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Sediment scour and deposition within harbors in California (USA), caused by the March 11, 2011 Tohoku-oki tsunami

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ABSTRACT

Tsunamis have caused significant damage to boats and docks within harbors and ports along the California coast. Sediment scour and deposition within harbors by tsunamis, though not extensively studied, have produced long-term impacts to the recovery and resiliency of affected maritime communities. The March 11, 2011 Tohoku-oki teletsunami generated strong tsunami currents (up to 7 m/s, or 14 kn) within Crescent City and Santa Cruz harbors that triggered sedimentation problems, regulatory issues with sediment disposal, and months of delays in the reconstruction process. Evaluation of video, pre- and post-tsunami bathymetric surveys, and harbor sediment analysis data helped develop a better understanding of tsunami flow regime and sediment transport within these harbors. In Crescent City, the scour effects of large tsunami surges were amplified by the narrow entrance to the Small-Boat Basin, increasing the sediment supply and trapping this material within the basin, causing shoaling that made the harbor unusable and creating long-term disposal issues. Within the entire harbor, at least 289,400 m^3 of sediment was scoured in an area of 0.67 km^2. A minimum fill volume of 154,600 m^3 was calculated with the sediment covering 55% of that portion of the harbor included in the bathymetric surveys. In Santa Cruz, the long, constricting layout and shallow nature of the harbor increased current velocities and scour in confined areas, and exacerbated sedimentation in between and beneath docks. At the harbor entrance, estimated scour volumes range from 2550 to 14,800 m^3, and fill estimates range from 120 to 8750 m^3, depending upon the surveys used to characterize post-tsunami conditions, while the area of deposition ranges from 6 to 64% of the survey overlap areas. About 83 m^3 of sediment was scoured in Santa Cruz North Harbor, while a minimum of 75 m^3 was deposited across 50% of that portion of the harbor common to pre- and post-tsunami surveys. Fill estimates are considered minimums, due to sediment deposited in locales not covered by the various surveys. In general, the southern part of the harbor near the entrance jetties was erosional while most of the northern part of the harbor was depositional. Analyses of tsunami currents observed on videos collected during the tsunami provide excellent support for the bathymetric change analyses, and together the two lines of evidence provide a means to predict flow patterns and areas at risk of damage from the tsunami by assessing harbor dimensions and layout, and analyzing observations/video from past tsunamis. Reducing constrictions and deepening channels within harbors would greatly reduce tsunami current speeds and the potential for scour. The maritime community and state regulatory agencies should work together to streamline the review process to assist recovery efforts after significant tsunamis.

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1. Introduction

Although the effects of tsunami scour and sedimentation on harbors have been noted and evaluated through wave-tank analyses and numerical modeling, and incorporated into design criteria for some harbors, relatively few detailed, real-world examples of these impacts have been documented until recently. Reinhardt et al. (2006) performed underwater geoarchaeological excavations to identify scour and sedimentation from an AD 115 tsunami that may have led to the rapid decline of the ancient harbor at Caesarea Maritima in present-day Israel. In the aftermath of the 2004 Indian Ocean tsunami, Goto et al. (2010) evaluated harbor changes for Kirinda Harbor in Sri Lanka where sediment up to 4 m thick was deposited within the harbor during the tsunami. The March 11, 2011 tsunami along the California coast provides an opportunity to evaluate the impacts of tsunami scour and sedimentation in greater detail.

California's 1100-mile-long coastline has over one-million residents and tens of millions of visitors each year that could be at risk

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to both local and distant tsunami hazards, with over 100 cities and 60 maritime vulnerable communities (Fig. 1; California Seismic Safety Commission, 2005). Since AD 1800, there have been over 100 tsunamis observed or recorded in California (Lander et al., 1993). Although the majority of these events have not caused widespread damage, most tsunamis produced strong currents and other tsunami hazards within harbors that created significant problems for many of the state's maritime communities. Sediment erosion and deposition within harbors have also caused longer-term impacts on recovery and resiliency of individual maritime communities.

Lander et al. (1993) reports that the 1960 Chilean and 1964 Alaskan teletsunamis caused scour and sedimentation in a number of harbors in California. During the 1960 tsunami, sediment 4 m thick was reportedly deposited in parts of Crescent City outer harbor. In 1964, in addition to significant flooding and 12 fatalities in Crescent City, a number of harbors experienced scour around pilings and sedimentation within access channels (NGDC, 2011). More recently, the Chilean tsunami of February 27, 2010 caused enough erosion in the channel entrance to Ventura Harbor that the harbormaster reported \$100,000 of savings in dredging costs (Wilson et al., 2010). Unfortunately, the harbor also sustained over \$300,000 in damage to docks from rapid water-level changes and strong currents.

On March 11, 2011, at 1446 Japanese Standard Time (JST) and March 10, at 2146 PST, a M_w 9.0 earthquake struck the eastern coast of the Tohoku region, northern Honshu Island, Japan, generating a large, locally destructive tsunami and a damaging teletsunami on the West Coast of the U.S. In California, the tsunami reached a peak amplitude of 2.47 m at Crescent City and created strong ebb/flow currents along much of its coastline. These conditions resulted in over \$50-million in damage to nearly two dozen harbors and ports (Fig. 1) (Wilson et al., 2011; Wilson et al., 2012). Significant damage occurred to docks and boats within Crescent City and Santa Cruz harbors where some of the most hazardous tsunami conditions were observed. These harbors were also two of the locations where significant channel scour and sediment deposition occurred, creating delays in reconstruction and recovery efforts. For this reason, these two harbors were the focus of this study.

The physical effects of sediment transport within Crescent City and Santa Cruz harbors during the March 11, 2011 tsunami, and the long-term recovery issues facing these harbor districts are discussed. Tsunami flow patterns, documented from video and eyewitness accounts, are used to help chronicle the event at each location. Sediment erosion and deposition are analyzed and compared to observed strong tsunami currents and the overall harbor layout. The impact of scour and sedimentation on harbor operations and recovery is assessed, and recommendations to help harbors become more resilient to tsunamis in the future are advanced.

2. Data use and analysis techniques

2.1. Field observations and video data

At the beginning of 2011, the California Geological Survey (CGS) received funding from the National Tsunami Hazard Mitigation Program to develop a pre- and post-tsunami field team program that would be tied to a statewide information clearinghouse for emergency response (Wilson et al., 2011). In the aftermath of the March 11, 2011 Tohoku teletsunami, the California Geological Survey (CGS)

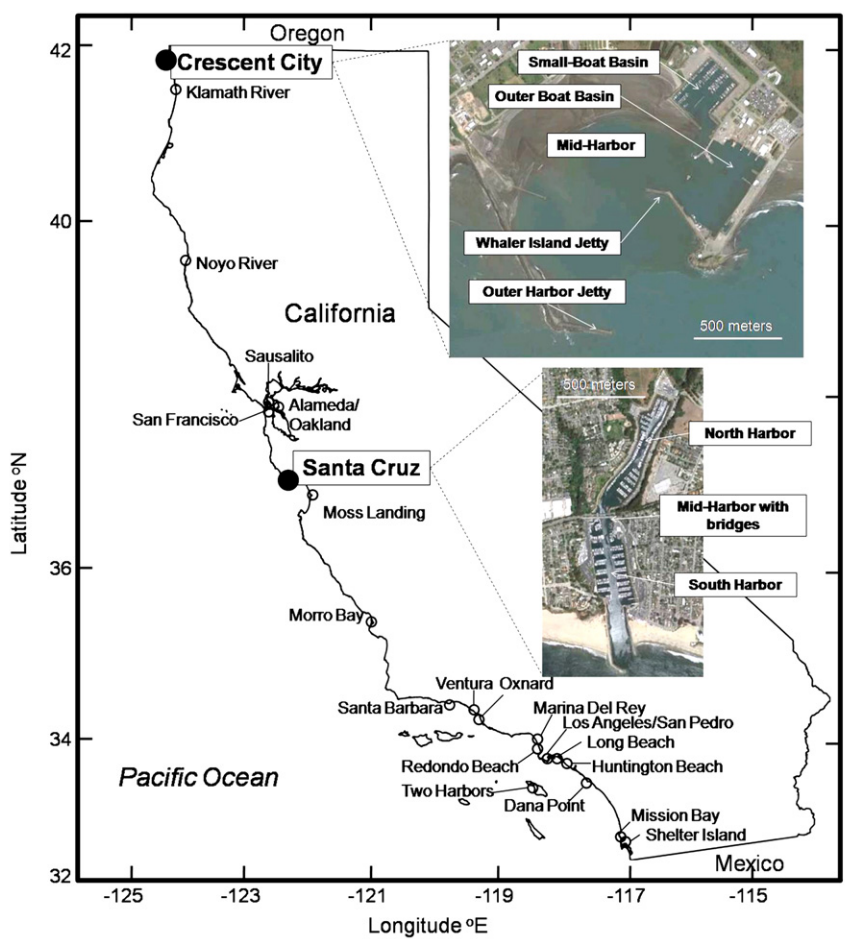

Fig. 1. Location map showing harbors impacted in California by the March 11, 2011 Tohoku-oki tsunami. Inset maps show regions of the Crescent City and Santa Cruz harbors, both the primary locations of this study.

coordinated with scientists and engineers from other agencies, universities, and private industry to deploy eight field teams to interview harbormasters and coastal State Park representatives, and record the transient physical effects of the tsunami. Information was gathered through questionnaires or in person by the field teams at over 180 coastal locations. In addition, hundreds of security camera and online videos from the ground and air were gathered to help document a time-history of the tsunami, specifically inside harbors. Thirty videos from Crescent City Harbor and over 70 videos from Santa Cruz Harbor were reviewed for this analysis.

Current velocities were estimated and flow patterns identified from tracking debris in videos during significant and likely damaging tsunami activity. Tsunami time-histories were developed and hazard areas were identified to assess where and why sediment scour and deposition occurred within these harbors. Beyond this study, information gathered from these videos and eye-witness accounts will be used to calibrate tsunami current velocity data from numerical modeling statewide, to help in the development of in-harbor hazard maps, offshore safety zones for boats, and guidance for the state's maritime community (Miller et al., 2011).

2.2. Bathymetric data

When it was determined that several California harbors had experienced considerable scour and sedimentation, available harbor bathymetric data were acquired in order to help evaluate tsunami currents and damage related to sediment movement. In California, these bathymetric data have been collected from various sources: the U.S. Army Corps of Engineers (USACE), the National Oceanic and Atmospheric Administration (NOAA), the U.S. Geological Survey (USGS), private companies, and the harbors themselves. Data collected from these groups are listed in Table 1. In order to measure the amount of erosional/depositional change, bathymetric data from before and after the tsunami were acquired and compared ("bathymetric change analysis") where available. Most pre-tsunami bathymetry was related to sediment dredging activities. Although some limited dredging may have occurred between the times various bathymetric data were collected, harbor masters indicated that dredging was not significant enough to account for the large changes observed in the bathymetry. A number of problems arose with these data sets due to: 1) the infrequency of collection, 2) different sounding techniques, 3) the poor resolution and distribution of harbor sounding coverage, 4) non-uniform projection of the spatial data, and 5) the non-digital format of a significant amount of the data. However, these data were still determined to be helpful in understanding tsunami-related scour and deposition of sediments.

The USACE provided pre- and post-tsunami bathymetric survey data for the Crescent City entrance channel in Environmental Systems Research Institute's (ESRI's) ArcGIS Geodatabase format (Moore, 2011). USACE also provided similar data related to many other harbors in California, however, most datasets were not collected close enough in time to allow the tsunami effects to be isolated, and therefore were not used. The NOAA provided pre- and post tsunami survey data (NOAA 2008 and NOAA 2011a, respectively) in grid format covering most of the Crescent City inner (Small-Boat Basin) and outer harbors and entrance channels, as well as a post-tsunami bathymetric survey covering most of the Santa Cruz Harbor (NOAA, 2011b). The USGS also provided post-tsunami gridded bathymetry data for the Santa Cruz Harbor (USGS, 2011), collected using an interferometric sidescan sonar system (see Foxgrover et al., 2011, for description of the system). Hard copies of sounding data collected shortly before the March 11, 2011 tsunami at the northern end of the Santa Cruz Harbor and before and after soundings of the entrance channel at the south end of the harbor were obtained from the Santa Cruz Harbormaster's files (Santa Cruz Harbormaster, 2011). Table 1 provides a summary of the various data providers and types used for this study.

The various data were first converted as necessary into a consistent format for analyses within ArcGIS 9.3. The harbormaster surveys were scanned and georeferenced using ESRI's World 2-D Imagery (ESRI, 2011) as a backdrop to control the "rubber-sheeting" effort. The NOAA and USGS grid files were converted to shapefiles, and all data sets were reprojected as necessary to the NAD83 State Plane 1 (Crescent City) or State Plane 3 (Santa Cruz) coordinate systems to match the earlier data provided by the USACE. All depths provided were relative to Mean Lower Low Water (MLLW). Triangular Irregular Network (TIN) depth surfaces for each data set were constructed; "TIN Difference" shapefiles comparing primarily pre- and post tsunami

Table 1
Summary of pre- and post-tsunami bathymetric data obtained for analysis.

Harbor	Data provided by	Collection dates	Collection method	Data type	Area of coverage
	NOAA	November 18–23, 2008	200% side-scan sonar and object detection multibeam echosounder	Grid format; converted to GIS shapefile by CGS	Most of outer harbor; partial coverage in northern mid-harbor; portion of NE-mid-harbor adjacent to Whaler Island jetty; entrance channel to Small-Boat Basin and channels between all and beneath some docks
	USACE SPN	February 21, 2010; March 30, 2011	Single-beam sonar	ESRI geodatabase	Main shipping channel, from outer harbor entrance to Small-Boat Basin entrance, and partially into Outer Boat Basin
	NOAA	March 17–21, 2011	200% side-scan sonar and object detection multibeam echosounder	Grid format; converted to GIS shapefile by CGS	Most of outer harbor; partial coverage in northern mid-harbor; portion of NE-mid-harbor adjacent to Whaler Island jetty; entrance channel to Small-Boat Basin and channels between some (eastern) docks
	Harbormaster	March 19–20, 2011	Multibeam sonar	Hard copy preliminary figure showing scour/fill depths, relative to "Oct 2009 Survey"; "rubber-sheeted" by CGS	Entrance to and most of Small-Boat Basin
Santa Cruz	Harbormaster	January 27–28 2011; February 21, 2011	Fathometer and tide-stick	Hard Copies North Harbor soundings; georeferenced and digitized by CGS	Northern part of north harbor (J-, X3-, I- and H-docks)
	Harbormaster	February 23, 2011; March 21, 2011	Fathometer	Hard copies entrance channel soundings; georeferenced and digitized by CGS	Majority of harbor entrance, ~80 m outboard and 120 m inboard of jetty tips
	NOAA	March 21, 2011	200% side-scan sonar and object detection multibeam echosounder	Grid format; converted to GIS shapefile by CGS	~25 meter wide swath outside and inside jetty tips; main channel and between most docks in south harbor; main channel and minor coverage in channels between docks, north harbor
	USGS	May 5–6, 2011	SWATHplus-M phase-differencing sidescan sonar	Grid format; converted to GIS shapefile by CGS	Main channel and most of channels between docks north and south harbors; ~65 meter swath at, and ~400 × 280 meter oval coverage outside jetty tips

datasets were subsequently prepared for each harbor to identify scour and fill locations and obtain volumetric estimates of sediment displacements. To facilitate contouring of bathymetric changes associated with the tsunami, TIN surfaces were converted to raster grid format, the pre-tsunami surface subtracted from the post-tsunami surface, and the resulting difference surface contoured. Figures showing bathymetric changes in this paper include both the TIN Difference and raster contours, and use ESRI's (2011) imagery to illustrate physical features of the harbors.

2.3. Sediment data

In addition to video and bathymetric data, physical characteristics of the harbor tsunami deposits were evaluated where these data were available. As part of normal dredging activities in Crescent City and Santa Cruz harbors, reconnaissance, pre- and post-dredging sediment surveys were completed by the harbors prior to the March 11 tsunami and were available for analysis. After the tsunami, detailed sediment studies, including grain-size, biological, and chemical analyses, were completed by both harbor districts to determine the suitability of disposing the sediment at sea. Cross-sections using bathymetric and sediment data were constructed to determine the depth and amount of tsunami erosion and deposition within portions of the harbors. This helped differentiate tsunami deposits from pre-tsunami material, and assisted in developing tsunami flow regimes within the harbors.

3. Tsunami scour and deposition in Crescent City and Santa Cruz harbors

The March 11, 2011 teletsunami was the largest tsunami to hit the California coast since the devastating 1964 Alaskan event. Although inundation of dry land was not notable, maritime communities along the coast endured considerable damage from the tsunami and lasting impacts from sediment scour and deposition, especially in Crescent City and Santa Cruz harbors. Scour and deposition also occurred at several other places, albeit to a lesser extent. The following results are presented based on analyses of video, bathymetry, and sediment deposited at these locations.

3.1. Crescent City Harbor

3.1.1. Background

The most severe tsunami effects in the state occurred within the Small-Boat Basin (SBB) at Crescent City, which is known for being vulnerable to tsunamis (Dengler et al., 2009). Maximum tsunami amplitudes (height above normal water level) of 2.5 m were forecast for Crescent City, initiating a full evacuation of the city's tsunami hazard zone on land and mass departure of the commercial fishing fleet from the harbor. Within the first 2 h of tsunami activity, the tide gauge located outside the SBB recorded a peak tsunami amplitude of 2.47 m, which fortunately occurred at low tide resulting in minimal inundation of dry land. Strong currents were observed throughout the outer harbor and SBB, with video particle-movement analyses indicating peak currents of 4.5 m/s at the mouth of the SBB (Fig. 2a; Admire et al., 2011). Large sea-level oscillations caused dangerously strong currents that lasted for over 24 h (Wilson et al., 2011). Almost all docks within the SBB were heavily damaged or destroyed (Fig. 2b). Although dozens of ships successfully evacuated from the harbor at Crescent City prior to the tsunami, of those remaining in the SBB, 16 boats were sunk and 47 were damaged according to Coast Guard reports. Overall, the harbor sustained \$20 M in damage to structures not previously damaged during the November 16, 2006 Kuril Islands tsunami. This earlier event also caused \$20 M in damage that had still not been fully repaired because of delays in funding (Richard Young, personal communication).

Fig. 2. Tsunami currents and damage in Crescent City Harbor. (a) Strong currents at the mouth of the Small-Boat Basin and across the center of basin; (b) heavily damaged or destroyed docks. Yellow arrows show areas of sediment accumulation; (c) sunk boat sits on shallow floor of Small-Boat Basin where sediment has accumulated; (d) failure of slopes caused by tsunami scour and undercutting.

Fig. 2b and c shows harbor debris and shallow areas where sediment accumulated, which appear to coincide with locations where eddies or low current velocity regions were visible on videos. A Federal Disaster was declared for the harbor that allowed for federal and state funding relief of $19 M of the $20 M repair costs, leaving the harbor district to pay $1 M (in addition to the $5 M it had to pay to repair damage from the 2006 tsunami, Richard Young, personal communications). According to Coast Guard records, a number of sunken boats leaked fuel and other petroleum products, initiating careful monitoring by state and federal agencies. The fuel was cautiously extricated from the fuel tanks of the sunken boats, which were then removed over a period of several months. Sampling of sediment deposited by the tsunami was required by state and federal agencies to make sure that it was not contaminated and that it was composed of sufficient coarse-grained material to allow for offshore disposal, which is significantly more cost effective than on-land disposal in a landfill. Sampling of the harbor sediment was put on hold for a number of months while regulatory agencies determined the best method to perform sediment analyses. The regulatory review determined that tsunami deposits were of suitable grain-size composition and lacked significant contamination such that they could be placed in USEPA's permitted disposal location (HOODS) offshore of Humboldt Bay, instead of in an onshore landfill, saving millions of dollars in disposal costs. Dredging of the SBB started in September 2011, and as of December 2011, the harbor was still being dredged of tsunami sediments, which totals some 150,000 m^3 of material (Weston Solutions, Inc., 2011). In addition, repairs to the protected slopes along the edge of the harbor were required after scour, undercutting and failure occurred (Fig. 2d). According to Harbormaster Richard Young, dredging delays significantly reduced harbor revenue needed to produce the harbor's matching funds required to obtain federal and state funds, a problem that will cause additional delays in harbor repair projects.

3.1.2. Analysis

Two sets of pre- and post-tsunami bathymetric data were obtained for the Crescent City Harbor. Single-beam sonar depth data was collected on 21 February 2010 and 30 March 2011 by the USACE (Moore, 2011) as part of their ongoing assessment of the harbor entrance channel conditions (e.g., “Conditional” survey). Datasets were limited to the main entrance channel and do not extend into the SBB or other parts of the outer harbor. NOAA's multi-beam bathymetry collected on November 18–23, 2008 and March 17–21, 2011 (NOAA, 2008 and NOAA, 2011a) provided additional sets of data with a larger area of coverage for Crescent City Harbor, including the SBB. There were no significant differences between the pre-tsunami bathymetric data from NOAA's 2008 and USACE's 2010 surveys where they overlapped, supporting the use of the larger dataset from 2008 for comparisons with the post-tsunami data. Therefore, comparisons between the NOAA 2008 and post-tsunami 2011 data were utilized in the bathymetric change analyses as shown in Figs. 3 and 4.

Following a meeting with the Crescent City Harbormaster, a third data set was discovered to exist for the SBB: a hard copy “Preliminary” figure (Stover Engineering, 2011) showing bathymetric changes between an “October 2009 Survey” and a “Survey conducted on March 19–20 by Terrasond Limited”. The CGS was unable to obtain these two digital datasets from their owners in time to prepare analyses for this study. However, after scanning and “rubber-sheeting” this figure to match the harbor layout (ESRI, 2011), changes on the Stover Engineering (2011) figure showed a good agreement with the NOAA dataset comparison where they overlapped within the SBB (Fig. 3a). The Stover Engineering figure also includes bathymetric change information from the western portion of the SBB, which was not part of the overlay area of the NOAA survey events. It was also assumed that the Terrasond and NOAA 2011 surveys are similar, due to the overlapping survey dates.

Figs. 3a and 4 show bathymetric changes observed between the 2011 and 2008 NOAA sounding events within portions of the Crescent City SBB and outer/mid-harbors, respectively. The area of overlap between the two survey events is approximately 0.67 km^2. Within the overlap area, about 289,360 m^3 of sediment was scoured. Deposition amounted to approximately 154,600 m^3, and covered approximately 55% of the survey overlap within both the outer and inner harbor areas. However, these numbers are minimums, because the surveys do not extend throughout all parts of the harbor, and they do not include deposition in the western portion of the SBB that was identified on the Stover Engineering figure (included on Fig. 3a). Overall, it appears that the tsunami removed sediment from the harbor (65% of total volume change), although deposition was significant and created navigation problems within portions of the mid-harbor and shoaling within the SBB to the point where much of the inner harbor was unusable.

Sediment composition in the exploration cores collected in the SBB by Weston Solutions (Weston Solutions, Inc., 2011) was compared to bathymetric changes to improve our understanding of erosion and deposition from the 2011 Tohoku-oki tsunami (Fig. 3a). Sediment samples were analyzed for sand (%), fines (silt and clay combined) (%), Percent Solids, Total Organic Carbon (%), petroleum material and various other contaminants. Fig. 3b is a cross-section showing post-tsunami bathymetry, sediment composition, and correlations between tsunami and non-tsunami deposits within the SBB. Based on grain-size differences and the depth of the materials, a clear distinction can be seen between the coarse-grained tsunami deposits and underlying fine-grained sediment. In most places, the tsunami deposit has two units: 1) an upper silty sand layer with “peat”, or organic debris, and 2) a lower silty sand layer without organics. The thickness of these units varies across the basin depending on areas of scour or deposition, but they generally terminate at a 3.2-meter depth. Below this normal, pre-tsunami basin deposits composed of sandy clays and clayey sands are present. The percent sand in samples selected to represent the upper 3.8-meters of material that can be dredged ranged from 43% (core CC-IH-7) to 93% (CC-IH-10), with the former being the only one below 70%. Because CC-IH-7 starts at a depth of 3.2 m and is close to the scour channel, the low sand value is likely a result of sampling mostly normal basin (pre-tsunami) deposits.

From bathymetry and sediment analyses, the areas of scour and sediment accumulation can be clearly defined. This information is combined with observations of various (30) ground-level and aerial videos to develop a tsunami flow-regime map (Fig. 5) identifying areas of strong currents, sediment erosion and sedimentation. Estimates of flow velocities from Admire et al. (2011) and the videos evaluated during this study are also shown on the map. These velocities were calculated by analyzing the movement of floating debris, comparing distance to travel time, during the first several hours of tsunami activity, the time of highest surge energy and, therefore, highest sediment transport.

Based on the overall analysis of videos, pre- and post-tsunami bathymetric differences, and sediment grain size, a detailed picture of how sediment transport occurred during the tsunami in Crescent City Harbor was constructed. During the period of the most energetic activity, the tsunami surged into and out of the outer harbor entrance, rapidly filling and draining the entire basin with water (Fig. 5). At the outer harbor entrance, strong currents were not as visibly apparent suggesting that the tsunami surge was spreading out and losing energy as it entered the expanse of the outer harbor. Both onshore and backwash currents likely scoured sediment from the entrance channel with deeper scour (2 to 5 + meters) occurring near physical structures on either side of the main harbor entrance (Fig. 4). The zone of scour narrowed from at least 100 to 60 m or less within the outer

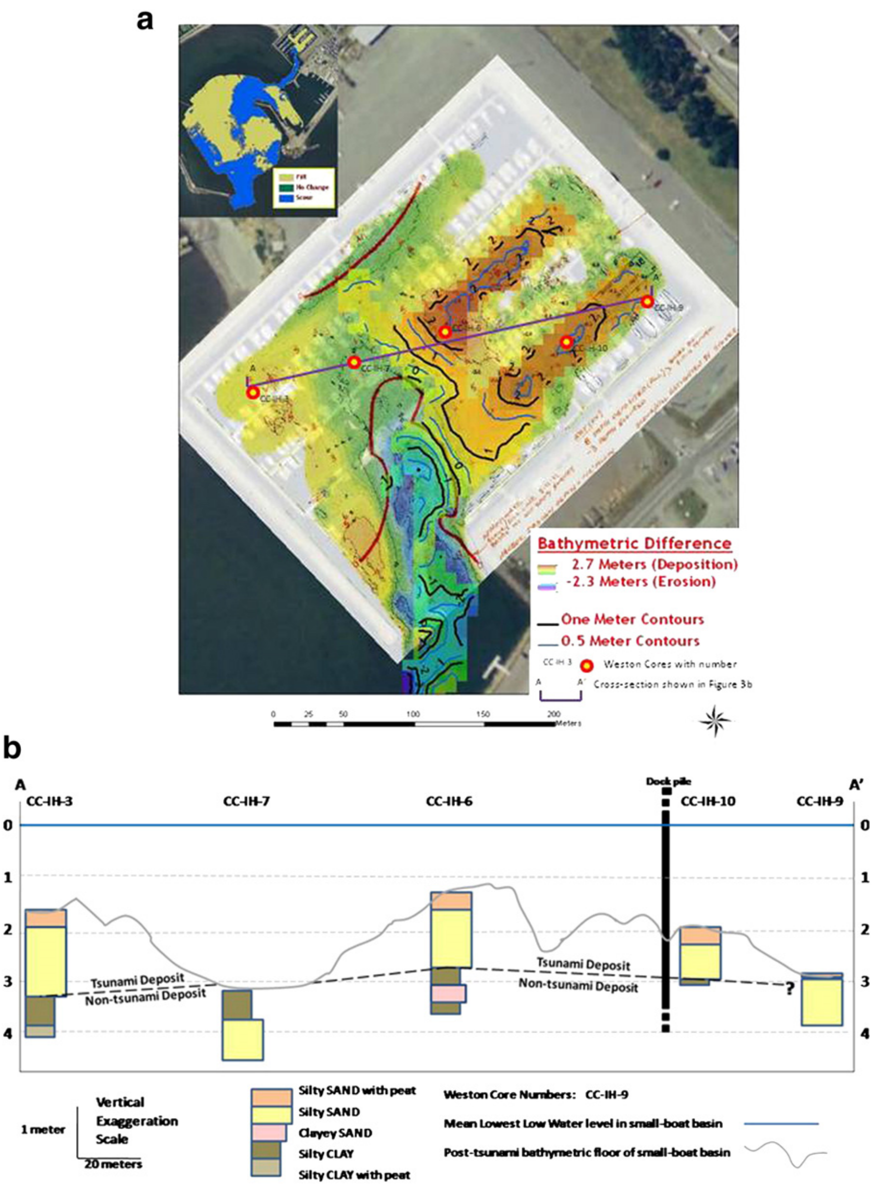

Fig. 3. (a) Areas of scour and fill in the Crescent City Harbor Small-Boat Basin determined by differencing multi-beam bathymetry collected by NOAA on March 16–21, 2011 and November 2008, superimposed on similar, more extensive raster image provided by Harbormaster (Stover Engineering, 2011); (b) cross section showing the post-tsunami bathymetry, sediment composition, and correlations between tsunami and non-tsunami deposits within the Small-Boat Basin.

harbor, while the net bathymetric difference decreased to nearly zero. Scouring was observed to increase in the vicinity of the Whaler Island jetty (as much as 4 m of scour off the jetty tip), with scour continuing along the backside of the jetty and into the southeast portion of the mid-harbor ("Outer Boat Basin"). Tsunami scour area also continued on through the mid-harbor area, parallel and adjacent to the SBB's southern pier towards the entrance to the SBB, scouring as much as 4 m along the northwest side of the entrance channel (Fig. 4). The depth of erosion within the channel into the SBB decreases to less than 1 m just inside the SBB entrance, increases for a short distance and, about 200 m north of the SBB breakwater's tip, the zone of scour changes to one of shallow deposition. Based on video evidence and relative deposit thicknesses, the tsunami wave front continued northwards to the northwest SBB boundary, with minor deposition (less than 1 m) occurring along the energy flow's longitudinal axis (Fig. 5). Localized scour of up to a meter occurred at the base of dock piles caused by strong swirling currents (Figs. 2a and 3b). There was minor scour where tsunami surges collided with the northwest SBB boundary. Thick plumes of suspended fine-grained material carried from outside the SBB may have increased the density of the water, possibly aiding the suspension and movement of the coarser material. Entrained sediment was deposited on either side of the scour/thin deposit zone, likely as a result of flow deceleration and slower water velocities caused by eddies and back-pressure from reflected waves. The decrease in flow velocity is associated with the tsunami's collision with the SBB boundary and, to a lesser extent, the docks before they were damaged. Thicker deposition throughout a larger portion of the SBB east of the main scour zone implies that much of the entrained sediment was directed this way, preferentially deposited in the channels between docks and around large accumulations of tsunami debris (Fig. 5).

Tsunami scour also occurred around the end of the Whaler Island jetty and extended southeastwards into the southeastern mid-harbor along the inboard side of the jetty (Fig. 4). A ridge of sediment up to 1 meter thick was deposited along the central portion of the entrance to the Outer Boat Basin (OBB), parallel to the scoured zone. Conditions resulting in observed scour and deposition relationships hypothesized above for the SBB may be similar for the OBB. The wave

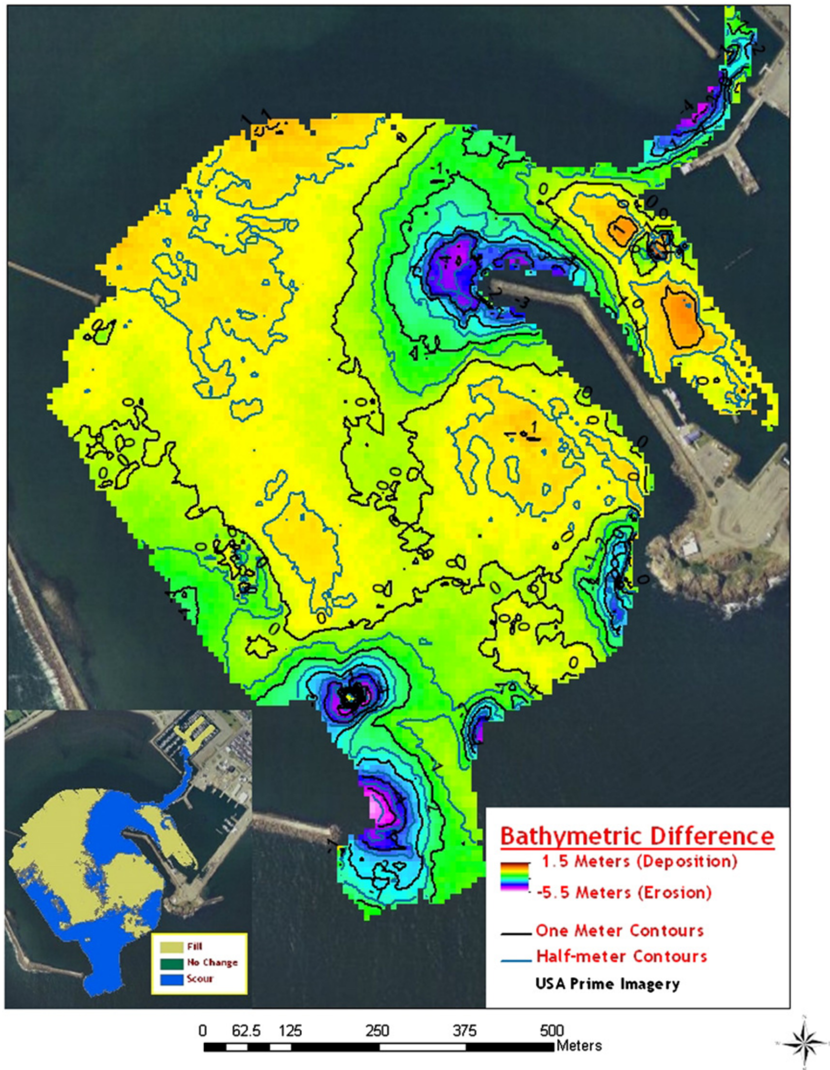

Fig. 4. Areas of scour and fill in the outer and middle portion of the Crescent City Harbor determined by differencing multi-beam bathymetry collected by NOAA on March 16–21, 2011 and November 2008.

Fig. 5. Tsunami flow-regime map for Crescent City Harbor. Current directions and velocities, and areas of sediment erosion and deposition are based on observations of the various (30) ground-level and aerial video, pre- and post-tsunami bathymetry, and sediment analyses.

front associated with the scour entering the OBB beneath and near the tip of the pier (where erosion was seen) at the entrance to the mid-harbor would continue until colliding with the levee connecting Whaler Island to the mainland. The scour previously described around Whaler Island jetty was likely created by the strong outgoing currents that vacated the OBB of water during the ebb of the tsunami surges. Disorganized flow and eddies between the scour zones at the mid-harbor pier and the Whaler Island levee and jetty provided sediment for deposition along the elongated sediment ridge extending into the OBB surrounding Bird Island.

Unfortunately, a lack of adequate bathymetric change information precludes a definitive correlation of conditions hypothesized for the OBB with those concluded for the SBB. Similarly, a lack of additional bathymetric change information across other portions of the Crescent City Harbor precludes an analysis of whether the scour, turbulence and depositional conditions observed in the SBB and suggested for the OBB existed in the northwestern mid-harbor and outer harbor. There certainly appears to be similarities with deposition of sediment on either side of the scour zone and the loss of scour depth along the scour zone's longitudinal axis observed within the outer and entrance to the northwest mid-harbor areas.

To summarize, major scour occurred at outer and mid-harbor jetties and at the mouth of the SBB due to water current velocities observed to be up to 4.6 m/s (9 kn) (Fig. 5). In the outer harbor, strong onshore and backwash tsunami currents scoured sediment around the abrupt edges of the jetties that interrupted linear flow patterns. Within the SBB, coarse-grained sediment was carried by currents ranging from 2 to 3 m/s (4 to 6 kn) with the jetting tsunami surge across the basin and along the northwestern side through suspension and saltation. Ultimately, like much of the debris within the SBB, the majority of the sediment came to rest where the observed currents slowed and formed eddies throughout the harbor. Both the debris, comprised of dock and boat material, and the accumulating sediment reduced the velocity of the currents, further decelerating the flow and decreasing sediment transport and facilitating additional sediment deposition.

3.2. Santa Cruz Harbor

3.2.1. Background

Though no tide gauge exists within Santa Cruz Harbor, peak tsunami amplitudes of 1.6 to 1.9 m were observed in the harbor (Wilson et al., 2011). In addition to strong currents causing damage to boats and docks (Fig. 6a), approximately 3 h after the first tsunami wave arrival, several large, fast-moving bores were observed traveling to the back (north) of the harbor, causing significant damage to dock infrastructure where the harbor narrows (Fig. 6b). The elongate shape of the harbor likely amplified incoming surges causing the strong currents and bores described (Wilson et al., 2012). The overall damage to the harbor was more than $28 M, with 14 boats sunk and dozens of others damaged (Mesiti-Miller Engineering, Inc., 2011; Chuck Izenstark, personal communication). Of the harbor's 29 docks, 23 sustained significant damage ranging from severe float cracking to complete destruction. Although sediment scour and deposition was not as significant in Santa Cruz Harbor as it was in Crescent City Harbor, it was still noteworthy in portions of the harbor. As of December 2011, repair work and dredging of tsunami-related sedimentation within the harbor were ongoing, partially because of delays in sediment analysis similar to that experienced at Crescent City.

3.2.2. Analysis

The comparison of pre- and post-tsunami bathymetric conditions was conducted using data sets obtained from the Santa Cruz Harbormaster, NOAA and the USGS. Hard copies of soundings collected by the harbormaster were reviewed and it was determined that relatively recent pre-tsunami information was only available for the northern end of the North Harbor (27–28 January and 21 February, 2011), and the harbor entrance channel and immediately seaward of the harbor jetties (various dates, 23 February and 21 March 2011 selected for analyses). Lack of relatively recent bathymetry between the harbor entrance and the northern extent of North Harbor precludes any assessment of sediment transport in this area at this time. Other data were available but of sufficient age such that comparisons to post-tsunami conditions would need to consider other factors such as shoaling, long-term sedimentation, and other effects.

Hard copies of sounding data, corrected to MLLW, were georeferenced, "rubber-sheeted", and digitized over the physical features of the north harbor and harbor entrance (ESRI, 2011). The 27–28 January 2011 pre-dredge and 21 February 2011 post-dredge soundings for the north harbor were combined into one "pre-tsunami" layer due to the short period of time between the two surveys and the limited amount of data available to analyze. Only January soundings for areas not covered by the less extensive February soundings were included in the combined pre-tsunami layer. Post-tsunami bathymetric data from two sources were available for this project. NOAA conducted a shallow water multibeam echosounder survey of the entire harbor system on March 21, 2011. The U.S. Geological Survey also conducted a survey of the entire harbor system on May 5–6, 2011, using interferometric sidescan sonar for swath mapping. These datasets were reprojected to the common projection/datum for the Santa Cruz area (NAD83 State

Fig. 6. Tsunami currents, erosion, and damage in Santa Cruz Harbor. (a) Strong currents cause damage to boats within harbor; (b) heavily damaged or destroyed docks as tsunami bores enter the northern part of the harbor; (c) base of bridge foundation exposed and scoured as receding waters rush through the central part of the harbor; (d) scour where drainage from Arana Gulch Creek enters the harbor at the north end.

Plane 3), and various TIN and Raster surfaces, difference and contour shapefiles, as discussed in Crescent City Harbor section above, were prepared for analysis at the harbor entrance and the north end of the harbor.

Fig. 7 shows bathymetric changes observed between pre- and post-tsunami Harbormaster surveys at the harbor entrance, while Fig. 8 illustrates bathymetric differences between Harbormaster and NOAA surveys conducted in the northern harbor before and after the tsunami respectively. The area of overlap between the two survey events at the harbor entrance is approximately 15,550 m^2 and approximately 11,950 m^2 in the north harbor area.

Comparison of the Harbormaster before- and after-tsunami surveys at the harbor entrance indicates that about 5,650 m^3 of sediment was scoured, while deposition amounted to approximately 9,900 m^3 and covered approximately 64% of the area common to both surveys. However, a different picture emerges when comparing bathymetric surfaces prepared from the Harbormaster pre-tsunami and the March 21, 2011 NOAA post-tsunami surveys. That analysis indicates that approximately 14,800 m^3 of sediment was scoured, while only 4150 m^3 was deposited over 4.5% of the area common to these two surveys. Causes for the disparity between the two comparisons are not clear at this time, but likely related in part to the differences in how depths were determined and errors introduced when transcribing approximate locations on the harbormaster's hard copies into digital format. A large part of the difference is likely related to the Harbormaster surveys recording significant shoaling along the inboard edge of the West Jetty, an area that was not covered by the NOAA survey.

At the far end of the North Harbor, recorded scour amounted to approximately 85 m^3 of sediment while approximately 70 m^3 was deposited across 50% of the area common to the Harbormaster's January/February sounding and the NOAA survey. However, these numbers are minimums, as the surveys did not extend throughout all parts of the harbor, and do not include tsunami fill beneath several of the docks paralleling the main channel within the North Harbor (Red Hill Environmental, 2011). Scour occurred at the far northern end of the harbor where Arana Gulch drains into the harbor, and localized erosion of over a meter was still evident in that area when comparing the Harbormaster's pre-tsunami survey with bathymetry collected by the USGS almost two months after the event.

As part of the harbors pre-dredge survey and Sampling and Analysis Plan to remove tsunami deposits, Red Hill Environmental (2011) collected sediment samples in the back part of the harbor (Fig. 8) on August 2 and 3, 2011. Samples collected from each location were described as tsunami (upper sample) or yearly (lower sample), and tested for sand (%), fines (silt and clay combined) (%), Percent Solids, and Total Organic Carbon (%). The yearly samples were typical of ongoing harbor sedimentation, while tsunami deposits were typically

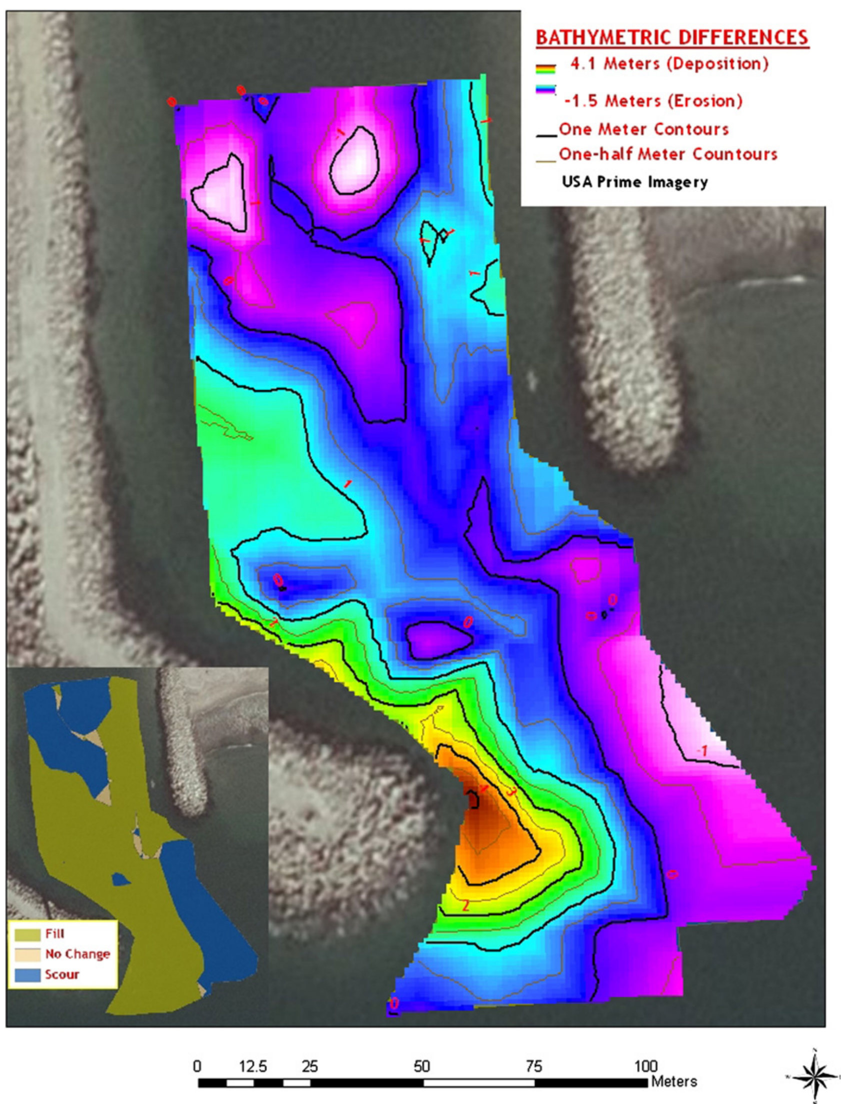

Fig. 7. Areas of scour and fill at Santa Cruz Harbor entrance, determined by differencing Harbormaster soundings collected on March 21, 2011 and February 23, 2011.

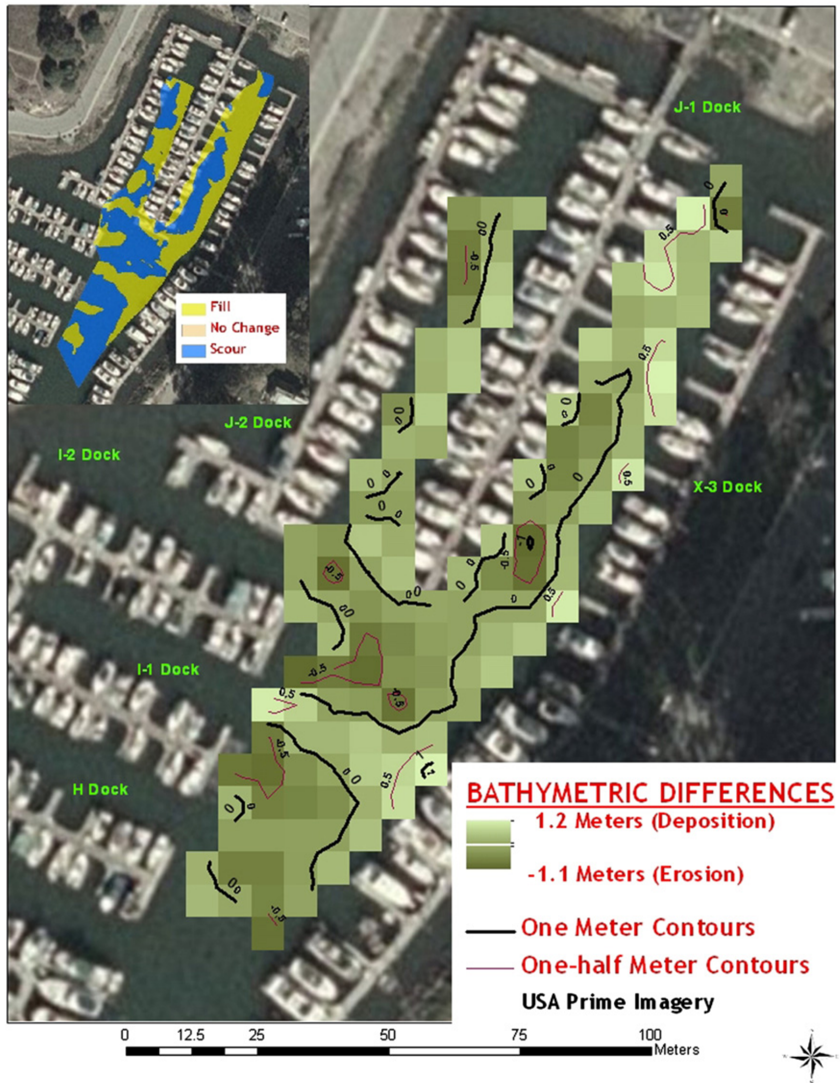

Fig. 8. Areas of scour and fill near the north end of the Santa Cruz Harbor determined by differencing Harbormaster soundings, collected on January 27–28, 2011, and February 21, 2011, with multi-beam bathymetry collected by NOAA on March 21, 2011.

(but not always) more sandy and lighter in color (Rick Krcik, personal communication 2011). The sand content of the tsunami deposits in the vicinity of X3 and J1 Docks ranged from 6% (below J2 Dock) to 29% (in channel between X3 and J2 Docks), greater than that recorded for the yearly sample. Similarly, the tsunami deposits contained increased sand contents 9% to 23% higher than the yearly sample taken beneath I1 and H Docks, respectively. However, the tsunami deposits contained lower sand percentages than the yearly deposits below the western side of J1, southern tip of J2 and I2 Docks, and in the "North Harbor Turning Area" located between the X3, J2, I2 and I1 Docks.

The average sand content for tsunami and yearly deposits in the X3–J2 channel was 91% and 69%, respectively. The "percent solids" was consistently greater for the tsunami deposits in this area, while the Total Organic Carbon percentages were two to three times higher in the yearly deposits. This pattern did not hold for other areas of the northern harbor; samples where the percent sand in the tsunami deposit was recorded lower than the yearly deposit had lower percent solids in the tsunami deposit while the Total Organic Carbon percentages were comparable (Red Hill Environmental, 2011).

Red HIll Environmental (2011) also collected composite surficial samples from transects normal to the entrance channel. Sand content in the composite samples ranges from 84 to 99%. Percent solids ranged from 71 to 77%, and TOC ranged from 1.0 to 1.4%. Based on visual comparison of sample locations (Red Hill Environmental, 2011) and the Harbormaster survey comparison presented in this study, with the possible exception of one transect, samples appear to have been taken from a range of both tsunami scour and fill areas. However, the Harbormaster versus NOAA bathymetric change analysis indicates a more consistent sediment transport (scour) in the area, but the overlap is not as wide as the sampling transect. Accordingly, correlations between measured physical parameters and tsunami versus normal process deposits are not attempted at this time.

Bathymetric change analysis in the harbor entrance area used a pre-tsunami Harbormaster survey (February 23, 2011) compared against a post-tsunami Harbormaster (March 21, 2011) survey as well as the NOAA and USGS post-tsunami surveys mentioned above. The Harbormaster comparison (Fig. 7) shows extensive shoaling in the vicinity of the west jetty tip, with additional fill alongside the east jetty. Scour zones are indicated within the central portion of the harbor entrance, both outboard and inboard of the jetty tips, while depths in the area between the two scour zones did not change.

Comparison of the NOAA post-tsunami versus Harbormaster pre-tsunami data shows similar scour patterns and is suggestive of some shoaling along the eastern jetty. However, scour appears more pronounced in this comparison than it does when comparing the pre- and post-tsunami Harbormaster surveys, and no indication of shoaling along the western jetty is observed. In general, dependant on the precise location within the harbor entrance, when compared against pre-tsunami data, the Harbormaster 21 March 2011 survey indicates up to 1–2 m more scour than that noted from the NOAA data, collected on the same date.

A minor amount of shoaling southeast of the jetty tips is indicated when comparing the NOAA and Harbormaster survey. Comparison of the USGS and Harbormaster pre- and post tsunami surveys shows extensive scoured areas still present throughout the harbor entrance two months after the event, with over 4 m of change recorded at and just outside the jetty tips. Minor shoaling is also observed in the vicinity of the eastern jetty and the east tip of the western jetty.

Scour is also apparent in portions of the entrance channel when comparing post-tsunami bathymetric data from May (USGS, 2011) and March (NOAA, 2011b), particularly between the jetty tips and parallel to the eastern jetty (two and 1 m of depth change, respectively). Some infilling apparently occurred between these two zones of erosion, while the remainder of the channel within the subject area received only minor deposition (less than 1 m) of post-tsunami sediment.

Over 70 videos from throughout Santa Cruz Harbor were evaluated for this study. Many of these videos captured the tsunami during its most active time, including the multiple bores that destroyed docks and damaged boats in the north part of the harbor (Fig. 6a and b). As with Crescent City, the analysis of the videos was combined with bathymetric and sediment analyses to develop a flow-regime map (Fig. 9). Peak observed current velocities and regions where scour was dominant were also identified. Videos also captured other unique features of the tsunami, such as the substantial drawdown and erosion of sediment during backwash tsunami flows (Fig. 6c) and scour where Arana Gulch Creek enters the harbor at the north end (Fig. 6d). The strongest currents (7 m/s [14 kn]) were observed just north of the two central bridges, and were likely generated because of the narrowing of the harbor in this area (Fig. 9). In general, the central channel throughout the south and north parts of the harbor displayed large current speeds of 4–5 m/s (8–10 kn).

In the southern part of the harbor, the tsunami appears to have scoured a significant amount of material from and seaward of the harbor entrance as it moved into the harbor, eroding more than 1 m of sediment from locations along the entrance channel (Figs. 7 and 9). Preliminary bathymetric comparisons between NOAA's March 21, 2011 multi-beam survey and the Harbormaster's February 23, 2011 soundings indicate that the depth of scour associated with the tsunami may have exceeded 3 m in locations along the channel entrance. The amount of scour decreased as the tsunami entered between the jetties, and then increased again once inland of the jetty tips. Some of this eroded sediment appears to have been deposited along the eastern jetty, with perhaps more significant deposition occurring in the vicinity of the west jetty tip and adjacent, inland areas (Fig. 7). Net scour was still observed at the northern end of the harbor entrance.

Alternating patterns of scour and sediment deposition occurred at the northern end of the harbor (Fig. 8). In the relatively open areas at the turning basin, alternating areas of erosion and deposition were oriented normal to the tsunami current directions. This pattern of alternating sediment ridge/trough development was interrupted by J1 Dock that bifurcates the end of the harbor. Here, the pattern of scour and deposition is elongated in the ebb/flow direction within the relatively narrow harbor channels on either side of J1 Dock.

Preliminary comparison of the May 2011 USGS post-tsunami survey with the harbormaster pre-tsunami survey helps assess harbor conditions two months after the event relative to pre-tsunami conditions. The ridge–trough relationships observed in the north harbor in the NOAA versus Harbormaster comparison became more subdued, with depths recorded by the USGS between zero and one meter shallower (deposition) than those recorded by the harbormaster. Scoured areas observed on the NOAA versus Harbormaster comparison no longer exist, but areas throughout much of the channels between docks still contain as much as one meter of sediment above pre-tsunami levels. Depths at the harbor entrance are deeper than before the tsunami, indicating that a significant amount of sediment has been moved from this area (locally as much as 7 m assuming the shoaling levels recorded by harbormaster on March 21, 2011).

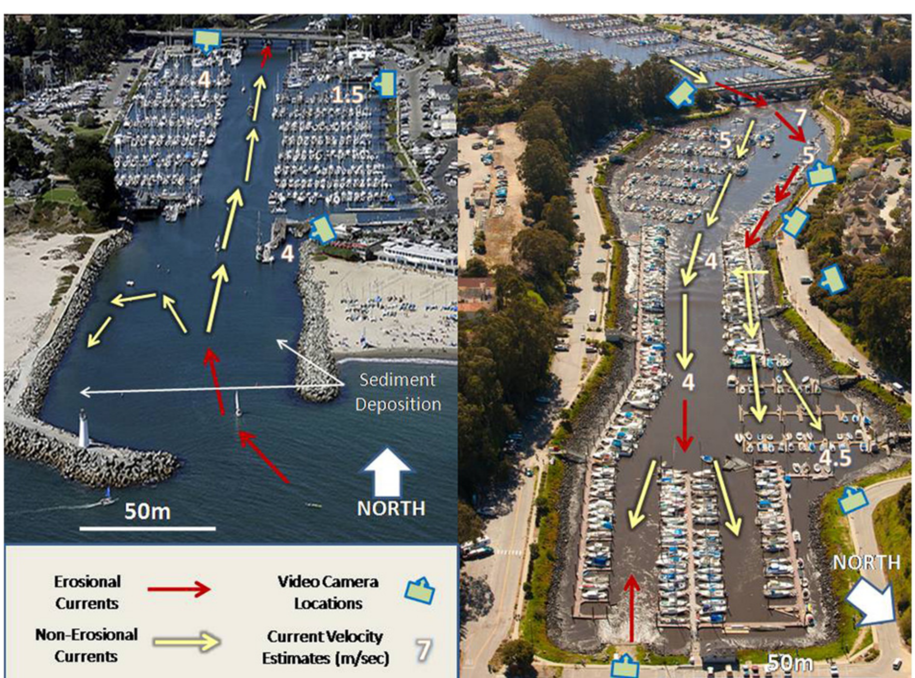

Fig. 9. Tsunami flow-regime map for Santa Cruz Harbor. Current directions and velocities, and areas of sediment erosion and deposition are based on observations of the various (30) ground-level and aerial video, pre- and post-tsunami bathymetry, and sediment analyses.

Therefore, harbor conditions two months after the tsunami exhibited net scour across most of the harbor entrance area and net deposition throughout the north harbor.

Preliminary comparison of the USGS and NOAA post-tsunami bathymetry also provides insight into the recovery of the harbor system from tsunami impacts. Scour between the two surveys is observed in the vicinity of the harbor entrance, locally as much as 2 m. However, the areal distribution and depths of residual erosion is much less than that observed when comparing the USGS (2011) data to that collected by the Harbormaster after the tsunami. Minor scour of shoaled sediment is indicated along the western jetty inland of the entrance. Minor deposition (0–1 m) is observed for the remainder of the harbor entrance, and is also recorded for the northern end of the harbor, while the ridge–trough relationships observed in the north harbor became more subdued in the six weeks between the NOAA and USGS surveys. The pattern of decreasing scour and net deposition in other areas indicates that sediment is being added to the harbor system by non-tsunami-related oceanic processes. Comparison of USGS and NOAA surveys throughout the remainder of the harbor indicates that shallow deposition within the main entrance channel and minor scour of sediment beneath docks along the edges of the channel has occurred between the two surveys.

Overall, the confining and shallow nature of the Santa Cruz Harbor appears to amplify the velocity of tsunami currents increasing the scour of sediment and exacerbating damage to docks and boats. Strong currents were observed within the access channel that goes from the harbor entrance in the south harbor, under the two bridges mid-harbor, and to the back of the north harbor. Fast moving currents and bores generated a peak velocity of 7 m/s (14 kn) and caused significant damage to boats and docks. Moderate tsunami scour occurred in parts of Santa Cruz Harbor where constrictions and previous shallow areas were present. These areas included the harbor entrance, beneath the bridges, and near the back of the North harbor. Sediments accumulated in areas where currents were slower, such as between docks and where eddies occurred outside the central channel.

4. Conclusions

Strong tsunami currents not only cause significant damage to boats and harbor structures, but they also produce significant sediment scour and deposition within harbors in California. Scour caused by the March 11, 2011 Tohoku-oki tsunami was typically observed along the entrance channels and adjacent to harbor structures such as jetties and docks that were controlling or altering the path of the tsunami currents. Scour can impact harbor structures by undercutting and weakening foundations within or adjacent to scour zones, while also producing a significant increase in sediment supply that is subsequently deposited in other sections of harbors, causing further problems for harbor infrastructure and usability. This deposition has caused significant long-term problems for some harbors because of regulatory restrictions on sampling, dredging and disposal of tsunami sediments.

Based on our observations at Crescent City and Santa Cruz Harbors, certain tsunami sediment transport correlations can be made:

- Bathymetric change analyses and analysis of tsunami current videos show close correlations for both scour and depositional areas.
- Narrow constrictions and protuberances within harbors that exist both at the entrance and within harbors can focus and constrict tsunami currents, resulting in faster flows that erode around the edges and base of harbor structures.
- Tsunami currents are focused as they approach harbors due to entrance constrictions and shallowing depths, enhancing the potential for fast-current scour. These currents appear to decrease in velocity once past the immediate entrance, resulting in less scour or even minor deposition before refocusing and continuing erosive activity as the tsunami currents advance further into the harbor.
- Backwash of tsunami currents appears to create similar scour and deposition patterns as the harbors are drained, and could produce an overlay of deposition in areas previously scoured by the incoming tsunami currents.
- Where harbor layout allows, deposition occurs on either side of the erosive currents in a manner similar to fluvial levee and/or overbank deposition. Deposition also occurs in areas of reduced flow speed.
- Eddies and reflected waves were produced from tsunami currents impacting and being diverted by harbor boundaries in a manner related to the geometry of the harbor layout and the direction of current flow.
- Tsunami flow patterns may be qualitatively predicted by analyzing harbor dimensions and layout, and analyzing observations/video of past tsunami inundations.
- Shallow portions of harbors can become exposed during tsunami drawdown and then heavily eroded when surging flows return.
- Floating masses of tsunami debris (boats and docks) can cause further damage and also slow down strong currents, facilitating sediment deposition.

Because tsunami flow patterns and effects can be anticipated, corrective measures can help reduce the problems associated with increased sediment transport. For example, increasing the width of harbor entrances may help reduce the potential for tsunami current jetting within a harbor. Increasing the depth of areas known to be susceptible to strong currents through dredging can also reduce the potential for high velocities and scour from tsunami focusing. Fortifying harbor structures (piles and docks) and removing boats before the arrival of a tsunami will reduce the amount of damage, debris, and potential for sediment accumulation and contamination within harbors.

Ultimately, a detailed plan for dealing with the short- and long-term effects of tsunamis would be beneficial for all harbors. Significant delays in the removal of sediment to restore harbor functionality can be at least partially attributed to not having a pre-approved sediment management plan in place. Given the extensive delays associated with characterizing and removal/disposal of tsunami deposits at both Santa Cruz and Crescent City harbors, a consistent statewide plan for sediment characterization of tsunami deposits would help streamline regulatory review and facilitate harbor repairs, thereby helping with the recovery and overall resiliency of harbors. Having a pre-permitted offshore disposal area located within an economically-reasonable distance of the harbor, or onshore locations that could use the deposits for restorative purposes would also facilitate regulatory review and decision-making.

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