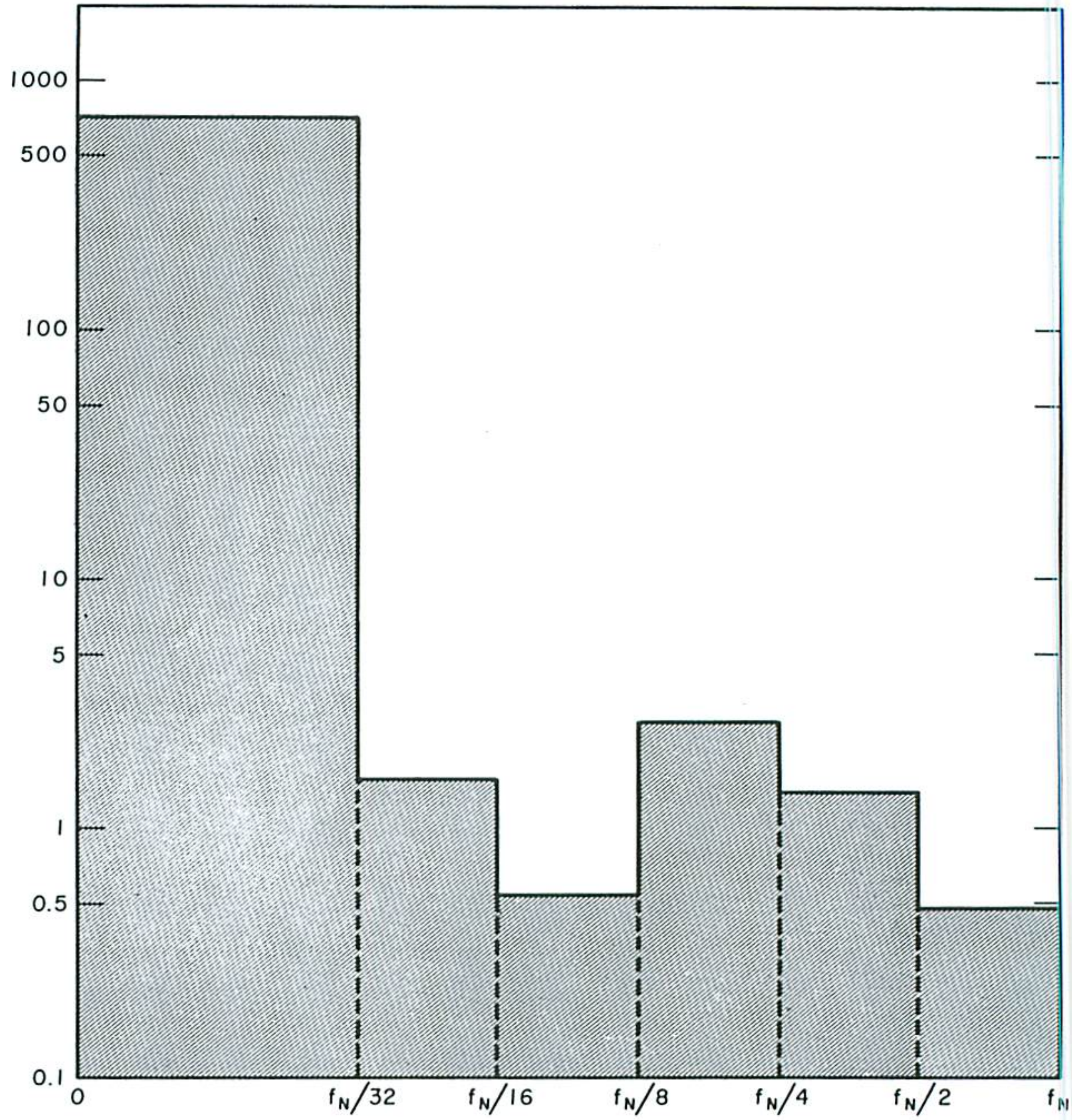

Figure 10. Blackman-Tukey pilot-estimate of the frequency distribution of current meter data indicates that the records contain mostly low frequency signals. $f_n = \frac{1}{2\Delta t}$ is the Nyquist frequency, where $\Delta t = 2.4$ sec.

horizontal plane. The groyne, acting as a partial barrier to longshore flow deflects water of higher particulate content (therefore greater density) sea ward, producing a one-sided convergence (15). In such a case, Defant states lighter water is often forced by the wind to spread out over the heavier mas a phenomenon we have observed with the GAF blue-insensitive film at Pt. Mugu whereby a dye plume is propagated seemingly undisturbed across a rip current (Fig. 11).

Konovalova (12) reports surface current velocities to increase with distance from shore in the Black Sea. Adding the information gained from th

Figure 11. Photographs of the nearshore zone taken with Ansco PF-17 (blue-insensitive) film shows the undisturbed propagation of a dyed water mass across a rip current.

Pt. Mugù tests, it can be seen that good correlation between distance from shore and velocities is shown by only one data point (Fig. 12). This point represents the diffusive state of the dye shortly after injection. Although the coastal circulation patterns may not be similar, and channeled flow is thought to be present at Pt. Mugu, results should be more comparable if advection had been calculated for the center of the dye mass rather than its leading edge. This

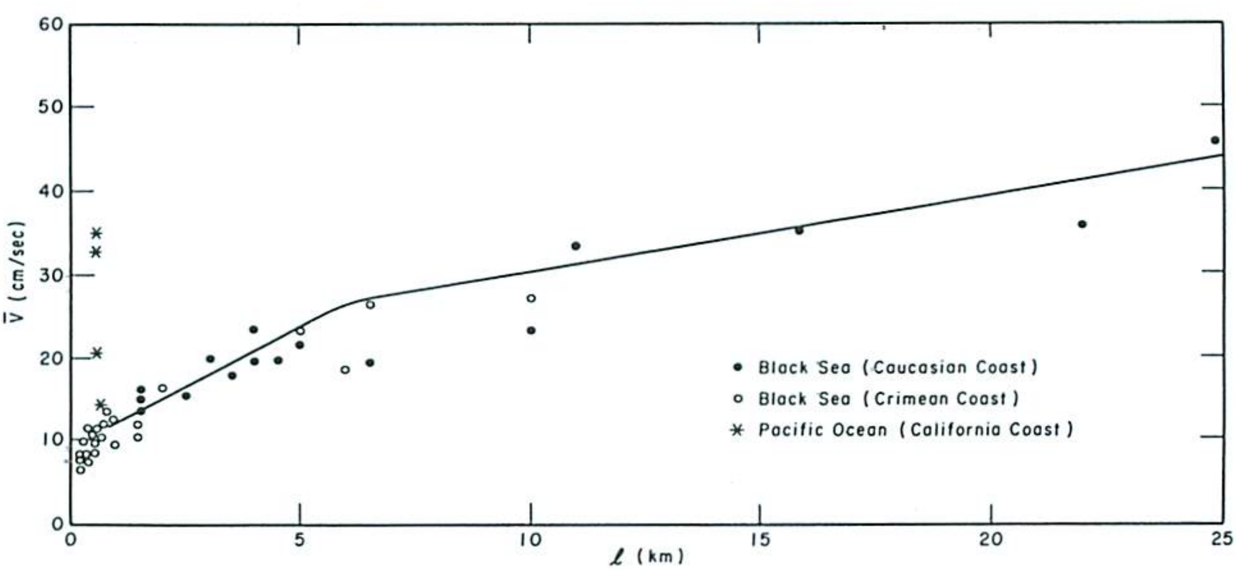

Figure 12. Velocities at the California coast determined from dye experiments exceed similar data collected by Konovalova (1972) for the Black Sea, except in the early stage of diffusion. The difference may be due to the channeling of flow in the Santa Barbara basin, but more likely to the differential diffusion rates for the total mass and its leading edge.

was not possible to do densitometrically as the area represented by the dye patch on the imagery was too small. The subject of shore normal velocity gra- dients nevertheless is an important facet of this research and will be further investigated.

Singularities in the current field were also observed in the January 1973 experiments at Oceanside, California. For several days waves were breaking against the breakwater (Fig. 7) and sediment-laden vortices were observed to be generated at the outer dog-leg of the structure. This phenomenon took plac in an area of accelerated flow, bounded on one side by the breakwater, and partly bounded on the seaward side by wave momentum flux. The eddies were tra ported without apparent changes in dimension to the harbor entrance where, thi being an area of divergence and reduced velocities, the eddies spread out and gradually dispersed.

As mentioned, accurate determination of the centers of mass in the eddies with digital density slicing was not successful, as technical difficulties kep us from setting the 32 density levels necessary for precise contouring. Inste 12 contours were used. Therefore the estimates obtained for the transport rat of the eddy (in Fig. 13) is based on mapping the position with time of the trailing edge. This edge was determined from reading the density gradient of the film across the edge of the plume. Current meter data were not collected in these experiments. Results of the dye studies have not been reduced to the point of allowing comparisons of propagation rates between dye and sediment.

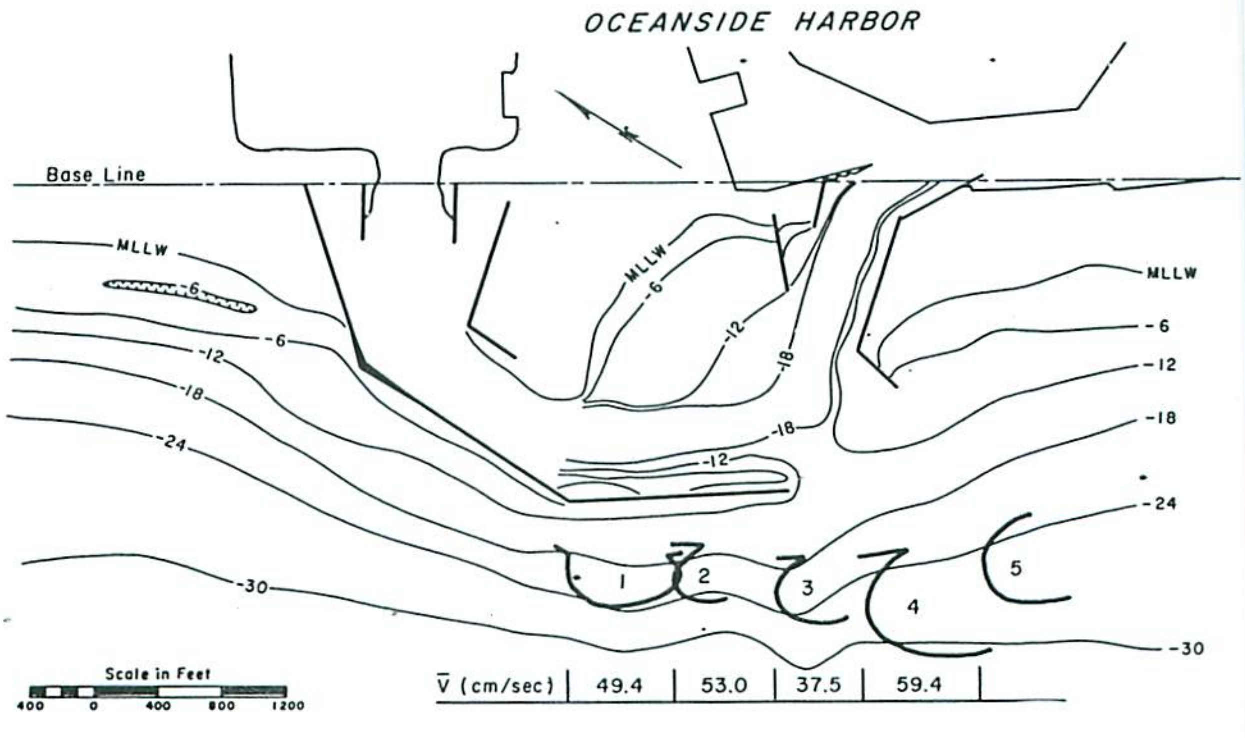

Figure 13. Transport velocities for a single eddy were obtained from rectifying oblique imagery of Figure 7 and mapping the position of the trailing edge in successive photographs.

DISCUSSION

The study of diffusion and turbulent mixing in the nearshore ocean with aerial photography and photogrammetric techniques is necessary for the proper interpretation of current measurements with stationary instruments. It must be realized, however, that there are as many gaps in the general knowledge about these processes, as there are in our methods of study and analyses of the data to date.

From the viewpoint of marine resources, the properties and processes of the continental shelf will come under greater and greater scrutiny. One of the first items on the list of research needs is the comprehensive study of coastal currents, whether it is in regard to site selection for marine structures, fishing resources, offshore construction or other tasks. Specifically, the following processes and problems need investigation: The shore-normal gradient of coastal currents, identification of water masses and singularities in the flow field and current velocities near the bottom. We have taken steps to study one of these; the identification of water masses from different sources (7).

In subsequent tests we intend to improve our analytical techniques by applying photodensitometry to the dye plumes, as we did to the sediment plumes, complimenting the work of Ichiye and Plutchak (16). This will require measuring dye concentrations at selected points, but at considerable savings in time and cost, to the practice of hydrographic surveys.

ACKNOWLEDGEMENTS

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