Bedform Morphology Under High-Energy Conditions at the Mouth of a Major Tidal Inlet, San Francisco, California

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Introduction

A multibeam sonar survey was recently completed that mapped for the first time in high resolution the seafloor morphology at the mouth of San Francisco Bay (Figs. 1-2). Highlights of the data set include one of the largest sand wave fields in the world (n= 40, max wavelength= 220 m, max height= 10 m, max depth= 106 m) and an extremely diverse array of bedform morphologies, scales, and orientations around the inlet mouth. Hydrodynamic and wave modeling suggest complex flow structures around the inlet mouth and offshore of adjacent Ocean Beach that are well correlated with observed bedform morphologies. The processes that control the morphology of the adjacent beach are intimately related to the processes that control sediment transport about the ebb tidal delta at the mouth of San Francisco Bay.

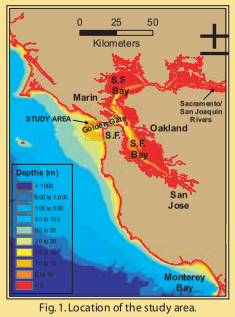

Fig. 1. Location of the study area.

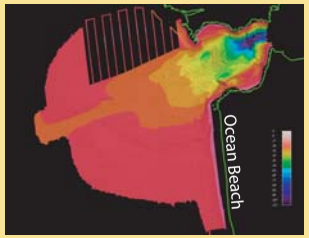

Fig. 2. Multibeam coverage area from fall 2004 survey. Image is 18 km across.

Methods

In fall 2004 and 2005 over 45 days of multibeam surveying were conducted at the mouth of San Francisco Bay (2004 data included here, 2005 data in process). Bedform statistics were generated using analysis tools in ArcGis and Fledermaus. During the summer of 2005, 4 tripods were deployed with Acoustic Doppler Current Profilers (ADCPs) and ~200 sediment samples were collected using both a grab sampler and digital bed sediment camera (Rubin, 2004) (Fig. 3). Tripods were deployed to get critical wave and tidal current measurements to calibrate and validate the numerical models being applied to the region, Delft3D and NearCom (Figs. 4-5). Sediment sample locations were chosen to cover the entire ebb tidal delta, with emphasis on measurements in and around the major bedform fields.

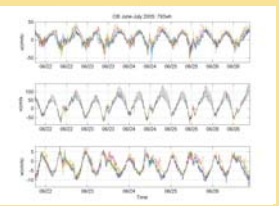

Fig. 4. Velocity measurements from the ADCP mounted on tripod #1 (see Fig. 3) located offshore of Pt. Lobos.

Setting

The mouth of San Francisco Bay is an extremely energetic tidal inlet environment, where wave heights commonly exceed 5 m during the winter. During peak flow, tidal currents approach 3 m/s at the Golden Gate, which carries a tidal prism of 2 x 10^9 m^3. Flow structure varies markedly spatially and temporally due to the complex interaction of wind, waves, and tides. The dominant patterns of this interaction are expressed in the bedform morphology of the tidal inlet, which in turn is an expression of the dominant sediment-transport pathways. Identifying pathways of sediment transport are essential for coastal managers in this region who direct dredging operations and seek the most efficient means of mitigating erosion on adjacent Ocean Beach.

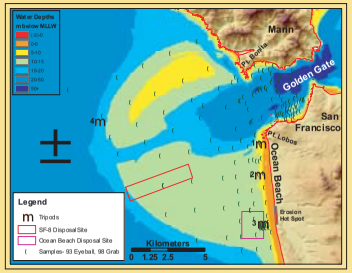

Fig. 3. Sediment samples and instrument locations from the summer 2005 field experiment.

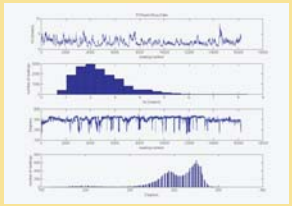

Fig. 5. Offshore wave statistics from 2002 using the CDIP directional wave buoy (http://cdip.ucsd.edu/).

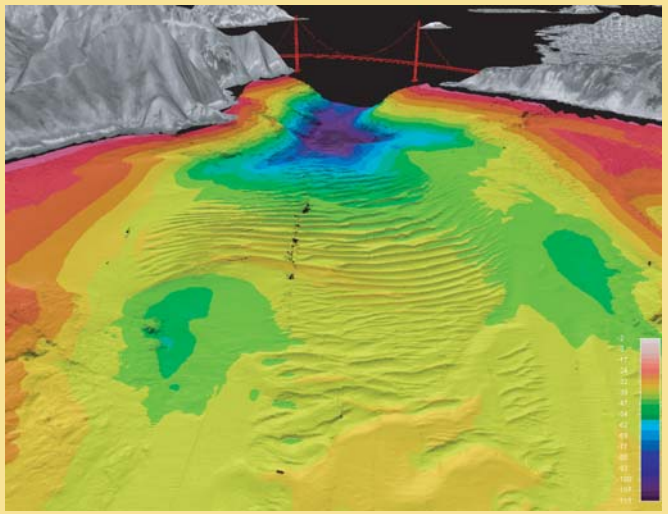

Fig. 6. Oblique view looking east of the massive sand wave field at the mouth of San Francisco Bay with 3 times vertical exaggeration. The adjoining land is imaged using DOQQs draped over USGS DEMs.

Results

Multibeam data document an incredible sand wave field at the mouth of San Francisco Bay (Fig. 6). This is among the largest sand wave fields every measured, and rivals the scale of features in well known sites such as the Bay of Fundy (Dalrymple et al., 1978) and Cook Inlet, Alaska (Bouma et al., 1977). Further analysis of the bedform morphology throughout the region illustrates a diverse array of bedform morphologies, scales and orientations which are strongly controlled by the complex interaction of wave and tidal influences (Figs. 7-13). Grain size analysis shows huge variation in sediment size across the study, ranging from fine sand and mud along the outer flanks of the ebb tidal delta to coarse sand and gravel in the massive sand wave field in the inlet throat. The importance of the ebb tidal delta morphology is evident in wave modeling results, which show sharp differences in wave focusing patterns due to swell direction. Predicted tidal current magnitude and direction from numerical models agree with the observed bedform morphology. The interaction of waves and tidal currents is significant along Ocean Beach, as is evident by both wave/current modeling and the observed bedform morphology. This, combined with potential grain size variations, has resulted in sharp transitions between bedform scales, morphologies, and variations.

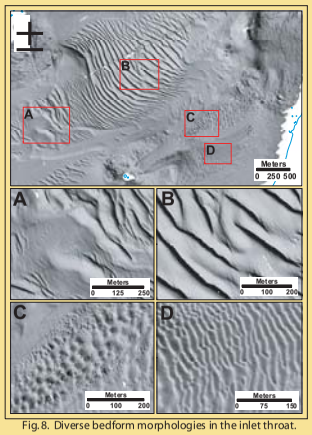

Fig. 8. Diverse bedform morphologies in the inlet throat.

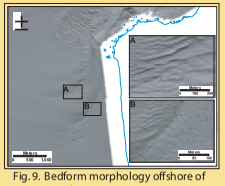

Fig. 9. Bedform morphology offshore of Ocean Beach.

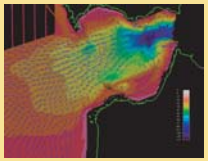

Fig.11. Current patterns during peak ebb flow overlying bedform morphology.

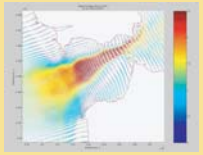

Fig. 10. Predicted tidal currents using Delft3D during peak ebb flow.

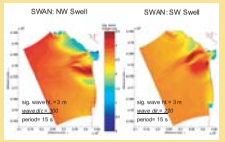

Fig. 12. SWAN modeling illustrating contrast in wave focusing patterns due to two common swell directions.

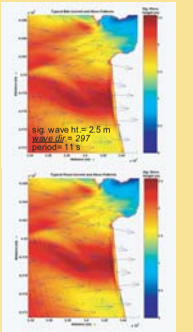

Fig. 13. Wave-current interaction during peak ebb and flood tide. Wave fronts in blue and current vectors in green.

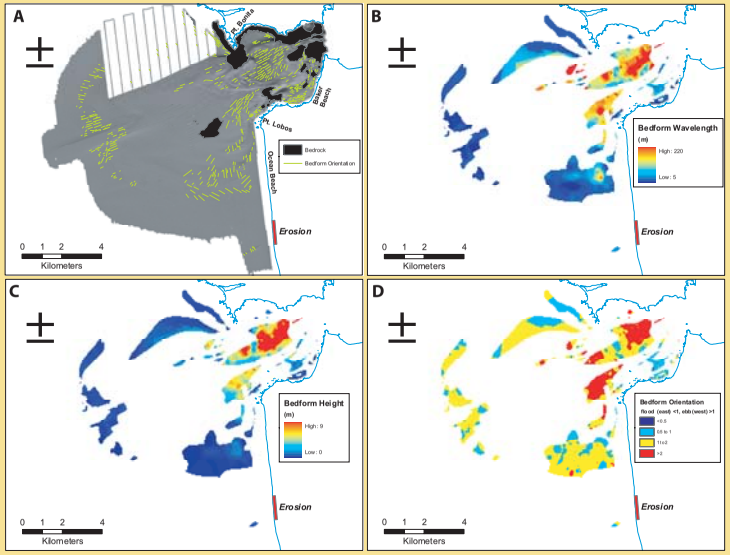

Fig. 7. Map view of the results of the bedform analysis at the mouth of San Francisco Bay. Within the coverage area (A), those regions shaded in white (B-D) indicate unresolvable bedforms (wavelengths < 5 m). The analysis of wavelength (B), height (C), and orientation (D), i.e. stoss to lee ratio, shows the prevalence of large, ebb-dominated sand waves in the inlet throat and off Pt. Lobos, flood-dominated sand waves through the peripheral flood channels and the eddy off Baker Beach, and smaller sand waves along the outer rim of the ebb tidal delta.

Conclusions

These data show that the mouth of San Francisco Bay contains among the largest and most diverse bedforms in the world. Statistical analysis of bedforms, current and wave measurements, preliminary grain size analysis, and numerical modeling illustrate that their distribution and orientation is controlled by the varying influence of wave and tidal processes, with the largest bedforms occurring in the inlet throat where tidal currents are strongest, and the most diverse occurring where the interaction of tidal current and wave direction is most complex, such as offshore of Ocean Beach and within strong eddies offshore of Baker Beach. Coastal managers are utilizing this improved knowledge of the dominant sediment transport pathways to more efficiently manage dredge material in the region.

References

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Dalrymple, R.W., et al. (1978), Bedforms and their hydraulic stability relationships in a tidal environment, Bay of Fundy, Canada, Nature, 275, 100-104.
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Web site: http://walrus.wr.usgs.gov/coastal_processes/intro.html

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