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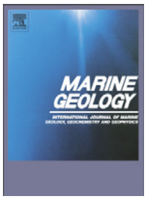

Changes in surfzone morphodynamics driven by multi-decadal contraction of a large ebb-tidal delta

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ABSTRACT

The impact of multi-decadal, large-scale deflation (76 million m^3 of sediment loss) and contraction (~1 km) of a 150 km^2 ebb-tidal delta on hydrodynamics and sediment transport at adjacent Ocean Beach in San Francisco, CA (USA), is examined using a coupled wave and circulation model. The model is forced with representative wave and tidal conditions using recent (2005) and historic (1956) ebb-tidal delta bathymetry data sets. Comparison of the simulations indicates that along north/south trending Ocean Beach the contraction and deflation of the ebb-tidal delta have resulted in significant differences in the flow and sediment dynamics. Between 1956 and 2005 the transverse bar (the shallow attachment point of the ebb-tidal delta to the shoreline) migrated northward ~1 km toward the inlet while a persistent alongshore flow and transport divergence point migrated south by ~500 m such that these features now overlap. A reduction in tidal prism and sediment supply over the last century has resulted in a net decrease in offshore tidal current-generated sediment transport at the mouth of San Francisco Bay, and a relative increase in onshore-directed wave-driven transport toward the inlet, accounting for the observed contraction of the ebb-tidal delta. Alongshore migration of the transverse bar and alongshore flow divergence have resulted in an increasing proportion of onshore migrating sediment from the ebb-tidal delta to be transported north along the beach in 2005 versus south in 1956. The northerly migrating sediment is then trapped by Pt. Lobos, a rocky headland at the northern extreme of the beach, consistent with the observed shoreline accretion in this area. Conversely, alongshore migration of the transverse bar and divergence point has decreased the sediment supply to southern Ocean Beach, consistent with the observed erosion of the shoreline in this area. This study illustrates the utility of applying a high-resolution coupled circulation-wave model for understanding coastal response to large-scale bathymetric changes over multi-decadal timescales, common to many coastal systems adjacent to urbanized estuaries and watersheds worldwide.

1. Introduction

Ebb-tidal deltas are common geomorphic features found on the seaward side of many tidal inlets (Hayes, 1980) and numerous studies have reported the significant influence of ebb-tidal deltas on the evolution and dynamics of the adjacent shorelines (e.g., Oertel, 1977; Finley, 1978; FitzGerald, 1984; Hicks et al., 1999; Cleary and FitzGerald, 2003; Robin et al., 2009). One of the most important features of the ebb-tidal delta is the capability to store (or release) large quantities of sediment. Ebb-tidal deltas and the corresponding inlet throat and back-barrier basin tend to remain in (dynamic) equilibrium to the large-scale hydrodynamic forcing (see Dean, 1988; Oost and De Boer, 1994; Stive and Wang, 2003). Conceptually, sediment supplied by the basin and via littoral transport on the outer coast accumulates in ebb and flood deltas where the flow decelerates after being constricted through the narrow inlet. The geometry of the back-barrier basin, in combination with tidal range, determines the tidal prism which in turn relates to the size of the inlet (O'Brien, 1931, 1969) and the volume of the ebb-tidal delta (Walton and Adams, 1976). The geometry and seaward extent of ebb-tidal deltas is a function of the tidal prism and strength of the ebb currents, the wave climate, and the supply of sediment (Hubbard et al., 1979; Hayes, 1980). A larger tidal prism and stronger ebb currents will tend to push the ebb-tidal delta further seaward while a more energetic wave climate will tend to drive the delta back toward the inlet (Oertel, 1975). There are also secondary external controls that influence inlet behavior, including basin geometry, sedimentation history, regional stratigraphy (e.g., presence of resistant bedrock layers) and freshwater discharge by rivers (FitzGerald, 1996; Elias and van der Spek, 2006).

Distortion of the equilibrium state will result in sediment exchange between the various geomorphic features that make up the inlet system (i.e., inlet, ebb- and flood deltas, shoreline) until a new equilibrium is

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achieved. Thus, ebb-tidal deltas can act as both a source and sink of sediment for the adjacent coastline (FitzGerald, 1984). Disequilibrium can result from natural- and human-induced factors, including sea-level rise, land reclamation of the back-barrier basin, decreased sediment availability, and inlet stabilization, all of which can cause the entire inlet system to shift towards a new equilibrium state. On a local scale, ebb-tidal deltas directly influence the adjacent beaches by altering the incident wave field through refraction and can shelter onshore beaches if waves are dissipated on the delta (Hubbard et al., 1979; Carter et al., 1982).

Here we focus on an ebb-tidal delta at the mouth of San Francisco Bay, CA (USA). Since development began along the shoreline of San Francisco Bay in the 19th century, the watershed, Bay, and coastal system have been heavily altered, including drainage damming, hydraulic and sand mining, ship channel dredging, and tidal wetland reclamation (Gilbert, 1917; Atwater, 1979; Knowles and Cayan, 2004; Wright and Schoellhamer, 2004) which together have removed or displaced well over 1 billion m^3 of sediment in the last century alone (United States Army Corps of Engineers, 1996; Chin et al., 2004). These disturbances are at least partly, if not entirely, responsible for the observed contraction of the 150 km^2 ebb-tidal delta found seaward of the Golden Gate, the inlet linking San Francisco Bay to the open sea, observed over the last century (Dallas and Barnard, 2011). In the present study we investigate the role of multi-decadal erosion and contraction of the ebb-tidal delta on hydrodynamics and sediment transport at adjacent Ocean Beach, a 7-km sandy shoreline adjacent to the inlet, using a process-based numerical model. The coupled flow-wave model is forced with representative wave and tidal conditions using the modern (2005) ebb-tidal delta bathymetry as well as that from 1956 to understand the cause of observed counter-clockwise rotation of the shoreline at Ocean Beach over the last century.

2. Study location and previous work

The Golden Gate is one of the largest tidal inlets on the west coast of the United States and services a tidal prism of approximately 2×10^9 m^3 (Dallas and Barnard, 2011), resulting in tidal currents that exceed 2.5 m/s in the inlet throat (Barnard et al., 2007). Seaward of the Golden Gate, the only entrance to San Francisco Bay, is an ~150 km^2 ebb-tidal delta known as the San Francisco Bar (Fig. 1A). The San Francisco Bar is a relatively symmetric, horseshoe-shaped ebb-tidal delta, with minimum depths of ~9.5 m and 10.5 m on the northern and southern lobes respectively. Bathymetric surveys of the ebb-tidal delta extend back to 1873 with Gilbert (1917) first documenting changes in the delta from inflow of sediment into San Francisco Bay resulting from hydraulic mining, which increased the sediment supply and reduced the tidal prism by decreasing storage in the basin. In addition to the cessation of hydraulic mining in 1884, sediment supply has also been reduced by damming of the major rivers that flow into the Bay (Wright and Schoellhamer, 2004). The tidal prism has been further reduced by tidal wetland infilling for construction projects and dyking for agriculture along the Bay shoreline (Atwater, 1979). It is estimated that the tidally-affected surface areas of the Bay were reduced by two-thirds from the mid-19th to late 20th century, reducing tidal marsh to ~4–8% of its original area (Jaffe and Foxgrover, 2006; Jaffe et al., 2007).

Directly south of the Golden Gate lies Ocean Beach, a 7-km stretch of sandy beach which forms the western boundary of the city of San Francisco and the landward attachment point for the southern lobe of the San Francisco Bar (Fig. 1B). The proximity to the tidal inlet leads to strong (~1 m/s) alongshore tidal currents along Ocean Beach, particularly at the northern end closest to the inlet (Barnard et al., 2007). Tides are mixed-semidiurnal in the San Francisco Bight with a mean range of 1.25 m and a maximum spring tide range of 2.65 m (National Oceanic and Atmospheric Administration (NOAA) Tides and Currents, 2011). The open coastline adjacent to San Francisco is subject to large winter waves with deep water significant wave height reaching up to ~9 m during winter storms (Coastal Data Information Program (CDIP), 2011).

The San Francisco Bar and Ocean Beach have been the subject of numerous previous research efforts. Hanes and Barnard (2007) reported 92 million m^3 (~60 cm vertical erosion) of sediment loss between 1956 and 2005 from the mouth of San Francisco Bay, including changes to the ebb-tidal delta and the Golden Gate. Dallas and Barnard (2011) documented, using four complete bathymetric surveys of the ebb-tidal delta, that between 1873 and 2005 the San Francisco Bar (not including the inlet) lost approximately 100 million m^3 of sediment with the outer lobe of the delta contracting on average 1 km back toward the Golden Gate inlet. Of the 100 million m^3 lost between 1873 and 2005, 76 million m^3 was lost between 1956 and 2005 (~45 cm vertical erosion), somewhat smaller than the 92 million m^3 reported by Hanes and Barnard (2007) which included both the ebb-tidal delta and inlet. Further, Dallas and Barnard (2011) showed, using several stationary SWAN wave model (Booij et al., 1999) simulations, that the changes in the ebb-tidal delta geometry have led to increased wave heights at the southern end of Ocean Beach, a persistently eroding stretch of shoreline (Hansen and Barnard, 2010). However, their wave simulations were not coupled to a hydrodynamic model to investigate the resulting changes in flow or sediment transport.

Along Ocean Beach, Hansen and Barnard (2010) documented, using more than 60 repetitive topographic surveys between 2005 and 2009, that the shoreline has exhibited a pattern of counter-clockwise rotation, with the north end of the beach accreting while the south eroded. Barnard et al. (2012a) extended the topographic data to 2010 and showed that the alongshore location of the transition from shoreline accretion to erosion along Ocean Beach is spatially correlated with the contraction pattern seen in the ebb-tidal delta between 1956 and 2005. The shoreline accreted at the north end of the beach onshore of areas of the delta that have also accreted, with the opposite occurring at the south end. A significant volume of the accretion observed in the ebb-tidal delta offshore of the north end of the beach is a result of infilling of a marginal flood channel that obliquely intersects the outer surfzone (Fig. 1B). This channel filled in with as much as 2 m of sediment between 1956 and 2005 (Fig. 2) (Dallas and Barnard, 2011; Barnard et al., 2012a).

The influence of the ebb-tidal delta on hydrodynamics along Ocean Beach has been investigated numerically by Shi et al. (2011) who showed that wave refraction over the ebb-tidal delta results in alongshore wave height differences and a corresponding set-up gradient. The set-up gradient causes an alongshore pressure gradient that can dominate the alongshore force balance (Shi et al., 2011). Elias and Hansen (2013-in this issue) investigated the hydrodynamics within the inlet and over the ebb-tidal delta using the present ebb-tidal delta bathymetry and found that both wave and tidally-driven sediment transport are important in both regions, with waves being important for mobilizing sediment on the delta and tides strongly advecting sediment into areas away from wave breaking. For example, during storms waves can break on the distal reaches of the ebb-tidal delta and entrain sediment which can then be advected into the inlet throat or offshore depending on the phase of the tide.

The previous research at Ocean Beach and the San Francisco Bar indicates that the ebb-tidal delta and Ocean Beach are inherently coupled. The results presented here demonstrate that the anthropogenically-driven changes to the San Francisco Bar have had a significant impact on the forcing, hydrodynamics, and sediment transport patterns at Ocean Beach. We focus on the differences in the ebb-tidal delta between 1956 and 2005, the two most recent complete bathymetric surveys of the ebb-tidal delta.

3. Numerical model

The numerical hydrodynamic and sediment transport model Delft3D (Lesser et al., 2004), coupled with the wave model SWAN