Temporal and spatial variability of bottom sedimentation for survey periodicity

P. C. Chu & N. S. Wheatley
Department of Oceanography, Naval Postgraduate School, Monterey, California, USA

Abstract

Bedforms determine survey periodicity. Sediment grain size, tides, currents, and wind-generated waves are influential in bedform formation. To investigate if sediment properties change over time, localized grab samples for a three-year period in San Francisco Bay were analyzed. The analysis showed little variability in sediment characteristics at a given location. A weighted suitability model based on the United Kingdom Hydrographic Office (UKHO) model has been constructed. Three layers were developed including sediment grain size, interpolated from 174 grab samples, tidal and current data from over 50 current stations and ripple height inferred from wind generated wave height. A weighting for each layer was determined. Regions indicating the presence of bedforms were assigned a low survey periodicity; as bedforms reduced, survey periodicity was increased.
Keywords: survey periodicity, sediment, bedforms, San Francisco Bay, suitability model.

1 Introduction

To retain maritime security, an up-to-date database of route surveys for mine or maritime improvised explosive device (IED) countermeasures are essential [1, 2]. Bedforms are an integral part of the survey periodicity problem. Sediment grain size, tides, currents, and wind-generated waves are influential in bedform formation.

San Francisco Bay (Fig. 1) is a large, shallow, dynamic estuary located in California on the west coast of the U.S. It is a major international shipping port, with large container facilities, which makes it a significant, economically

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important port. It is an extremely busy waterway used by both commercial and recreational vessels. Approximately 40% of water drainage from the central coast rivers enters the Pacific Ocean through the Golden Gate channel. This represents a high freshwater discharge rate approximate 800 m^3/s, and has the potential to carry a significant amount of sediment into the area. The San Francisco Bay area is subject to a complex semi-diurnal tidal regime, this leads to temporally and spatially variable currents that can exceed 2.5 m/s. This leads to a diverse and complex pattern of bedform formations, which were first mapped using side-scan sonar in the late 1970's, and are now mapped using high resolution multi-beam surveys [3].

In this study, the Golden Gate region is investigated in detail (Fig. 1). A comparison study of localized sediment grab data in the same positions for a three year period is assessed and analyzed. This data is then compared to the Naval Oceanographic Office (NAVOCEANO) High Frequency Environmental Acoustics (HFEVA) sediment database, and an assessment of the validity of this database is made. Multi-beam data, obtained by the USGS is examined and the impact of these findings on the mine warfare route survey periodicity assessed.

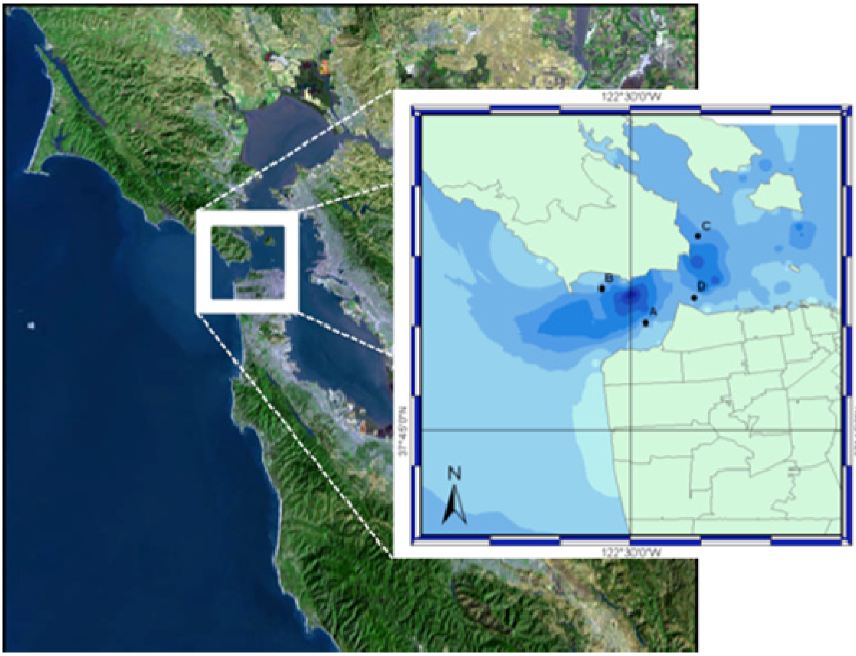

Figure 1: San Francisco Bay and sample locations for study.

2 Sediment

In the winter of 2007, 2008, 2009, sediment samples were collected in the vicinity of the Golden Gate region of San Francisco Bay, onboard the R/V Point

Sur in four locations (A, B, C, D) (Fig. 1). The samples were all collected using a double trap Van Veen sediment grab (Fig. 2), deployed off the stern of the ship using a crane. The Van Veen grab is a light weight stainless steel sampler designed to take samples of soft bottom sediment. Water is able to flow through the grab as it is lowered. When it hits the seabed, the doors of the grab close due to tension on the cable, they remain closed while the grab is raised and recovered on deck. Upon recovery of the grab a representative sample of the sediment was then collected in a quart mason jar. The jar was then sealed, labeled and stored, for laboratory processing [4].

Figure 2: Van Veen grab on board R/V point Sur.

The sediment sample analysis was conducted in the oceanographic laboratory at the Naval Postgraduate School. Laboratory analysis can be broken down into phases. The first phase involved emptying the contents of each jar into a standard plastic Rubbermaid basin; the sample was rinsed with fresh water while being agitated. The sample was then left to settle – the time this took depended on the consistency of the sample, with silty samples taking much longer. The samples were generally left overnight; this allowed all the sediment to return to the bottom, leaving clear water on top. Following the settling period, any particulates or biologic material floating on the water was removed. The fresh water was then decanted out, being careful not to pour out any sediment. If necessary, this process was repeated.

The rinsed sediment was then transferred into a pre-weighed 8×8 inch, Pyrex casserole dish. Sediment was transferred by pouring, scraping using a spoon, and rinsing by squeezing a fine stream of water into the bowl. Once transferred, the sample was placed in the laboratory oven overnight to dry. The oven was set at approximately 90^{o} C. Once the sample was completely dry, it was weighed and prepared for the sieving process. The dried sample was broken up, in some cases this could be achieved by using a spoon. However it was necessary to use a hammer to break up some of the more difficult samples. These tended to be the finer samples that had become like baked clay. The broken up sample was then place in a pre-weighed plastic bag. The bagged sample was weighed and the result recorded.

The next phase, the sieving phase was achieved by using a Ro-Tap automated sieve. A 100 ml glass beaker was weighed, a quantity of the sample was added to the beaker and it was re-weighed, both weights were recorded. This was the part of the sample to be analyzed. The Ro-Tap sieve used in this experiment utilized 14 sieves ranging from 2.00 mm to 0.070 mm in mesh diameter. The sample was poured into the top sieve (2.00 mm), and then sieved through the column of sieves for 15 minutes. The sample collected in each sieve was carefully collected, by pouring it onto a sheet of card and removing any residue from the sieve with a wire brush, it was then transferred into a pre-weighed plastic bag. The bag and sample was then weighed and the results recorded. A loss of less than 1% of the sediment weight had to be achieved if the result was to be deemed accurate.

The sediment grain size varies drastically from smaller than 0.0002 mm to larger than 256 mm. The Udden-Wentworth scale,

$$\varphi = -\log_2(X) \tag{1}$$

is used with $\varphi = -8$ corresponding to $X = 256$ mm and $\varphi = 12$ corresponding to X = 1/4096 mm. The sediment can be classified by calculating the percentage of each sample within each range, then calculating the mean grain size for that sample and converting this to φ units. Usually, the sediment size distribution, $f_i = f(X_i)$, must first be calculated. From this, the mean grain size, standard deviation, and skewness

$$\overline{\varphi} = \sum_i f_i \varphi_i, \quad \sigma = \sqrt{\sum_i f_i (\varphi_i - \overline{\varphi})^2}, \quad \alpha = \sum_i \frac{(\varphi_i - \overline{\varphi})^3}{\sigma^3}, \tag{2}$$

can be calculated. Table 1 shows the $\overline{\varphi}$-values of the sediment samples collected in 4 locations (A, B, C, and D) marked in Fig. 1 during three cruises in 2007, 2008, and 2009. Fig. 3 shows the breakdown of percentage sample mass for the location-A each year.

Table 1: Sediment classification based on $\overline{\varphi}$ values for positions A–D.

	2007	2008	2009
A	2.48 Fine Sand	2.52 Fine Sand	2.51 Fine Sand
B	2.31 Fine Sand	2.29 Fine Sand	2.11 Fine Sand
C	1.47 Medium Sand	1.75 Medium Sand	1.90 Medium Sand
D	2.25 Fine Sand	2.17 Fine Sand	2.20 Fine Sand

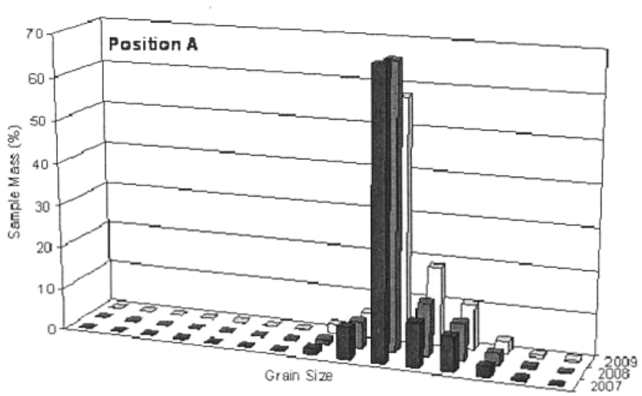

Figure 3: Variation of sediment size distribution in three years: 2007 (dark black), 2008 (light black), and 2009 (white) at the location-A from largest grain size (left) to smallest grain size (right).

3 Bedforms

When sediment begins to move bedforms start to form. A flat bottom can become deformed, with a series of undulations. As water flow increases, drag will be increased, and this increases in the shear stress available at the bed to create grain movement [5]. In laboratory investigations, the sequence of bedforms with increasing flow intensity is: Flat bed, Ripples, Dunes, High Stage Plane Bed, followed by Antidunes. If the average current velocity, water depth and sediment size are known factors, then the expected bedforms can be predicted.

Table 2 shows the estimated ripple heights from waves and characteristics for positions A to D. The wave conditions were obtained from marine gridded climatology data provided by Fleet Numerical Meteorology and Oceanography (METOC) Detachment in Ashville. Values were calculated by re-analysis of data from 1857 to 1997. Location-A results show all the ripples classed as orbital, the ripple height varies from 0.3 cm to 0.4 cm. This indicates a limited amount of variability at position A over the time period. Location-B results also show the ripples are classified as orbital in all cases. The ripple heights vary from 2.5 cm to 3.1 cm. Although this position has more variability it remains at less than 1 cm, so cannot be deemed significant. Location-C results, again, classify the ripples as orbital, while the ripple height varies from 1.9 cm to 3.1 cm. Although the variability is slightly larger than the other two positions the range of ripple heights remains relatively small and inconsequential. Location-D shows the largest variability, all ripples remain orbital, but heights range from 1.4 cm to 3.4 cm. The range of phi values is from 2.17 to 2.25, which is not a large range, however the depth at which the grab samples were obtained is more variable for this position, which could explain the variability in results. The difference of 2 cm ripple height over a three year period is not large enough to be a significant problem.

The ripple heights for each position show a degree of variability, although not on a large scale. The variation at each location is in the order of a centimeter, the estimated ripple heights from waves are all relatively small and would be inconsequential for mine burial at these positions. However, this does not take into account the currents in this region. Although the ripple height is assessed as too small to bury a mine it still remains an important issue in the mine warfare survey periodicity problem. Smaller ripples in the order of centimeters can cause a significant problem in mine detection due to scattering of acoustic rays [4].

Table 2: Ripple characteristics at locations A–D.

		2007	2008	2009	Mean	SD
A	φ	2.48	2.52	2.51	2.50	0.02
	Depth (m)	60	63	63	62	1.73
	Orbital Diameter (mm)	0.019	0.015	0.015	0.016	0.0023
	Orbital Velocity (m/s)	0.017	0.013	0.013	0.014	0.0023
	Ripple Height (cm)	0.4	0.3	0.3	0.33	0.0577
	Ripple Classification	Orbital	Orbital	Orbital		
B	φ	2.31	2.29	2.11	2.23	0.11
	Depth (m)	37	35	38	36.6	1.52
	Orbital Diameter (mm)	0.128	0.151	0.118	0.132	0.0169
	Orbital Velocity (m/s)	0.115	0.135	0.106	0.119	0.0148
	Ripple Height (cm)	2.7	3.1	2.5	2.77	0.3055
	Ripple Classification	Orbital	Orbital	Orbital		
C	φ	1.47	1.75	1.90	1.71	0.21
	Depth (m)	38	41	35	38	3.00
	Orbital Diameter (mm)	0.118	0.093	0.151	0.120	0.0291
	Orbital Velocity (m/s)	0.106	0.083	0.135	0.108	0.0261
	Ripple Height (cm)	2.5	1.9	3.1	2.5	0.6
	Ripple Classification	Orbital	Orbital	Orbital		
D	φ	2.25	2.17	2.20	2.21	0.04
	Depth (m)	40	45	34	39.67	5.508
	Orbital Diameter (mm)	0.101	0.067	0.164	0.116	0.0492
	Orbital Velocity (m/s)	0.090	0.060	0.147	0.099	0.0442
	Ripple Height (cm)	2.1	1.4	3.4	2.3	1.01
	Ripple Classification	Orbital	Orbital	Orbital		

4 Comparison to existing database

The Maritime environment is an extremely important factor in determining the route survey periodicity. The United Kingdom Hydrographic Office (UKHO) model included seabed sediment types, sediment deposition, bottom texture, gas presence and vessel traffic. The data was obtained from many different sources, bottom texture and bottom contacts data was taken from the UKHO Route Survey Database (RSDB) and processed in Microsoft Excel, allowing it to be imported easily into ArcGIS. The British Geological Survey (BGS) supplied the seabed sediment type data in a digital map. In order to determine total suspended matter, satellite data from the NASA MODIS satellites were used. The density of fishing vessels was obtained from the Centre for Environment, Fisheries and Aquaculture Sciences (CEFAS). Gas presence was taken from the UKHO Geological Database (GEODB) and vessel traffic was supplied by NAVOCEANO. Table 3 shows our 2009 data to the NAVOCEANO HFEVA database.

Table 3: 2009 sediments samples compared to NAVOCEANO database data.

	Phi	Wentworth Sediment Classification	HFEVA Database
A	2.51	Fine Sand	Fine Sand
B	2.11	Fine Sand	Fine Sand
C	1.90	Medium Sand	Medium Sand
D	2.20	Fine Sand	Fine Sand

5 Accuracy and errors

There are issues involving the accuracy and errors associated with this investigation. Although, during the collection and laboratory processing, as much care as possible was taken to limit or eliminate errors. During the collection phase, the bridge of the R/V Point Sur was given the positions of previously collected samples, the ship aimed to stay in station at these locations as accurately as possible during the deployment and retrieval of the grab. However, from comparing the positions over the three years, it can be noted that although the positions are extremely similar, they are not exactly the same. This is reflected in the depths used in calculating ripple height and is the main reason for the variation in the ripple height.

In order to gain a better representation of sediment type, it would be preferable to take a selection of samples at each position, so that the average result could be used, rather than relying on one sample. This would allow any erroneous sediment samples to be excluded, or have a minimal effect on the results used for comparison. The laboratory procedure for sediment analysis was carried out in such a way to minimize error. In order to be deemed a valid result less than 1% sample loss could occur during the sieving process. There were problems that occurred that could introduce error. Finer samples proved problematic after the baking phase. The aim was to break up these samples as much as was possible, however, this proved difficult at times and could have caused a skew in results indicating a sample was coarser than it actually was. Every care was taken to avoid this.

During the sieving phase, care had to be taken to ensure that all of the sediment samples were removed from each sieve – at times this could be difficult and was achieved by using a wire brush or a sharp pencil to poke any remaining sediment grains from the sieve. The sieves available for the Ro-Tap sieve ranged from 2.00 mm to 0.070 mm. This limited the sediment classification range, from fine gravel to very fine sand, in the case of these sediment samples this range appeared adequate.

6 Determination of survey periodicity

To determine the survey periodicity for San Francisco Bay, a weighted suitability GIS model, utilizing a similar methodology to the UKHO model [6], was developed. The model is established based on the fact that waves, tides, currents and sediment size affect bedform formation and sediment processes; this in turn will affect the survey periodicity requirement. The concept of the weighted suitability model used here is summarized in Fig. 4. It utilizes three main input layers; predicted bedform type (green), predicted bottom current (blue) and predicted wave generated ripple height (red). Each of these layers can be thought of as a sub-model, similar to those used in the UKHO model.

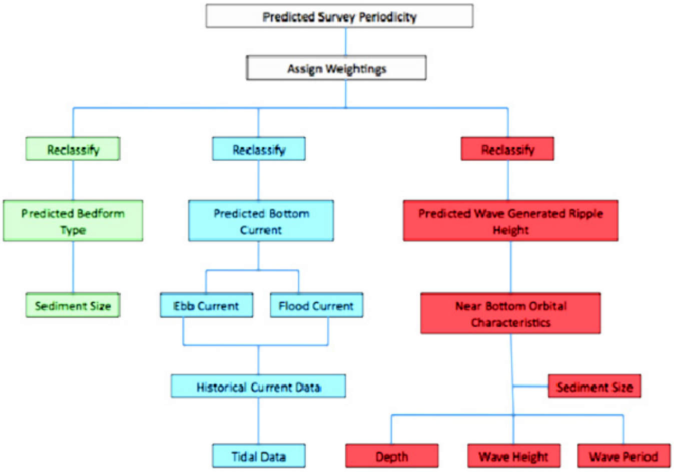

Figure 4: Flow chart showing the three layers used to predict survey periodicity.

In order to predict the bedform type, 174 grab samples were obtained from the USGS. The grab samples were taken during surveys dated between 2004 and 2008. In addition the grab samples detailed in Section 2 were also included. The data included latitude, longitude, depth, and sediment grain size. The dataset was compiled in excel and entered into the GIS software program ArcMap (Fig. 5). Tidal data, from NAVOCEANO predictions is examined and the variability in this region (not shown). Historical current data, provided by NAVOCEANO is analyzed. Using linear wave theory and climatological data, the estimated wave generated ripple heights are calculated. Sediment data

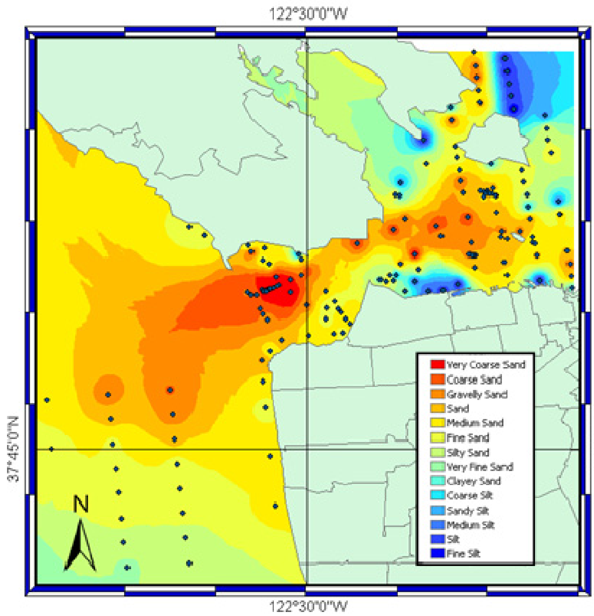

Figure 5: Sediment type constructed from grab samples in San Francisco Bay.

obtained from grab samples provided by USGS is utilized. This data is weighted and combined, and a model for survey periodicity is obtained. Using linear wave theory, the depth, mean wave height and mean wave period, the near bottom orbital velocity and near bottom orbital diameter were calculated. Applying the Wiberg and Harris model, and including the sediment grain size data the predicted ripple height was calculated. These data were then combined in order to obtain wave generated ripple height layer. Fig. 6 shows January ripple heights. Smaller ripple heights are shown in pink, with the greatest ripple heights shown in orange and brown, as according to the color scale shown. It can be seen that the greatest ripple heights occurred seaward of the San Francisco Bay region in January, this coincided with the larger wave heights [4].

Due to the importance of flood and ebb dominated currents in bedform formation, further interpolation of this data was conducted. The currents were interpolated into a raster dataset and separated into ebb dominated and flood dominated regions. Bottom ebb currents were assigned a negative value, and flood currents were assigned a positive value and the residual differences between the two calculated. Ebb dominated regions are indicated in red and flood dominated regions are shown in green. In order to determine the survey periodicity, the weighted option layers were classified. With 45% weighting for the sediment layer, from the background theory it was extremely apparent that sediment grain size was particularly important in sediment transport mechanisms and in bedform formation mechanisms. Currents were weighted at 35%, this demonstrates the importance of currents, in this case due to a particularly strong

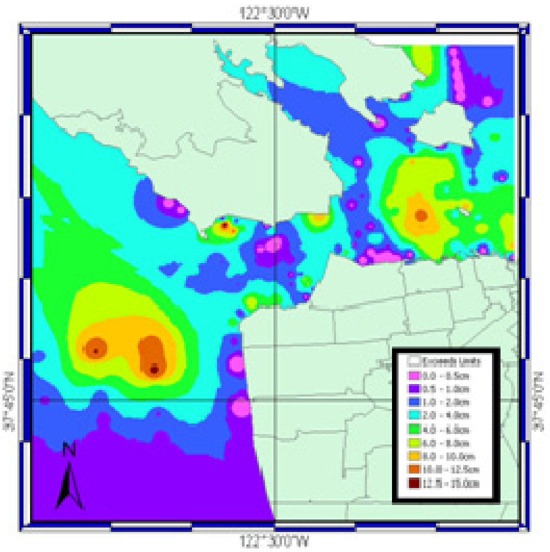

Figure 6: Wave generated mean ripple heights (cm) in January in San Francisco Bay.

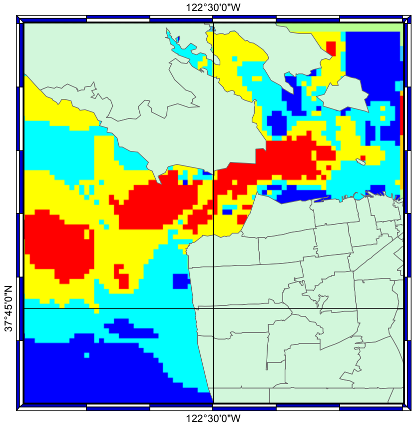

Figure 7: Recommended survey periodicity for San Francisco Bay. The yellow regions should be re-surveyed every 5–7 years, the light blue regions every 7–10 years and the dark blue every 10–15 years.

tidal regime, the importance of currents was also apparent from the background theory of sediment transport [7,8]. Waves had a weighting of 20%, the lower weighting was due to the smaller magnitude of ripple heights due to wave motion.

Fig. 7 shows the model results for the survey periodicity. The red colored regions (priority-1) occupying throughout the Golden Gate Channel and the Alkatraz Shoal, have highest seabed changeability, those that should be surveyed most often (every 3–5 years). This is due to its significant economic and commercial importance. The yellow regions should be re-surveyed every 5–7 years, the light blue regions every 7–10 years and the dark blue every 10–15 years.

7 Conclusions

The route survey periodicity model developed for San Francisco Bay. The sediment size, tides and currents and ripples generated from wind waves are used as input for the survey periodicity model since they are critical in bedform formation and sediment size.

This model is comprised of three input layers: bedform type, bottom current, and wave generated ripple height. Each of these layers can be thought of as a sub-model. Each layer was weighted, the weighting scheme was used, and each layer was re-classified with a scale of 0 to 9, with 0 representing a high degree of change, and 9 representing little change. As these layers had not been used before, the weighting schemes used were based primarily on background theoretical concepts. The bedform type layer weighting of 45%, in all background theory literature sediment size was shown to be the most important factor in bedform type and hence size. The predicted bottom current layer had a weighting of 35%, indicating that currents, in this case due to the tidal regime had a greater importance than waves, which were given a weighting of 20%. A lower weighting was given to waves due to the fact that the ripple heights capable of being generated were much smaller than those generated by currents. Near the mouth of the San Francisco Bay, the seabed changeability is high, a survey interval of 3–5 years is suggested.

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