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Wave-Induced Scour Burial Experiments in Carbonate Sediments near Oahu, Hawaii

Michael D. Richardson[1], Edward F. Braithwaite III[1], Paul A. Elmore[1], John Bradley[2], and Roy H. Wilkens[3]

Abstract— **Wave-induced scour burial experiments were conducted at two shallow-water sites along the southern coast of Oahu, Hawaii. Sediments at both sites were moderately well-sorted, fine carbonate sand. Instrumented cylinders were deployed at the Kilo-Nalu coastal observatory during the summer-fall of 2007 and in the Halekulani Sand Channel off Waikiki Beach during the summer of 2008. Water depth at both sites was 12 meters. Two different patterns of burial were observed during the experiments at the Kilo-Nalu observatory. Two instrumented cylinders buried to approximately their diameter (53 cm) after exposure to a single high-wave event (greater than 1.25-m significant wave height). The remaining two instrumented cylinders buried more slowly and to approximately 50% of their diameter (25 cm). Burial measured as surface area covered by sediment varied (5 to 50%) as scour pits developed and were infilled as a result of local sediment transport. The different burial patterns were controlled by sediment layer thickness, with the shallow-buried cylinders actually resting on the coral basement by the end of the experiments. Burial predicted by models for wave-induced scour were in close agreement with burial measured on cylinders deployed in the thicker sediments but the predicted burial was much greater than measured burial for the cylinders limited by sediment thickness. Measured and predicted burial during the second experiment in Halekulani sand channel was less than measured and predicted burial at the Kilo-Nalu experiments. Three instrumented cylinders buried to 40-60% of their diameter after two events with significant wave heights of approximately 1 meter. However the fourth cylinder buried to only 10% of its diameter. We have been unable to explain the shallow burial of the single cylinder. Predicted burial was between 40-50%. The greater measured and predicted burial during the first experiments at Kilo-Nalu compared to burial during the Halekulani Sand Channel experiments were related to the increased scour from the higher significant wave heights during the first experiment (1.25 m vs. 1.0 m). Other variables such as sediment type, mean grain size, and water depth were the same for both experiments. These results demonstrate the applicability of the wave-induced scour burial model to model predict burial in unconsolidated carbonate sediments.**

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I. Introduction

Naval mines have been used in littoral warfare for over 200 years. They provide a cheap and effective way to significantly alter naval operations. Bottom mines in shallow water are particularly difficult to detect and classify when they are partially or wholly buried. The Office of Naval Research (ONR) and Naval Research Laboratory (NRL) conducted an experimental and modeling program to determine when and where bottom mines are likely to bury. As part of that program, acoustic instrumented mines were developed to measure burial of bottom mines in shallow sandy environments.

Burial mechanisms studied include wave-induced scour, current-induced scour, and burial by sand wave migration. The instrumented mines were designed to measure the actual burial and the environmental processes responsible for that burial. The acoustic instrumented mine (AIM) utilizes acoustic transducers to measure burial and scour, localized flow rates, and sediment size and concentration in the water column. In addition, the AIM contains sensors for measuring orientation, bottom pressure fluctuations, water temperature, and motion resulting from sediment liquefaction or rolling into scour pits. Hydrophones are used to measure acoustic energy impinging on the mine's surface from search and classification sonar. The data from each of these sensor sub-systems, when processed, provides a look at conditions of the environment around the AIM location, such as significant wave height, wave period, and tides. In areas where reference pressure data are available from a fixed node, AIM pressure data can be used to calculate an estimated burial with respect to the sediment water interface. Data from the acoustic sensors are used to calculate percent of the AIM's surface covered with sediment and to determine the morphology of the surrounding scour pit. Data are collected at a user specified frequency and stored within the AIMs internal electronics package. Data can be processed in near-real time in an area where an offshore data node is available or offloaded to a processing computer after the AIM has been recovered.

Scour burial experiments have been conducted in the northeastern Gulf of Mexico and off Martha's Vineyard.

These experiments provided environmental and burial data used to develop and validate physics-based burial models and to develop the expert system mine burial model transitioned to the Naval Oceanographic Office [1]. The mine burial experiments conducted off Hawaii provide an opportunity to validate these models in a carbonate environment.

II. DESCRIPTION—EXPERIMENT

A. Kilo-Nalu Observatory experiments: Mine burial experiments were conducted during Summer-Fall of 2007 at the Kilo-Nalu Oahu Reef Observatory on the south shore of the island of Oahu, Hawaii (Fig. 1). This observatory provides an observation window into the nearshore coral reef physical, biological and chemical environment. The observatory is managed and maintained by the University of Hawaii at Manoa's Department of Ocean and Resources Engineering (ORE), School of Ocean and Earth Science and Technology (SOEST). All four AIMs were deployed in an area of moderately well-sorted fine carbonate sand in about 12-m water depth [2]. Two of the AIMs were orientated in an E-W direction, one N-S, and the fourth NE-SW. The AIMs were initially deployed June 7, 2007. The following week, two of the AIMs were repositioned to areas of greater sediment thickness, about 10-m inshore of original deployment. The mines were recovered 110 days after initial deployment.

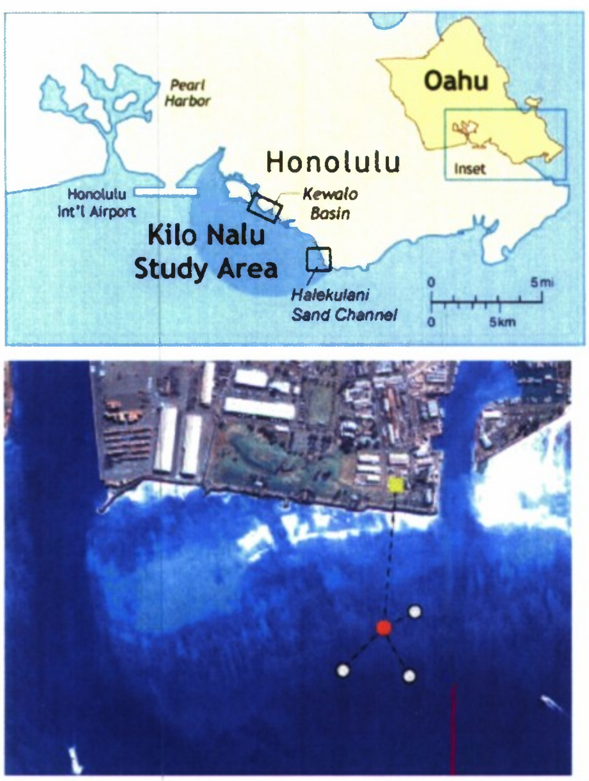

Fig. 1. Location of mine burial experiments at the Kilo Nalu Observatory and in the Halekulani Sand Channel (top). Mines were deployed on carbonate sands at Kilo Nalu Observatory near the red circle (21.2888N; -157.8649W) which is approximately 100-m offshore (bottom).

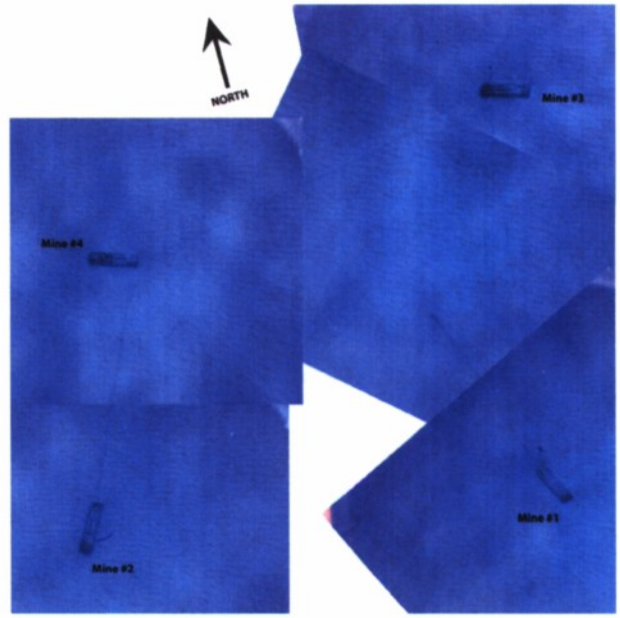

Fig.2 Orientation of the four AIMs mines at the beginning of the 2008 experiments in the Halekulani sand channel (21.2709N; -157.8380W). The presence of sand ripples demonstrates recent sediment transport. The sand ripples have a roughly 30 cm wavelength and a strike parallel to AIMS3 and AIMS4 (110° by 250°).

B. Halekulani sand channel experiments: Mine burial experiments were conducted approximately 1 km south of Waikiki Beach in the Halekulani Sand Channel. Water depths (12 m) and sediment type (moderately well-sorted fine carbonate sand) were the same as for the Kilo-Nalu observatory site. The Halekulani sand channel is a large, well defined sand deposit that extends from the shore to water depths greater than 30 m. The active wave climate reworks the sediments producing a poorly compacted sand deposit that shows no indication of post-depositional cementation [3]. AIMS 1 and 2 were deployed in an approximately N-S heading and AIMS 3 and 4 were deployed in an approximately E-W heading (Fig. 4). The AIMS were deployed on 29 May 2008 and recovered 74 days later on August 11, 2008.

III. DESCRIPTION OF THE AIMS

A. Mechanical Overview

The AIMs are mine-like shaped, blunt-end, bronze cylinders with a 0.53-m diameter and a 2.03-m length. The fully loaded mass is approximately 800 kg and has an approximate density of 1980 kg/m^3. The mine shapes have flush-mounted transducers to maintain a smooth outer surface which minimizes unwanted turbulence from protrusions. Internal acquisition electronics are primarily located within an internal pressure vessel which provides secondary protection in the event of a seawater leak. A more detailed physical and operational description of the AIMs is reported by Bradley *et al.* [4] and only the sensors used for this paper are described.

B. Burial Sensors

There are 112 acoustic burial transducers installed on the surface of each AIM. Six are located in each end cap and twenty rings of five transducers are evenly distributed over the cylinder surface. The transducers operate at 1.5 MHz and are designed to provide data to determine the burial state (covered or uncovered) of each sensor. Data acquired from these sensors can also be analyzed to characterize changing dimensions of the surrounding scour pit, for detection of bedload transport, and to estimate suspended sediment size and concentration.

C. Environmental Sensors

a. Orientation: The orientation sensors consist of a commercial off-the-shelf, three-axes, flux gate compass and three-axis accelerometer for roll and pitch. Heading accuracy is approximately ±2.0° and roll/pitch accuracy is approximately ±0.5°.

b. Pressure: Changes in water pressure are monitored by six sensors on the instrumented mine surface. Water pressure fluctuations (0-700 kPa sampled at 10 Hz) provide input to calculate mean water depth and surface waveheight and period. Comparisons of the mean water depth changes to nearby tidal measurement or NOAA tidal data are used to estimate the burial of the instrumented mine relative to the sediment-water interface. Each pressure transducer is sampled for 20 minutes once an hour at ten samples per second.

c. Temperature: Water temperature is measured by a commercial off-the-shelf thermistor on each of the end caps of the instrumented mine. Temperature range is from -2 to 38°C and accuracy is approximately ±0.15°C.

IV. ENVIRONMATAL MEASUREMENTS AND MINE MOVEMENT

A. Surface Sediment Description

The first experiment was located at the Kilo Nalu Oahu Reef Observatory on the south shore of the island of Oahu, Hawaii. All four AIMs were deployed in a channel of fine carbonate sand between coral outcroppings in about 12-m water depth. The fine carbonate sand was a shallow 10-75 cm deposit over a relict coral reef. Mines were placed at locations with the thickest cover, as determined by diver probes. The second experiment was located in 12-m water depth in Halekulani sand channel which is about 1 km off Waikiki Beach. Previous experiments at this site indicated that the depth of the sand layer was several meters. Sediment samples were collected by divers near each AIM location at the beginning of each experiment. Grain size distribution for both sites was determined by dry-sieving the sand fractions at quarter-phi intervals and by pipette for assaying the silt and clay fractions. Sediments were moderately well-sorted fine carbonate sand (Table 1). Percent sand-sized particles were 95% with less than 0.5% gravel-sized particles. Most sand grains were composed of eroded carbonate reef material. Grain density was 2.77 gm/cm^2.

B. Oceanographic observations

The pressure series measurements were used to calculate tidal range, surface wave period, and significant wave height (Fig. 3). Together with the sediment description (Table 1) and water depth, these data are used to predict burial by wave induced scour (see section IV). The tidal data presented in Figure 3 is later compared to similar tidal data from the Kilo-Nula fixed node and to NOAA tidal data to determine mine burial relative to the sediment-water interface. During the 2007 experiments at the Kilo Nula Observatory, two small storms with significant wave heights greater than 1.0-m and periods greater than 10-s were observed near the beginning of the deployment (day dates 168 and 182). These storms coincided with mine movement and burial relative to the sediment water interface (Figs. 4 and 5). Later storms were of insufficient strength to generate any additional movement or burial of the AIMs. Significant wave heights calculated from pressure series measured at the mines and the fixed node at Kilo Nula were nearly identical. However, wave periods calculated from the fixed node were much longer than calculated from pressure series from the mines. The differences are probably a result of different algorithms used to calculate wave period. Algorithms used by Kilo-Nalu emphasize the longer period swell versus shorter period local storms by the mines. Significant wave heights during the 2008 experiments in the Halekulani Sand Channel never exceeded 1.0 m with four wave events with significant wave heights ranging between 0.8 m and 1.0 m (day dates 158, 164-170, 198, 209-211). Changes in mine orientation and percent burial relative to the sediment water interface during the 2008 experiments were restricted to the first two storms (Figs. 6 and 7) . Later storms did not provide any additional movement or burial of AIMs.

Table 1. Mean grain size for carbonate sediments collected near the AIMs mines: KNO are samples from the Kilo Nalu Observatory site; HSC are samples from the Halekulani sand channel. Mean grain size and sorting were determined by the graphical methods of Folk and Ward where sorting is the graphical standard deviation in units of phi [4].

	Mean Grain Size (Phi (Φ))	Sorting (Phi (Φ))	Mean Grain Size (mm)
KNO-1	2.52	0.53	0.174
KNO-2	2.40	0.63	0.189
KNO-3	2.60	0.57	0.165
KNO-4	2.36	0.62	0.195
HSC-1	2.42	0.60	0.187
HSC-2	2.22	0.56	0.215
HSC-3	2.30	0.64	0.203
HSC-4	2.17	0.61	0.222

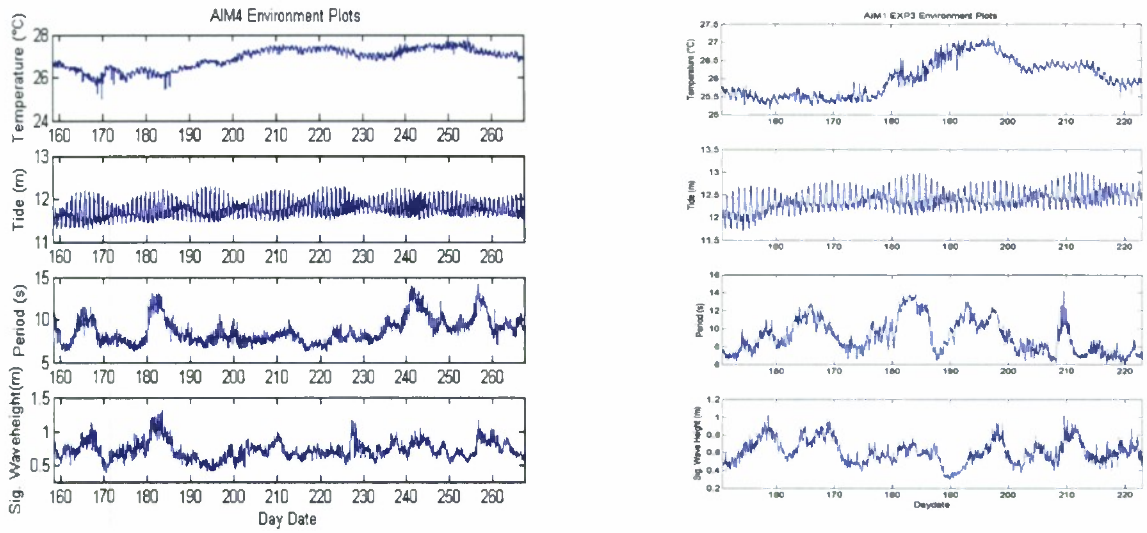

Fig. 3. Oceanographic conditions measured during the experiments by AIM's sensors. Data on the left were collected using AIM4 during the 2007 experiments at the Kilo Nalu Observatory; data on the right were collected by AIM1 during the experiments conducted in the 2008 experiments in Halekulani sand channel. Data from the other mines were nearly identical.

C. Mine Movement

The heading-, pitch-, and roll angle, and significant wave height were recorded for each mine over the entire 110 day experiment at the Kilo Nula Observatory (Fig. 4) and the 74 day experiment in the Halekulani Sand Channel (Fig. 6).

Kilo Nalu Observatory: Diver observations two days after initial deployment showed that AIM1 and AIM3 were resting on top of coral reef material with most of the sand-sized particles scoured from underneath the mines. AIM1 was buried about 40% relative to the sediment-water interface and AIM3 was buried about 10% relative to the sediment-water interface. It appeared that AIM1 and AIM3 were significantly scoured during the first day of deployment and that both mines rolled nearly 50 degrees in opposite directions as they settled on reef material. As a result, divers moved these two instrumented mines about 10-m inshore towards the center of the sand channel to a location with a thicker sediment layer (on day date 170).

All mines exhibited significant movement within the first day after deployment. Initial roll was -50°, +20°, +40°, and +15° for AIM1-AIM4, respectively. Subsequent movement of the mines coincided with the first two sea surface wave events with significant wave height events greater than 1-meter and wave periods greater than 10 seconds (approximate day dates 165-167 and 180-182). During the second two-day period (day dates 180-182) AIM1 rolled +65°, added 4° pitch, and changed heading from 160° to 144°. AIM2 rolled +5°, pitched 1.5°, without an obvious change in heading. AIM3 rolled +10°, pitched through 4°, and changed heading from 160° to 130°. AIM4 rolled -40°, pitched 2° without a change in heading. Following the second period of higher significant wave heights, little or no movement was recorded for any of the four instrumented mines for the remaining 90 days of the experiment.

Halekulani Sand Channel: All AIMs exhibited significantly less change in orientation during the 2008 experiments in the Halekulani Sand Channel than during the 2007 experiments at the Kilo Nula observatory (Fig. 5). For all AIMs, the range in change in heading, pitch, and roll was 2-4°, 2-3°, and 4-12° respectively with the exception of AIM1 which change heading by 13°. Most of the change in orientation was observed during the first 20 days of the experiments during the first two high significant wave events. After day date 170 very little change in orientation was recorded.

V. MINE BURIAL RESULTS

A. Mine Burial Relative to the Sediment-Water Interface

Kilo Nalu Observatory: Two different patterns of burial were observed during the 2007 experiments. AIM1 and AIM2 buried to approximately the diameter of the mines after exposure to a single high wave event (Fig. 5). AIM2 buried to 90% of its diameter during the first wave event (day date 165-166) and AIM1 which was moved after the first wave event promptly buried to 80% of its diameter after the second wave event (day date 180-182). In contrast AIM3 and AIM4 only buried to approximately 50% of their diameter. Diver observations at recovery were in agreement with the final measured burial and the AIM3 and AIMS4 were observed to be resting on top of the underlying reef material.

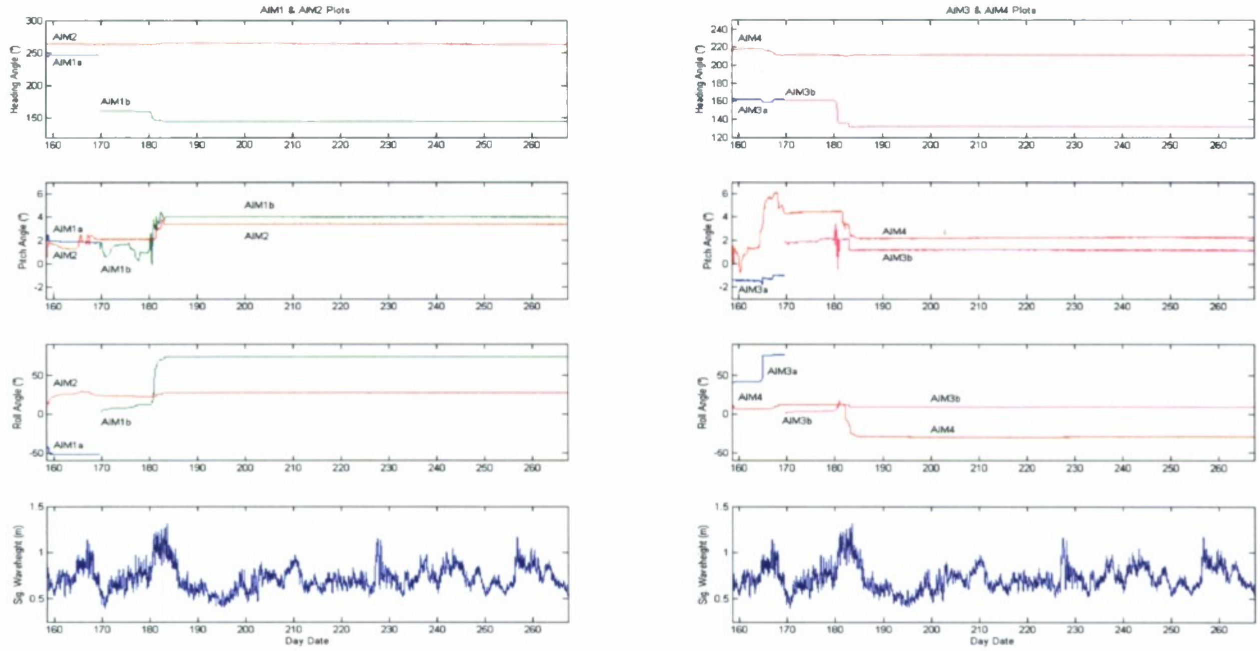

Fig. 4. Changes in AIM orientation compared to significant wave height for the four AIMs during the 110-day deployment at the Kilo Nalu site. AIM1 and AIM3 were redeployed at Day Date 170. Most of the AIM movement occurred during the first two high wave events where significant wave heights exceed 1 m. Day date 1 begins at 00:00:00HST January 1, 2007.

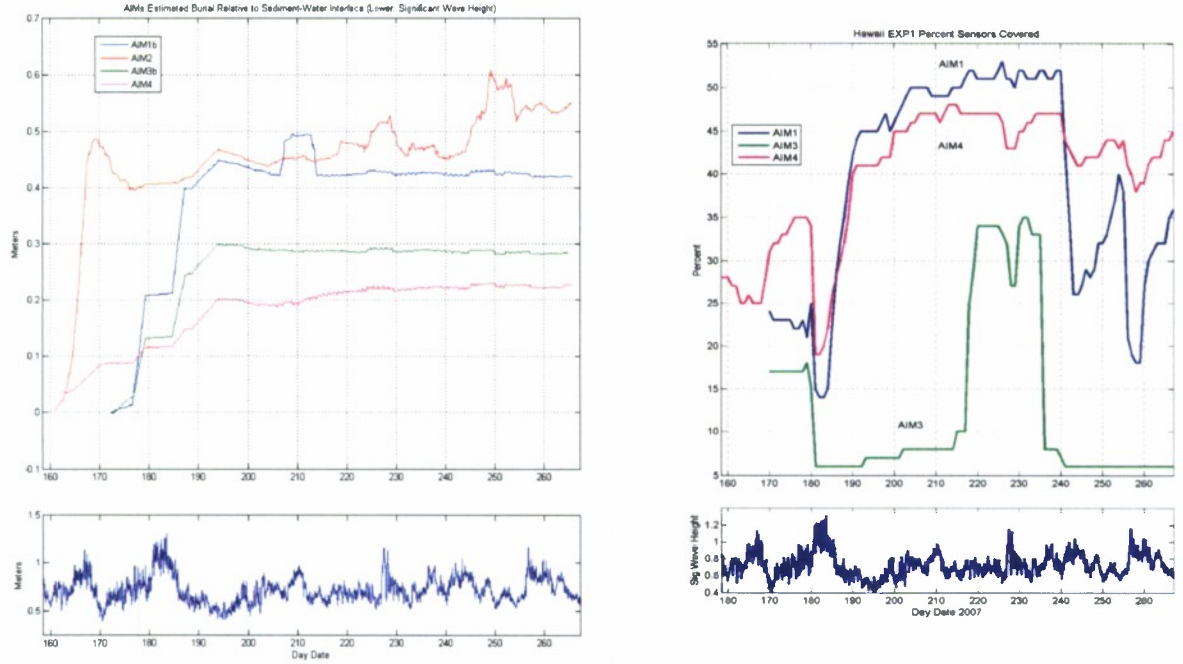

Fig. 5. Estimated mine burial relative to the sediment water interface (left) and percent surface area covered (right) compared to significant wave heights during the 110-day deployment at the Kilo Nalu site. AIMs burial measurements relative to the sediment surface are based on comparison of pressure series measured using AIMs and the fixed pressure transducers at the Kilo-Nalu observatory. AIMs burial calculated as surface area covered is based on the percent acoustic sensors covered.

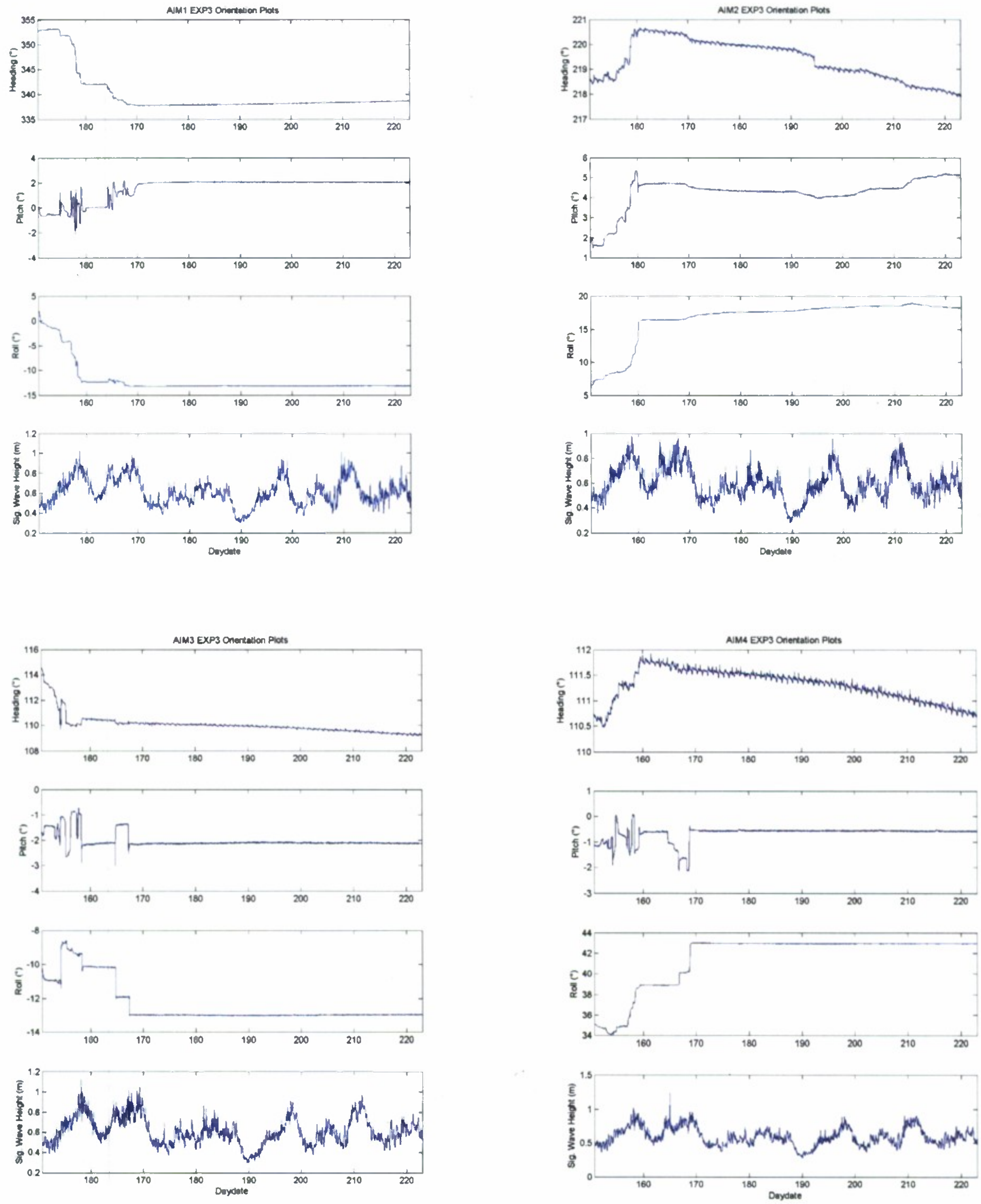

Fig. 6. Changes in orientation compared to significant wave height for the four AIMs during the 74-day deployment at the Halekulani Sand Channel. Day date 1 begins at 00:00:00HST January 1, 2008.

Halekulani Sand Channel: Three of the AIMs buried to between 40-60% of their diameter after the first two wave events. Burial was in two steps with 30-40% of the burial occurring during the first wave event (day date 158-160) and the rest occurring during the second wave event (day dates 164-170). The burial coincided with changes in mine orientation. In contrast, AIM2 only buried to approximately 10% of its diameter. Diver observations at the end of the experiment were in agreement with the measured burial for all AIMs. Neither underlying reef material nor gravel-sized shell material was found in the vicinity of AIM2.

B. Burial Relative to Percent Surface Area/Sensors Covered.

Kilo Nula Observatory: The surface area of the mines covered with sediment ranged from 5% to 50% (Fig.5). e were unable to process the acoustic sensor data from AIM2. For AIMl and AIM4, the lower percentages of the surface area covered with sand occurred after periods of increased significant wave heights and lower wave periods which scoured sediments from around the AIMs. During periods of lower significant wave heights some infilling of the scour pits occurred and the percent of the surface area of the AIMs covered with sand increased to nearly 50%. The surface area of AIM3 that was covered with sand was often less than 10%. Diver observations during recovery of AIMs found AIM3 was again purchased on the relict coral material with most of the fine sand scoured from underneath the mine. The roughly 35% surface coverage of AIM3 during day dates 217-236 was most likely the result of infilling from sediment transport and later scour. The percent burial measured as surface area covered was always less than estimated burial measured relative to the sediment water interface (Fig.5) suggesting that the scour pits were never fully infilled after each scour event. Divers observed large scour pits around the mines during mine recovery and photographs from periodic surveys with tethered underwater vehicle also reveled large scour pits around the AIMs.

Halekulani Sand Channel: At recovery the relative percentage burial as expressed as AIM surface area covered (Fig. 8) followed the same pattern as the percent burial relative to the sediment surface (highest to lowest percent burial: AIM1, AIM4, AIM3, AIM2). However, the temporal pattern of burial was different. Most of the burial relative to the seafloor occurred during the first two periods of high significant wave heights (Fig. 7). Burial relative to the AIM surface area covered also increased with time but more gradually. This more gradual burial was probably a result of a slow infilling of the scour pits after the initial scour events. AIM2 only had 30% of the surface area covered at recovery which is equivalent to the approximately 10% burial relative the sediment surface.

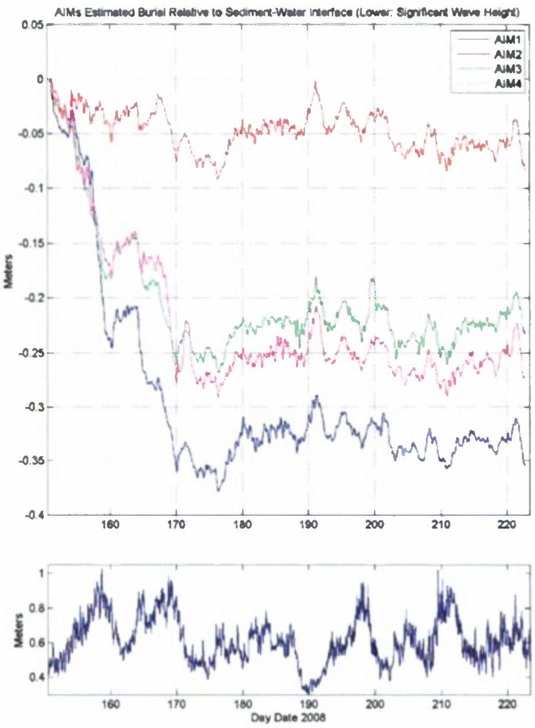

Fig. 7. Burial of AIM1-AIM4 relative to the sediment-water interface measured during the 74-day deployment at the Halekulani Sand Channel.

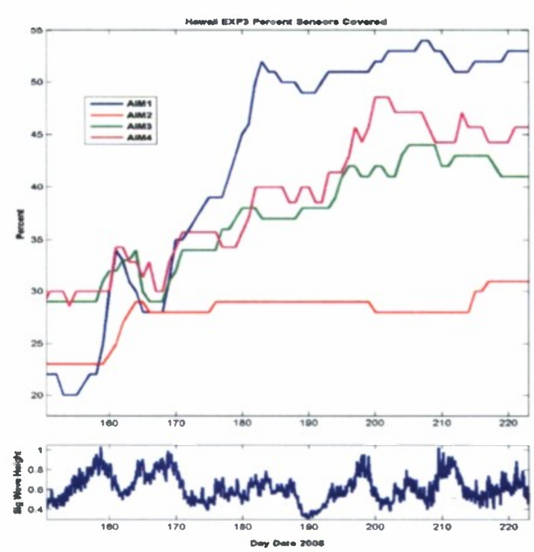

Fig. 8. Burial of AIM1-AIM4 expressed as surface area covered by sediments during the 74-day deployment at the Halekulani Sand Channel.

VI. MINE BURIAL PREDICTION

Predictions of burial relative to the ambient level of the seabed were made using the implementation of the HR Wallingford scour model described in Trembanis et al. [5]. The predictions of scour are based on the assumption of no scour-pit infilling and are plotted against experimental data (Figs. 9 and 10). The measured median grain size was 180 and 200 µm for the Kilo-Nalu Observatory and Halekulani Sand Channel experimental sites. The grain density was 2750 kg m^{-3} for both fine grained carbonate sediments. Time series input (Fig. 3) to the model was constructed from the significant wave height and peak period data sets obtained from sensors within the AIMs cylinders. These data were interpolated using the piecewise cubic Hermite polynomial interpolation [6] algorithm in MATLAB [7] in order to get data series of equal sampling rates and equivalent starting and ending times. Burial data from the four AIMs cylinders (Fig. 5 and Fig. 7) were similarly interpolated.

***Kilo Nalu Observatory*:** The model tends to over predict burial for AIM3 and AIM4 and under predict burial for AIM1 and AIM2 (Fig. 9). The time series differ as AIM1 and AIM3 were redeployed after divers observed the mines setting on top of reef material after initial scour. Over prediction of burial for AIM3 and AIM4 can be explained by diver observations that the AIMs were resting on top of the underlying reef material which would limit burial to the thickness of the sand layer. AIM1 and AIM2 buried 80-100% of their diameter (53 cm) which was slightly greater than the 70% burial predicted by the wave-induced scour model.

Halekulani Sand Channel: Final predicted burial during the Halekulani experiments was 40% based on the significant wave heights calculated from pressure series from AIM1. Measured burial ranged between 40-65% for three of the AIMs and was only 10% burial for AIM2. Measured burial of AIM3 and AIM4, which were deployed parallel to the incoming waves (perpendicular to the ripples in Figure 2), closely matched predictions of the burial model (Fig. 10). However, AIM1 and AIM2, which were deployed perpendicular to the predominant wave field, were respectively higher and lower than the predicted burial. It seems unlikely that differences in water depth, sediment type, or wave-induced bottom orbital velocity could account for the differences in measured percent burial for mines deployed within 20 m of each other. We can not rule out the near surface presence of relict coral, bed armoring, or cementation accounting for the restricted burial of AIM2 but neither relict coral nor bed armoring was observed by careful and purposeful examination of the sediments under the AIMs by divers at the time of recovery. At this point the difference in measured and predicted burial, especially for AIM2 remains unknown.

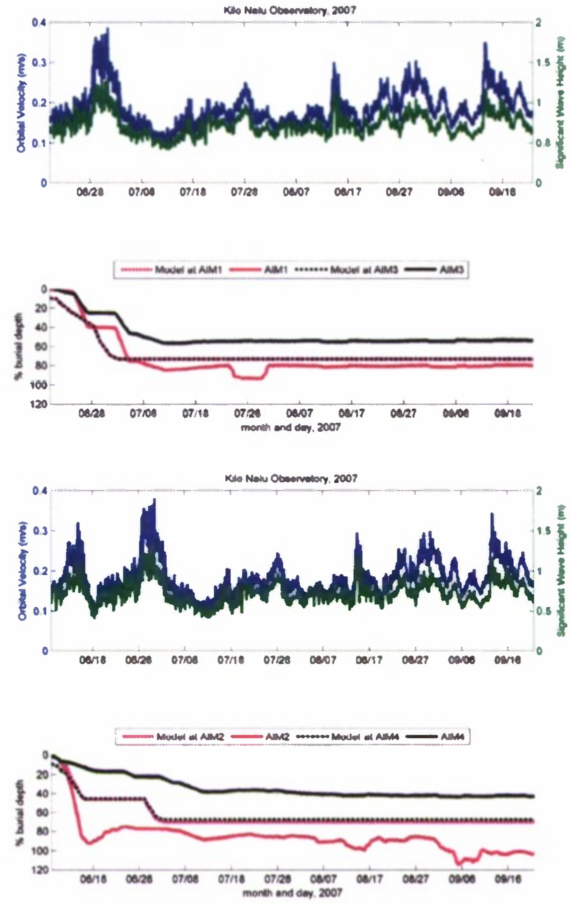

Fig. 9. Significant wave height (upper blue), calculated orbital velocity (green), measured burial (lower blue), and predicted burial for the four AIMS deployed in 2007 at the Kilo Nalu Observatory. AIM1 and AIM3 (bottom panel) were repositioned 10 days after the start of the experiment and exhibited a slightly different predicted rate of burial.

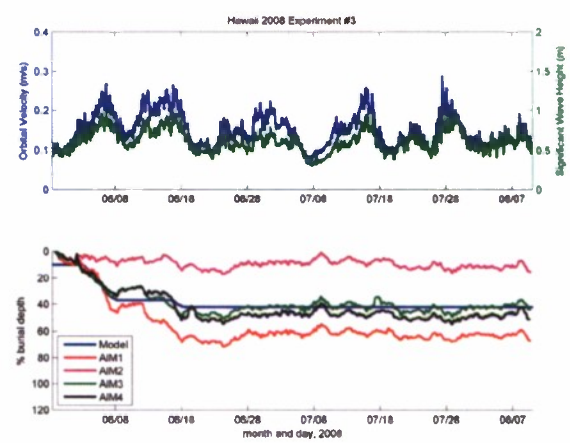

Fig. 10. Significant wave height (upper blue), calculated orbital velocity (green), measured burial (lower blue), and predicted burial for AIMS during the 2008 experiments in the Halekulani Sand Channel.

VII Conclusions

The instrumented mines buried as a result of wave-induced scour at both the Kilo Nalu Oahu Reef Observatory and the Halekulani Sand Channel experimental sites. Wave-induced scour results in observable movement of the cylinders as they roll into the surrounding scour pits. Additional burial requires higher energy wave events but the scours pits can infill and again scour with lower energy events that exceed the threshold of sediment movement in the vicinity of the mines. The deeper burial, as measured relative to the sediment surface, coincided with higher significant wave heights. The deepest burial (80-100% for AIM1 and AIM2) occurred as significant wave heights exceeded 1.2 m at the Kilo Nula Observatory. Burial in the Halekulani Sand Channel was between 40-65% (AIM1-AIM3) with significant wave heights no greater than 1.0 m. Other variables that could influence burial rates such as sediment type, mean grain size, and water depth were the same for both experiments.

Predicted burial based on the Trembanis et al. [3] implementation of the HR Wallingford scour model were equal to or slightly greater than the measured burial relative for five of eight the AIM deployments. However, in three cases measured burial was much less that predicted burial. In two of these cases, burial was limited by the depth of the fine sand layer. During the Kilo Nalu Coastal Observatory experiments AIM3 and AIM4 only buried to approximately 50% of their diameter compared to the predicted 70% burial. The presence of reef material underlying a thin layer of fine sand restricted burial to about half the diameter of these mines. During the Halekulani Sand Channel experiments AIM1 buried to about 10% of the diameter of the mine compared to a predicted 40% burial. The cause is for this low percent burial is unknown.

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