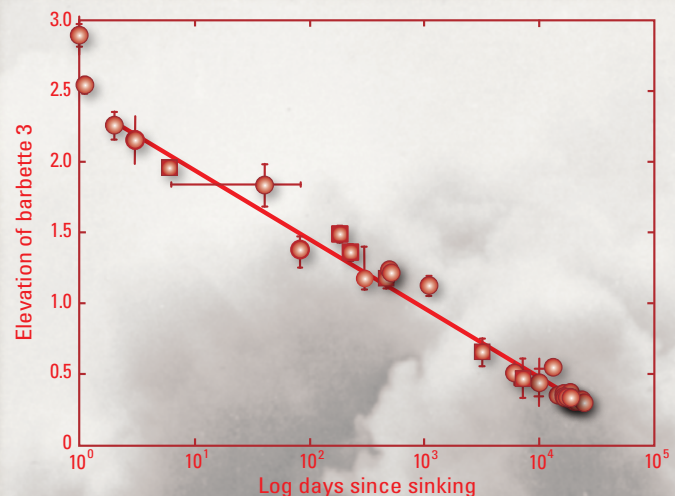


Settlement of the USS *Arizona*, Pearl Harbor, Hawaii



Scientific Investigations Report 2013–5096

COVER

The USS *Arizona* burning on December 7, 1941, as seen from near the stern looking forward. National Archives photo NA 80G-32424. The superimposed plot shows the settlement of barbette 3 of the vessel over time.

Settlement of the USS *Arizona*, Pearl Harbor, Hawaii

By Brad A. Carlin and Robert E. Kayen

Scientific Investigations Report 2013–5096

**U.S. Department of the Interior
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Settlement of the USS *Arizona*, Pearl Harbor, Hawaii

By Brad A. Carkin and Robert E. Kayen

Abstract

The U.S. Geological Survey, in collaboration with the National Park Service Submerged Resources Center, undertook investigations at the USS *Arizona* Memorial at Pearl Harbor, Hawaii, in 2002, 2003, and 2005 to characterize geological factors affecting the deterioration and movement of the hull of the USS *Arizona*. Since sinking on the morning of December 7, 1941, the hull of the USS *Arizona* has been slowly but steadily disappearing below the surface of Pearl Harbor. Continuous sediment coring at three of four locations around the hull of the *Arizona* was only partially successful, but it was sufficient to identify a varied sedimentary substrate beneath the hull. A boring near the stern reveals a thick, continuous sequence of soft, gray clay to the bottom of the boring. In contrast, borings near the bow and starboard side, below about 5 meters subbottom depth, indicate the presence of very stiff, brown clay and coral debris and an absence of soft clay.

Multisensor core logger scanning of the recovered cores distinguishes the lower density of the soft, gray clay at the stern from the higher density of the stiff, brown clays and coral debris at the bow and starboard side. Uniaxial consolidation testing of the soft gray clay indicates a normally consolidated sequence, whereas the stiff, brown clay and coral debris are overconsolidated. Profiles of shear wave velocity vs. depth obtained through spectral analysis of interface wave testing around the perimeter of the hull in 2005 identified areas of higher velocity, stiffer sediment at the bow and starboard side, which correspond to the dense, stiff clay recovered near the bow and starboard borings. Low shear-wave velocities at the port midship and quarter of the hull correlate with the lower density, softer sediment recovered from the boring at the stern. Cross sections of the subbottom of the Memorial combine results from the sediment borings and geophysical surveys and depict a wedge of soft clay unconformably overlying the stiff clays and coral debris beneath the aft half of the USS *Arizona* and thickening toward the stern. The 2008 position of the hull has been documented using both tide-based and differential Global Positioning System (GPS) measuring systems.

Analysis of historical and recent photographs was done to create a record of settlement from the time of sinking in 1941 to the present. By examining shadows in suitable photos, the sun azimuth, local time of day, and tide levels were determined to derive tide-adjusted and sea-level-rise-corrected elevations for structures on the hull and from these elevations to obtain settlement and tilt trends. The settlement trends, most complete for barrette 3, have two components. An early, nonlinear component ends on December 9, 1941, and represents the initial

penetration and displacement of the bottom sediment by the hull. A linear, long-term trend of normal consolidation continues to the present day. Long-term settlement rates are greatest at the stern and decrease linearly to the midship, showing that the aft half of the hull is moving as an intact, rigid body. The recent rate of settlement near the stern is about 3.5 mm/year; rates at the starboard midship and forward part of the hull are less than one-third of the stern rate. The aft half of the USS *Arizona* hull presently tilts about 2 degrees to port, an increase of at least 1.5 degrees since the initial sinking of the ship.

The results of this study identify differential settlement of the *Arizona* hull, due to the wedge of soft clay underlying the aft half of the hull, as the cause of the movement of the hull beneath the surface of Pearl Harbor. Calculation of sediment consolidation using lab-determined properties of the soft clay demonstrates that the observed settlements can be reproduced by projecting appropriate clay thicknesses beneath the hull. Several of the high-quality photographs analyzed for the historical settlement analysis highlight some of the limitations of this retrospective technique for determining tide-based elevations. In these cases, calculated structure elevations do not conform to the settlement trend, indicating that there can be complicating factors affecting the interpretation of the photos. Conflicting dates for events during the salvage operations were also encountered.

Introduction

The USS *Arizona* Preservation Project (Russell and Murphy, 2004), a partnership between the National Park Service (NPS) and the Department of Defense, was a multiyear program designed to document the natural processes of corrosion and deterioration affecting the USS *Arizona* located in Pearl Harbor, Hawaii. Important parts of the Preservation Project are geological and metallurgical studies aimed at understanding the changes in elevation of the USS *Arizona*, the rates of corrosion of the hull, and the subbottom geology upon which the hull of the ship rests. Scientists from the United States Geological Survey (USGS), working in a collaborative partnership with archaeologists from the NPS-Submerged Resources Center (SRC), conducted a suite of geological and geophysical studies of the USS *Arizona* during the period 2002 to 2005.

The remains of the USS *Arizona* were designated a National Historic Landmark on May 5, 1989, and are administered cooperatively by the NPS and the U.S. Navy.

2 Settlement of the USS *Arizona*, Pearl Harbor, Hawaii

The site is among the most recognized and visited war memorials in the United States. The present USS *Arizona* Memorial structure spans the ship's hull midships and receives more than a million visitors every year.

Since its sinking during the attack on December 7, 1941, the USS *Arizona* has been steadily disappearing beneath the water surface of Pearl Harbor. A casual comparison between photographs of barrette 3 (the cylindrical base upon which the gun turret rests) taken shortly after the December 7 attack with those taken today (fig. 1) shows the extent of the disappearance.

The NPS established a research program to assess the cause of this disappearance, with the primary hypotheses being deformation of the foundation sediment and (or) structural deterioration of the ship. The USS *Arizona* Preservation Project addressed another important issue, the retention of as much as 600 thousand gallons (Foecke and others, 2010) of Bunker C fuel oil that has been slowly escaping since 1941. This oil, an environmental contaminant, is contained within the corroding hull. Results to date, especially from a finite element model developed by the National Institute of Standards and Technology (Foecke and others, 2010), indicate that a single catastrophic oil release is not considered likely because of the highly segmented nature of the fuel oil bunkers and the fact that the oil-containing structures are all below the present harbor bottom, where corrosion rates are lowest.

The major areas of study addressed in this report are: (1) the results of coring operations and geophysical surveys around the hull; (2) lithologic, stratigraphic, and geotechnical analyses based on the recovered cores and geophysical surveys; (3) analysis of historic and recent photographs of the USS *Arizona* to determine the settlement history of its hull; and (4) calculation

of settlement of the hull based on laboratory-measured geotechnical properties of the sediment underlying the USS *Arizona*. Appendixes A through J contain supplementary information documenting testing results and analysis details of most of the photographs examined for this report.

Brief Historical Background

The keel for the USS *Arizona* (battleship BB-39) was laid on March 16, 1914, at the Brooklyn Navy Yard, and the ship was subsequently launched on June 19, 1915. Major revisions to the ship were carried out between May of 1929 and March of 1931, resulting in the near-final configuration. The ship has an overall length of 185 m and comprises 152 “frames,” each 4 feet (1.22 m) long. The maximum beam is 32.4 m (29.6 m at waterline), and the fully loaded displacement was 37,654 short tons (<http://www.ussarizona.org/history/statistics.htm>, last accessed March 21, 2013).

At 7:43 a.m. on December 7, 1941, forces of the Japanese Imperial Navy began the first wave of a surprise attack, Operation Hawaii, on the naval and air force facilities at Pearl Harbor. The USS *Vestal* was moored to the port side of the USS *Arizona* at the start of the attack. At about 8:10 a.m. a bomb struck the forward magazine of the USS *Arizona* causing a large explosion within the forward part of the ship. As a result nearly a third of the ship's length collapsed and the ship was set afire. The first wave of the attack ended around 8:25 a.m. and was followed by a second wave that started around 8:40

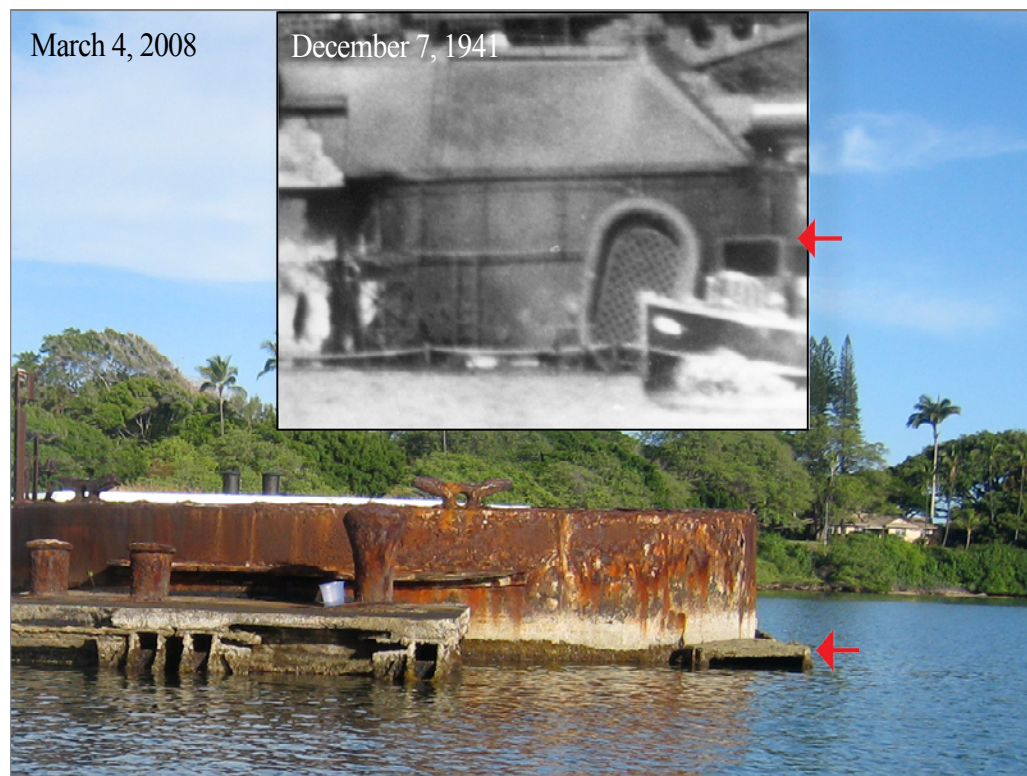


Figure 1. Photographs showing the settlement of the USS *Arizona* barrette 3 and attached port-side vent (red arrows) from the morning of December 7, 1941, to 2008.

Figure 2. Aerial photograph showing locations of borings B1/B1A, B2, and B3 around the hull of the USS *Arizona*, southeast side of Ford Island, Pearl Harbor, Hawaii. Fox mooring quays Fox 7 South (F7S) and Fox 7 North (F7N) are situated on the starboard (northwest) side of the ship.

a.m.. Mooring lines to the USS *Vestal* were cut at 8:45 a.m., and she maneuvered away from the USS *Arizona*. The second wave ended about an hour later at 9:45. Little or no effort was made to put out the fire on the USS *Arizona* during December 7. According to deck logs of the USS *Tern* (<http://www.history.navy.mil/docs/wwii/pearl/ph118.htm>, last accessed March 5, 2013), the fire on the USS *Arizona* was declared to be out two days later, at 12:35 p.m. on December 9.

Salvage operations on the USS *Arizona* began almost immediately and were completed by October 1943. Between November 25, 1944, and January 16, 1945, a concrete platform with mooring bitts was added to the port side of barrette 3 as a new location of the Fox-7 mooring quay. Similar platforms were likely added during this time at the midship port side and the port side of turret 2, although the platform on turret 2 was later removed. Also during this period the USS *Arizona* hull became a temporary storage site for large steel trusses stacked on the decks.

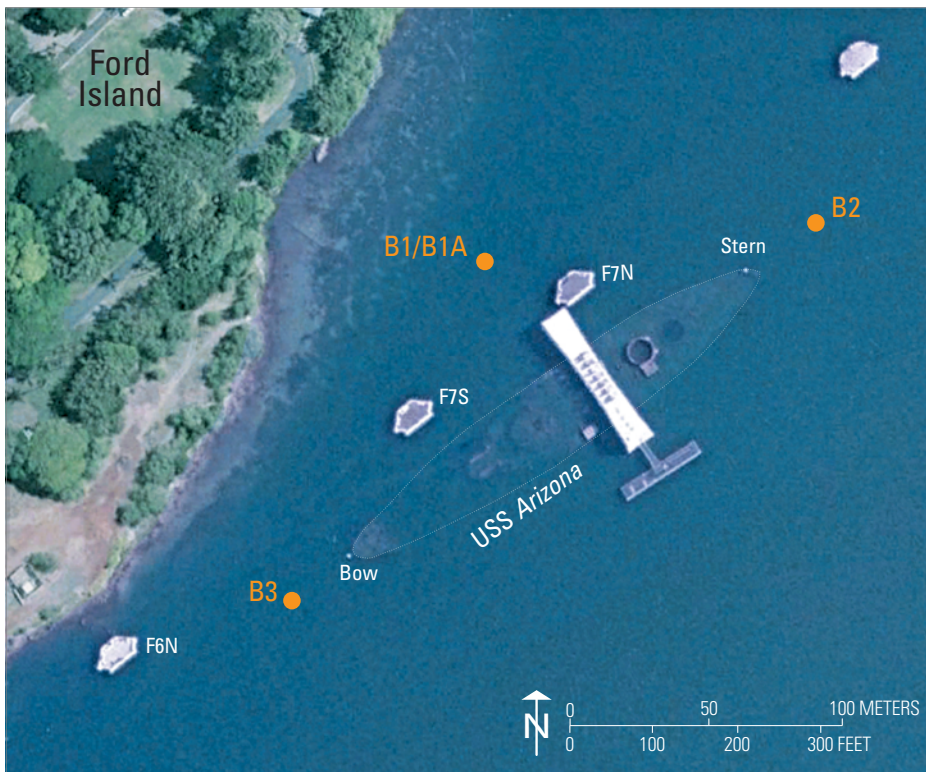
In 1950 Admiral Arthur Radford, Commander in Chief of the Pacific Fleet, ordered a memorial to be erected on the USS *Arizona* hull. This original memorial consisted of a flagpole attached to the remains of the mainmast and a commemorative plaque. The flag was raised for the first time at this site on March 7, 1950. President Eisenhower approved the design for the present memorial in 1958. Site preparation began in early 1960 and construction started late that year. During construction, the substantial remaining emergent part of the superstructure between frames 78 and 94 was removed, leaving barrette 3 as the largest remaining part of the hull visible above the water surface. The memorial was dedicated on Memorial Day, May 30, 1962. The USS *Arizona* was declared a National Historic Landmark in 1989.

The USS *Arizona* Memorial Geophysical Surveys and Sediment Borings

In August 2002, a seismic-reflection survey (unpublished memoranda by M. Field and P. Hart, 2002, and by P. Hart and M. Field, 2002—see appendix J; Russell and Murphy, 2004) was carried out by a USGS–NPS team in order to identify the thickness of sediment and depth to coral bedrock in Pearl Harbor around the USS *Arizona* Memorial and the USS *Utah* (USGS Field Activity ID: C1-02-HW). The cruise identified several subbottom reflectors in the sediment near the USS *Arizona* that bound distinct units that are interpreted to be of sedimentary origin. However, the presence of methane gas within the upper harbor sediment greatly limited the view into the deeper subbottom, where information could be derived about the lithology of the units. Subbottom reflectors interpreted to be coral bedrock were identified at depths between 50 and 55 m below the sea surface. Following the seismic-reflection survey, four sites around the hull of the USS *Arizona* were chosen for coring and sample collection. In the fall of 2003, the NPS contracted a private drilling company, Ernest K. Hirata & Associates, Inc., to drill and sample sediment at the four locations surrounding the USS *Arizona* Memorial. The USGS and the NPS–SRC cooperated to mobilize the USGS multisensor core logger (MSCL) to Hawaii in November of 2003 in order to log the cores recovered from these borings.

The coring and core logging operations took place during the period November 10 to 21, 2003. In the end, time restrictions allowed for only three of the four boring sites to be completed. A drilling services report containing boring logs and drilling methods, dated December 17, 2003, was produced by Hirata and Associates (Hirata, 2003). The USGS Coastal and Marine Geology Team took possession of the cores for testing after the coring operation, and they remain in refrigerated storage.

The locations of three completed borings around the Memorial site are shown in figure 2. Coring operations took place from a small temporary barge anchored over each coring site (fig. 3). Continuous coring using 91-cm-long, thin-walled, enameled Shelby tubes was employed at each site. Shelby tubes were driven using the cathead and rope method with a 63.5-kg hammer dropped from a nominal height of 76 cm (Hirata, 2003). Because of



4 Settlement of the USS *Arizona*, Pearl Harbor, Hawaii

Table 1. Depth intervals, sample recovery, and lithology for all recovered cores from the USS *Arizona* borings.

[For Shelby tubes, recovery percentage is the volume of the potential sample space in the tube that is filled without regard to the condition of the sediment; --, no data]

Boring	Sampled Depth		Liner	Recovery (percent)	Lithology
	Meters	Feet			
B1	0–8.54	0–28	Shelby	0	--
	8.54–9.45	28–31	Shelby	92	sand
	9.45–17.2	31–56.5	Shelby	0	--
	17.2–18.1	56.5–59.5	Shelby	98	stiff clay
B1A	0–6.10	0–20	0	0	--
	6.10–7.62	20–25	3.5" steel pipe	9	stiff clay
	7.62–9.15	25–30	3.5" steel pipe	60	stiff clay/coral debris
	9.15–10.7	30–35	3.5" steel pipe	67	stiff clay/coral debris
	10.7–12.2	35–40	3.5" steel pipe	56	stiff clay/coral debris
	12.2–13.7	40–45	3.5" steel pipe	68	stiff clay
	13.7–15.2	45–50	3.5" steel pipe	61	stiff clay
B2	0–5.34	0–17.5	Shelby	0	--
	5.34–6.10	17.5–20	Shelby	98	soft clay
	6.10–8.38	20–27.5	Shelby	0	--
	8.38–9.15	27.5–30	Shelby	82	soft clay
	9.15–9.90	30–32.5	Shelby	0	--
	9.90–10.7	32.5–35	Shelby	82	soft clay
	10.7–11.4	35–37.5	Shelby	96	soft clay
B2	11.4–12.2	37.5–40	Shelby	0	--
	12.2–13.0	40–42.5	Shelby	100	soft clay
	13.0–13.7	42.5–45	Shelby	87	soft clay
	13.7–14.5	45–47.5	Shelby	100	soft clay
	14.5–15.2	47.5–50	Shelby	100	soft clay
	15.2–16.0	50–52.5	Shelby	80	soft clay
	16.0–16.8	52.5–55	Shelby	100	soft clay
	16.8–17.5	55–57.5	Shelby	93	soft clay
	17.5–18.3	57.5–60	Shelby	100	soft clay
	18.3–19.1	60–62.5	Shelby	87	soft clay
	19.1–19.8	62.5–65	Shelby	100	soft clay
	19.8–20.6	65–67.5	Shelby	100	soft clay
	20.6–21.3	67.5–70	Shelby	100	soft clay
B3	0–0.91	0–3	Shelby	0	--
	0.91–1.83	3–6	Shelby	93	sand/soft clay
	1.83–2.74	6–9	Shelby	100	soft clay
	2.74–3.66	9–12	Shelby	100	sand/clay
	3.66–4.57	12–15	Shelby	95	sand
	4.57–8.23	15–27	Shelby	0	--
	8.23–9.15	27–30	Shelby	49	stiff clay
	9.15–9.91	30–32.5	Shelby	75	stiff clay
	9.91–10.7	32.5–35	Shelby	79	stiff clay
	10.7–11.4	35–37.5	Shelby	96	stiff clay
	11.4–12.2	37.5–40	Shelby	95	stiff clay
	12.2–13.0	40–42.5	Shelby	88	stiff clay/coral debris
	13.0–13.7	42.5–45	Shelby	92	stiff clay/coral debris
	13.7–14.5	45–47.5	Shelby	100	stiff clay/coral debris

Figure 3.

The Hirata and Associates drilling barge shown anchored at boring location B3 near the bow of the USS *Arizona*. National Park Service photo by Brett Seymour.



possible damage to the tubes caused by hard coral layers or other granular materials, some Shelby tubes were enclosed within 1.5-m-long (7.5 cm outer diameter) schedule 40 steel pipe to protect the tubes during sampling (Hirata, 2003). In most cases, cylindrical plastic foam rod was cut to fill the empty space at the top of each core at the drilling barge before transportation and logging.

Sediment Recovered from the USS *Arizona* Memorial Borings

Lithologic descriptions and a derived subbottom stratigraphy are based on the material observed at the tops and bottoms of the recovered cores and on material extruded from the bases of the tubes for testing purposes. The six sections of steel pipe liner from boring B1A were cut into shorter segments as needed for extrusion and examination. A list of all depth intervals, recovered samples, and recovery percentages for each boring is given in table 1. The depths in feet are as reported by Hirata (2003); depths in meters are calculated from the depths in feet. The condition of the top and bottom interior of the Shelby tubes at the time of extrusion, as well as the lithologic notes, are compiled in appendix A as core notes on the gamma density plots for each core. Sample recovery, depths, and lithology for all four borings are shown graphically in figure 4.

Borings B1/B1A

The B1 coring site (E608813, N2362945, UTM zone 4N) is located between the Ford Island shore and the starboard side of the USS *Arizona* (fig. 2). The water depth here was 8.5 m at 11:24 a.m. on November 13, 2003 (Hirata, 2003), at a tide elevation of 0.77 m MLLW, based on the Honolulu Harbor tide station. An initial attempt at B1, using Shelby tubes alone, resulted in poor recovery because of difficult coring conditions at depth. However, two Shelby tubes were recovered, one at 8.5 m below seafloor and another at 18.1 to 19.0 m, the bottom of the boring.

The Shelby tube recovered at 8.5 m contains loose, pale brown, silty sand and shell fragments, with hard, angular coral rubble fragments up to 6 cm across. The Shelby tube recovered from the bottom of the boring contains very stiff brown clay with minor fragments of coral, basalt, and possible basaltic glass.

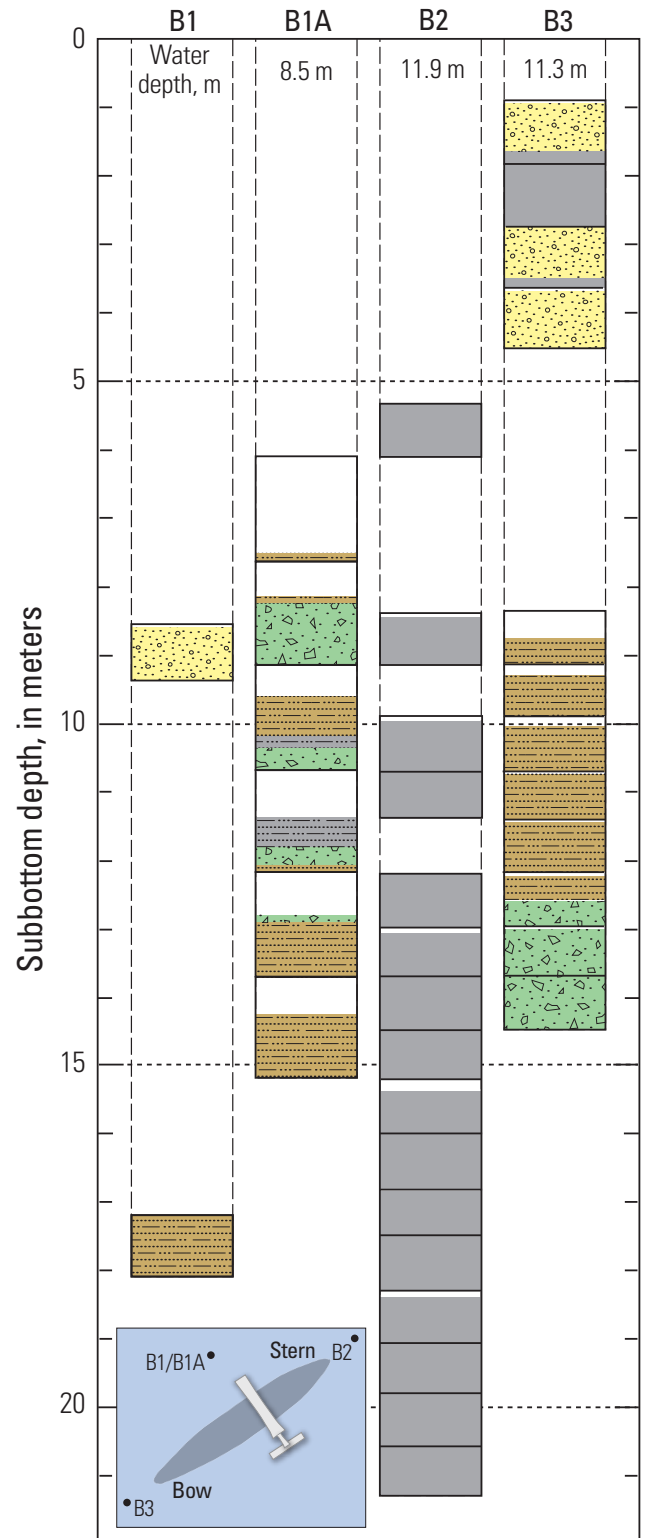


Figure 4. Graphical representation of depths and lithology for all recovered cores from the USS *Arizona* borings. See table 1 for exact depths, liner type, and recovery. Each solid rectangular box represents a recovered core. Nonrecovery is shown as dashed lines between cores and as blank space within cores. For boring B1A, reworked or winnowed material occupying part of the nonrecovery zones within cores is not shown.

EXPLANATION

- Sand, silt, and shell fragments
- Soft, gray clay with minor shell fragments
- Very stiff, brown silty-sandy clay
- Very stiff, gray-brownish to gray, silty clay
- Stiff, greenish-gray clay with coral rubble fragments

An alternate coring method, resulting in boring B1A adjacent to B1, involved repeatedly driving 1.5-m-long sections of steel pipe (8.9 cm outer diameter) down the hole to a final depth of 15.2 m. The overall recovery amounted to approximately 6.1 m (40 percent of the 15.2 meter depth penetrated). There was no recovery in the first 6.1 m penetrated (first four pushes), or this interval was not sampled, but below this point six sections of pipe contained material for a total recovery of 67 percent. Empty liner above the recovered materials in each section was cut off before logging with the multisensor core logger. Because of the extra time involved in dealing with coring difficulties at B1 and B1A, a planned fourth boring site B4, to be located on the port side of the USS *Arizona*, was abandoned.

The sediments recovered from B1A (see fig. 4 for distribution and proportions) consist of: (1) very stiff, dark brown, silty to sandy clay; (2) very stiff, gray-brown to gray clay; and (3) stiff, mottled, greenish- to yellowish-gray clay containing variable amounts of hard, angular, pale tan to gray, calcareous coral debris clasts (green, fig. 4). The mottled clay is referred to as coral rubblestone in the Hirata (2003) report. The matrix and clasts are highly effervescent in HCl. The very stiff brown to gray clays are the sandy/silty clay (CL/CH) of the Hirata (2003) report.

Four of the six cores from B1A contain from 7 to 46 cm of loose or muddy sand and gravel at the top of each core, amounting to 23 percent of the recovered material. This upper material is composed mostly of hard shell fragments, weathered coral, with lesser crystalline limestone, fine-grained limestone (micrite), and traces of basalt. This loose material overlies other soft and mixed, disturbed materials, which in turn overlie intact, very stiff clays. The loose material is probably a washed and winnowed residue remaining after the borehole casing was flushed with water between coring pushes. Because of partial recovery and disturbance caused by the coring process, actual thicknesses and original contacts are largely obscured within much of B1A.

Boring B2

Boring B2 is located (E608943, N2362957) about 30 m northeast of the stern of the USS *Arizona*. Water depth was 11.9 m at 8:38 a.m. on November 18, 2003 (Hirata, 2003). The tide elevation at the time of depth measurement was 0.44 m MLLW, based on the Honolulu Harbor tide station. Shelby tubes were enclosed within schedule 40 steel pipe down to a depth of about 7.6 m subbottom depth to protect them from damage (Hirata, 2003). Fifteen Shelby tubes deployed in 2.5-foot (approximately 76 cm) pushes were recovered from B2, which reached a planned depth of 21.3 m (70 feet) at the base of the last tube. The total recovery amounted to about 61 percent, with no recovery from the harbor bottom to a subbottom depth of 5.3 m. Twelve Shelby tubes make up a nearly continuous sequence from 12.2 to 21.3 m. All of the recovered sediment from B2 consists of soft, gray to greenish- or blackish-gray clay or silty clay containing minor shell fragments.

Boring B3

Boring B3 is located (E608749, N2362811) about 30 m southwest of the bow of the USS *Arizona* (fig. 3). Water depth was 11.3 m at 11:25 a.m. on November 15, 2003 (Hirata, 2003). The tide elevation at the time of depth measurement was 0.48 m MLLW, based on the Honolulu Harbor tide station. Twelve Shelby tubes were recovered from the boring, representing a total recovery of 66 percent of the total depth sampled. Eight tubes form a nearly continuous recovery sequence beginning at 8.2 m subbottom depth to the bottom of the boring at 14.5 m.

Four Shelby tubes containing sediment obtained from 3-foot (approximately 91 cm) pushes were recovered from the subbottom interval 0.91 to 4.57 m. These cores represent the only sediment recovered from the upper part (< 5 m subbottom depth) of the three boring sites. The recovered sediment consists of sand, silt, shell fragments, and soft gray clay. From 8.23 to 12.2 m, five Shelby tubes, driven in 2.5-foot (approximately 76 cm) pushes, contain stiff, dark brown, silty to sandy clay, with minor dark granules up to about 3 mm across. The clay is not effervescent with HCl (table 2) and is similar to the dark brown, stiff clay recovered from B1 and B1A. Two Shelby tubes, from 13 to 14.5 m subbottom depth, contain stiff, mottled, greenish- to yellowish-gray clay containing variable amounts of hard, angular, pale tan to gray, calcareous coral debris clasts (green, fig. 4). The clay matrix and the fragments are highly effervescent in HCl. This is the coral rubblestone of the Hirata (2003) report and is similar to that recovered from boring B1A.

Mineralogy

Semiquantitative mineralogy of six samples from Borings B2 and B3 was determined by x-ray diffraction (XRD) at the USGS facilities in Menlo Park. The results are shown in table 2.

H₂O₂ reactivity is a measure of the organic content of the sediment; HCl reactivity reflects the content of carbonate. The strong HCl reactivity of the B3 sample (13–13.7 m) is an indication of high content of calcareous debris within the green clays. Expansion occurred in the low-stress steps during consolidation tests involving samples containing the calcareous coral rubble, represented by the B3 sample (13–13.7 m) and indicates the presence of some expandable clay.

Spectral Analysis of Interface Waves (SAIW) Testing

In early June of 2005, the USGS survey conducted seafloor spectral analysis of interface waves testing around the hull of the USS *Arizona*. In subaqueous environments, waves traveling at the transition of the seafloor and the water column are interface waves that leak energy into the

Table 2. Semiquantitative X-ray diffraction (XRD) mineralogy and reactivity (H_2O_2 and HCl) of samples from borings B2 and B3.

[Reactivity levels: 0 = no reaction, 1 = minor, 2 = moderate, 3 = strong. Asterisk (*) indicates a delayed reaction and may indicate a different type of organic matter]

Boring	Sub-bottom depth, m	Core depth, cm	Lithology	XRD Mineralogy	Reactivity	
					H_2O_2	HCl
B2	5.34–6.10	88.6–89.2	soft gray clay	Aragonite, Hematite, Tosudite (Chlorite/Smectite) or Kaolinite or Halloysite, Pyroxene	3*	2
	14.5–15.2	82–86	soft gray clay	Calcite, Halloysite, Hematite, Kaolinite?, Covellite?	3	2
	20.6–21.3	76–81.3	soft gray clay	Halloysite, Magnetite, Hematite, Montmorillonite?, Kaolinite?	3*	1
B3	9.15–9.91	80.7–84	v. stiff brown clay	Halloysite, Hematite, Kaolinite?	1	1
	10.7–11.4	82.3–86.3	v. stiff brown clay	Halloysite, Hematite, Tosudite (Chlorite/Smectite)	1	0
	13–13.7	84.5–87	stiff clay w/coral debris	Calcite, Kaolinite, Magnetite	3	3

water column and have high damping. Our study sought to determine the shear wave velocity of the seafloor surrounding the hull of the USS *Arizona* in order to determine the thicknesses of compressible units observed in the three borings. Settlement and subsidence effects are most extreme in the subaqueous environments of ports, harbors, and open waters, where saturation is 100 percent and extremely soft sediments are deposited.

Spectral analysis of interface waves (SAIW) testing is an efficient method for noninvasive investigation of soil properties that is linked to engineering analysis of material stiffness. At the USS *Arizona*, the surface wave test system we used is based on a computer-controlled, electromechanical, harmonic wave source (“shaker”) manufactured by APS Dynamics. The test is performed along linear arrays where the shaker is placed on the seafloor at one end of the array line. A harmonic wave signal from a sine-function generator is sent to the shaker, after being boosted by an amplifier. The electro-motor on the shaker drives reaction weights that are suspended by silicon bands and causes them to slide up and down, producing gentle, harmonic surface waves. In the seafloor SAIW test, geophone receivers are used to pick up the waveform of the surface waves. As the test progresses through a suite of stepped frequencies, each signal is analyzed using the fast Fourier transform to compute linear spectra, cross power spectra, phase lag (wrapped or unwrapped phase), and frequency response. This allows for the calculation of phase lag across the frequency range for any pair of seismometers (Nazarian and Stokoe, 1984). The harmonic wave vibrator sweeps through low frequencies, typically 2–100 Hz, to shake the seafloor and capture the surface wave dispersion characteristics of the seafloor. The ability to perform near real-time frequency domain calculations and monitor the progress and quality of the test allows us to adjust various aspects of the test to optimize the capture of the phase data. These aspects include the source-wave generation, frequency step size between each sine-wave burst, number of cycles per frequency, total frequency range of all the steps, and receiver spacing.

The test apparatus consists of a 36-channel geophone streamer, a low frequency spectrum analyzer/signal generator, and one or more computer-controlled electro-mechanical shakers and amplifiers. The shaker is arrayed at the end of an SAIW test line of seismometers. Spacings between the geophones, and between the first receiver and source, are stepped geometrically from 1 m to 24 m (half the streamer length). Each pair of two seismometers is separated by distance d , and the source is usually placed at a distance d from the inner seismometer. Rayleigh wavelengths (λ) are computed by relating the seismometer spacing (d) and the phase angle (θ , in radians determined from the peak of the cross-power spectrum) between the seismometers:

$$\lambda = 2\pi d/\theta \quad (1)$$

The surface wave velocity, V_r , is the product of the frequency, f , and its associated frequency dependent wavelength:

$$V_r = f\lambda \quad (2)$$

Computing the averaged grouped dispersion curve for a site requires that we collect a suite of individual dispersion datasets for specific array geometries. Regardless of the array dimensions, we compute phase velocities for phase angles between 120 degrees and 1,080 degrees, corresponding to wavelengths of $3d$ and $d/3$, respectively. If the data are not optimal, the range is narrowed to between 180 degrees and 720 degrees, or $2d$ and $d/2$. For example, if the array separation (d) was 3 m, phase velocities can be computed for wavelengths of 1 to 9 m under ideal conditions, or 1.5 to 6 m under normal conditions. Longer wavelengths sound more deeply into the ground and extend the overall profile to greater depths. These long wavelength data are associated with low frequencies and large array separations. The array dimension is changed by selecting different geophone pairs. A group of individual dispersion curves is captured to cover the target

range of wavelengths. The averaged grouped dispersion curve is calculated from these profiles and is the basis for inverting the velocity structure of the ground. Dispersion curves are the surface wave velocities, calculated using equation 2, plotted against frequency or wavelength.

The three components of the seafloor SAIW apparatus are a large cylindrical containment vessel for the harmonic-vibrator, a lead-weighted 36-channel geophone streamer cable for the receivers, and a 300-m conductor cable for powering the shaker, providing cable scope, and acquiring the transmitted waveforms (fig. 5).

The pressure vessel is made of a 0.5 in (1.27 cm) thick aluminum cylindrical section with a 24 in (79 cm) inner diameter having a base plate welded to the bottom and a gasket-ringed aluminum cover plate. Power supply is delivered to the vibrator through a marine cable-connect mounted on the cover plate. The other end of the power cable is connected to the shaker-amplifier unit. A weighted geophone cable with 36 individual 4-Hz receivers is placed on the seafloor. Channels 1 to 24 are spaced 1 m apart, and the remaining channels 25 to 36 are spaced 2 m apart, for a total array separation length of 48 m. The test can be run in multichannel analysis of interface waves (MAIW-mode), gathering all the channels simultaneously, or in 2 or 4 channel SAIW-mode. To run the test in MAIW or SAIW mode, we built a custom multichannel streamer breakout box to collect data for different seismometer separations (fig. 6).

The seafloor system is designed for continental shelf water depths of 100 m or less. To allow for currents and drift

of an anchored deployment vessel, the conducting cable has 300 m of scope. The long conducting cable requires that the signal from the receivers be amplified, and this is accomplished with an in-line amplification unit. The maximum design hydrostatic pressure that can load the pressure vessel without causing leakage is 100 m. In order to reach greater depths, a thicker walled cylinder or a nonconducting oil-filled chamber would be needed.

Inversion Procedure

A geophysical inversion process is used to estimate the soil stiffness model whose computed theoretical dispersion curve is a best fit with the experimental dispersion data collected in the field. That is, we invert shear-wave velocity profiles using an inversion code that finds the best-fit shear-wave velocity profile with a theoretical dispersion curve that is a closest match to the averaged field dispersion curve. The term “best fit” refers to the minimum sum of the squares of residuals from the differences between the theoretical and experimental dispersion curves (fig. 7). The inversion algorithm, SASW-C (Pelekis and Athanasopoulos, 2011), uses an automated numerical approach that employs a constrained least-squares fit of the theoretical and experimental dispersion curves. We also use independent inversion algorithms, *inverse.m* (Lai and Rix, 1998) and *WinSASW* (Joh, 1996), to validate the profiles computed from SASW-C, a method discussed in Kayen and others (2013).

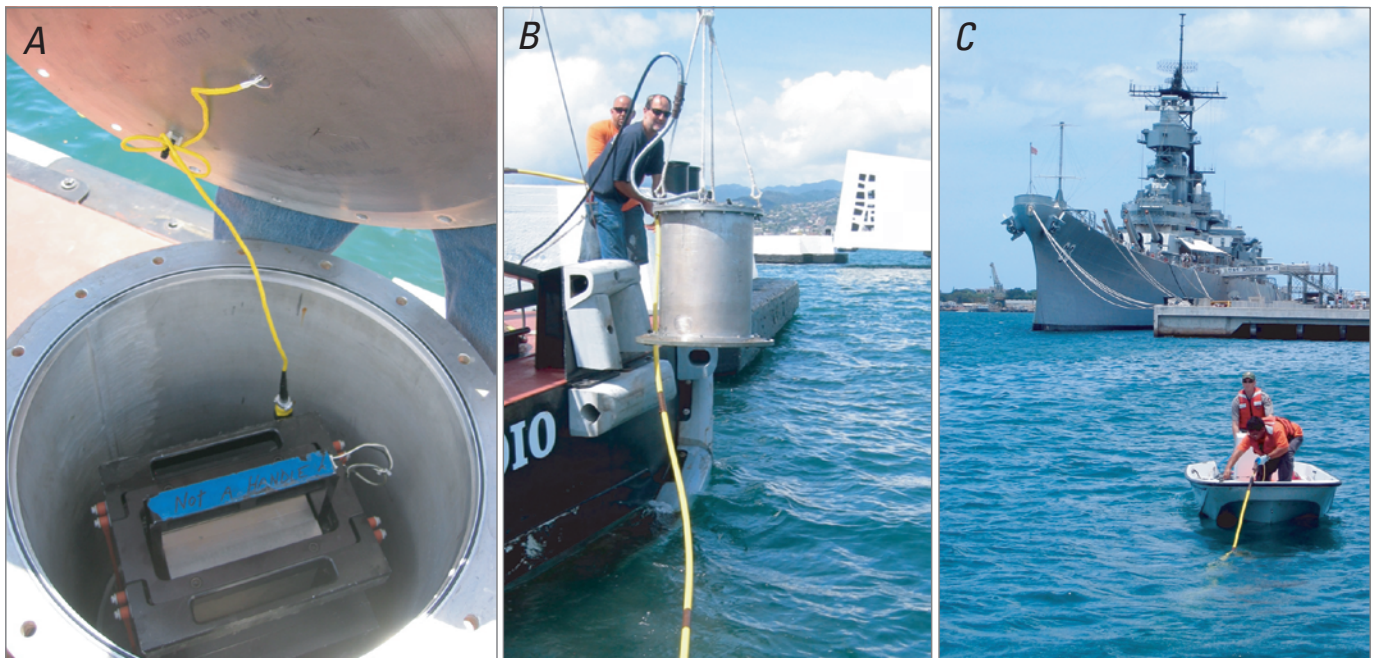


Figure 5. Deployment of the seafloor SAIW system at the USS *Arizona* Memorial. *A*, A single harmonic wave vibration source is sealed within a gasket-lined aluminum pressure vessel. *B*, The pressure vessel is deployed over the side of a research platform. The multi-channel streamer cable is Yale-gripped to the pressure vessel. *C*, The streamer cable is straightened into a linear array using a launch. The streamer is weighted to sink into the seafloor sediment.

Inverse problems are concerned with the estimation of model parameters (in this case soil stiffness) from a set of observations. This is possible because we can calculate the forward problem that relates the model parameters to the measurements. The surface-wave inversion problem is an ill-posed inverse problem. Mathematical problems that are well-posed have unique solutions that exist, and the solutions are stable. The term ill-posed in relation to inverse problems refers to inverse problems with nonunique solutions and potentially unstable solutions. Ill-posed inversion problems are typically approached using regularization methods. For example, the Levenberg-Marquardt method, a damped least-squares best fit regularization method hunts for nonunique solutions that minimize instability. The parameters can be chosen such that the difference between the observations and the output of the forward problem are minimized, which is called optimization. For ill-posed problems, a priori information is important to constrain the output velocity model.

SAIW testing has revealed zones of differing shear wave velocity around the hull of the USS *Arizona*. In figure 8 the profiles of shear wave velocity versus depth resulting from the inversion procedure are arranged around the hull of the USS *Arizona*. Low, intermediate, and high velocity classifications in figure 8 are ranges relative to the USS *Arizona* site. These values are based on the $V_s/15$ value, which is the average velocity of the top 15 m of the profile. Low values are defined as 0 to 250 m/s, intermediate velocities are 250 to 350 m/s, and high velocities are >350 m/s. The shear modulus, one measure of the stiffness of sediment, is directly proportional to density and the square of the shear wave velocity. The shear wave velocities are therefore a direct measure of the relative stiffness of the sedimentary foundation beneath the *Arizona* hull.



Figure 6. Data acquisition unit for the seafloor MAIW/SAIW system. It includes an Agilent VXI digital recorder for MAIW, custom breakout box for the multichannel streamer, channel amplifier box, and a 4-channel spectral analyzer for SAIW.

The high velocities measured at the bow are noteworthy, and this area corresponds to the occurrence of the stiff, brown clays recovered in boring B3. Also noteworthy are the low velocities measured along the port quarter. This area is near boring B2 and its continuous sequence of soft, gray clay. In contrast to the port quarter, the area adjacent to the starboard quarter has high shear wave velocities similar to those at the bow. Site 727 at the midship port side has a pronounced velocity increase at about 15 m subbottom depth. The spatial and depth variability of the shear wave velocities is another indication that the sedimentary foundation of the *Arizona* Memorial area is not homogeneous or layered in a simple manner.

Subbottom Stratigraphic Modeling

Three cross sections have been produced of the subsurface in the area of the USS *Arizona* Memorial. The stratigraphic columns compiled for the three borings (fig. 4) are the primary sources of information for the three cross sections in figures 9, 10, and 11. The depiction of the present bottom surface in the sections is guided by the depths resulting from the C1-02-HW seismic survey, the depths reported by Hirata (2003) at the boring locations, and the depiction of the bottom along the port side of the USS *Arizona* hull in the drawings from Lenihan (1989). The 2005 USGS SAIW survey provides significant guidance in defining the lateral distribution of stiff versus soft

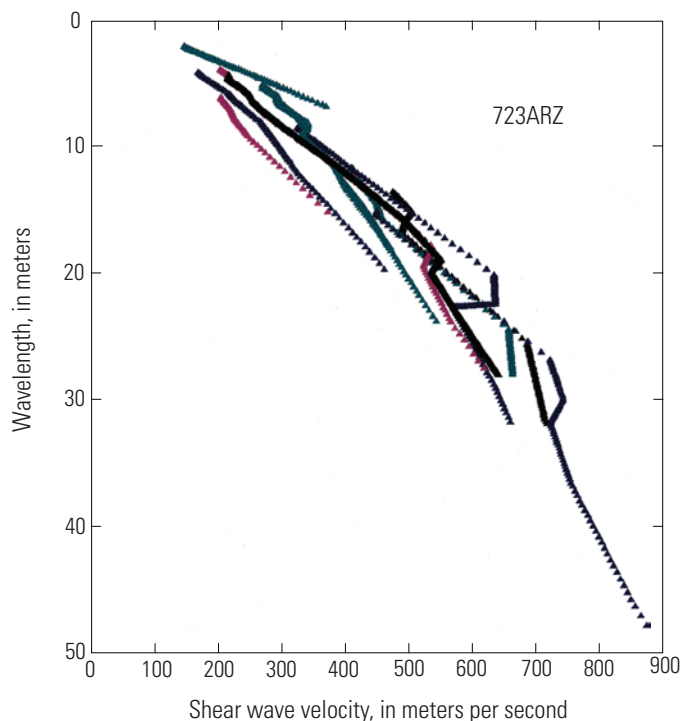


Figure 7. Graph showing an example of grouped experimental dispersion curves from one site at the bow of the USS *Arizona*. See figure 8 for site location.

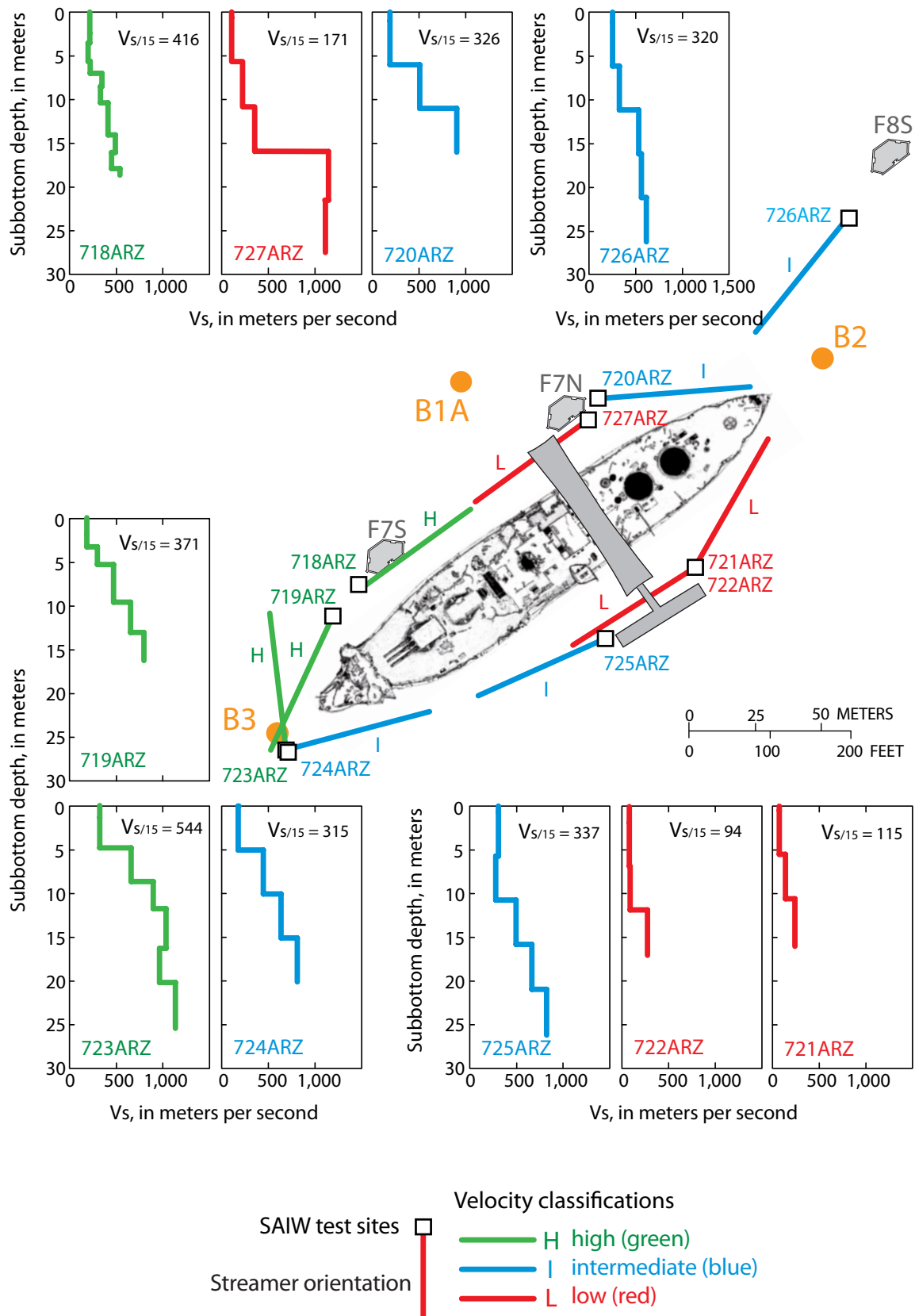


Figure 8. Shear-wave velocity profile data from the seafloor test system measured at various points around the perimeter of the USS Arizona. The seismic streamers used are 48 m long. Full-size site plots are in appendix I, figures I-1 to I-10.

sediment in the immediate vicinity of the hull. No correlations have been made between the recovered sediments of the three borings and any previously mapped geology of Ford Island or Pearl Harbor.

The entire drilling services report from Ernest K. Hirata and Associates is included in this report as appendix C. There are some significant discrepancies between the sediment observed in the recovered cores and what has been depicted in that drilling report. These differences are portrayed in appendix D, where the stratigraphic columns from the Hirata report and the ones developed in this study are compared. The columns for boring B1A are sufficiently similar to be considered identical. In boring B2, there is no evidence for the presence of the stiff brown clay (CL-CH) between approximately 6.5 and 12.5 m subbottom depth as depicted by Hirata (2003), either as material observed at the tops and bottoms of the Shelby tubes or as densities obtained from the multisensor core logger. There is also no evidence for the sand, silt, and shell fragments reported by Hirata below 12.5 m subbottom depth to the base of the boring. For boring B3, the stiff brown clay (CL-CH) occurs at a shallower depth in the recovered cores than depicted in the Hirata report. In addition, there is no greenish-gray coral rubblestone reported by Hirata at the base of boring B3, as is observed in the three deepest recovered cores. The Hirata report contains a record of recovery of seven cores from B3, whereas we are in possession of twelve. The columns for borings B2 and B3 from Hirata (2003) are not used for guidance in this study.

In light of the generally poor recovery from the upper 5 to 8 m of the four borings, these intervals are designated as undifferentiated and are regarded as comprising unknown proportions of sand, silt, clay, and shell fragments. The recovery from the upper part of boring B3, approximately 1 to 4.5 m subbottom depth, is the basis for the composition of the undifferentiated interval. These undifferentiated intervals are shown with a light gray color in the stratigraphic columns of appendix D. In the cross sections, this interval is further subdivided into preattack and postattack sediments, though the boundary between them is in part speculative.

The water at the Fox 7 mooring quay at the time of the December 7, 1941, attack is cited as having a depth of 7.5 fathoms (13.7 m) (Friedman and others, 1978). The forward draft of the USS *Arizona* at that time was 9.9 m; the aft draft was 10.1 m. The height from the USS *Arizona* keel to the upper deck is approximately 16.5 m as measured from ship drawings (Friedman and others, 1978; Foecke and others, 2010). Based on a uniform water depth of 13.7 m, if the ship were resting on the bottom with no penetration into the harbor sediment on the morning of December 7 at 10:21, the bulwark at the port side upper deck at Frame 83 would be about 2.8 m above the surface. In appendix F, figure F-1, we show that the upper deck edge (top of the bulwark) at this point was 0.77 m above the water surface. This observation would suggest a penetration of about 2 m into soft harbor sediment by 2.2 hours after the explosion that sank the ship. A similar calculation done for the bow indicates as much as 3 m

of penetration by the afternoon of December 7, as indicated by the deck at the bow being completely submerged. The cross sections of figures 10 and 11 are drawn assuming 2 m of penetration at the port edge. To this is added the measured settlement of the USS *Arizona* at various points around the hull into the preattack sediment during the years since sinking.

The upper surface of the preattack undifferentiated sediment (the harbor bottom on December 7, 1941) is depicted in figure 11 based on a water depth of 13.7 m. After the attack no dredging or maintenance of the mooring area took place, allowing accumulation of the postattack sediment. The USS *Arizona* hull has acted as a barrier to the tidal circulation and allowed accumulation of sediment along the starboard side.

The location and site plan drawing for the new Memorial structure (Johnson & Perkins, Preis & Associates, 1961) provides measurements of the water depths at the port and starboard midship areas during the early 1960's. Profiles drawn from these depths are the dashed lines in figure 11 on the starboard and port sides of the hull and serve as an indication of the thickness of sediment accumulated since the early 1960's. The datum associated with these depths is not known, so the lines are an approximation of depth.

The C1-02-HW seismic survey (unpublished memorandum by M. Field and P. Hart, 2002) results for the area of boring B3 reveal a reflector sloping toward the deeper harbor at a subbottom depth of about 8 m. This probably corresponds to the contact between the undifferentiated preattack and postattack sediment and the underlying stiff brown clay and coral debris. Recovery of the brown clay within the Shelby tubes begins at about 8.5 m subbottom depth, and the cross sections are drawn assuming a contact at this depth. Any subbottom layering in the area of boring B2 is obscured by gas in the C1-02-HW seismic survey.

An important aspect of the subbottom stratigraphy in the area of the USS *Arizona* hull is that the thick sequence of soft gray clay at B2 is not present at B1A or B3 (see fig. 4). This clay must pinch out or diminish considerably in thickness on the line between B2 to B1A (fig. 9) and B2 to B3 (fig. 10). The nature of the contact between the soft gray clay of B2 and the stiff clays of B1A and B3 was not observed, but given the significant difference in physical properties, the soft gray clay is not considered to be an age-equivalent facies of the stiff clays or to be interbedded with them. The soft gray clay therefore likely onlaps an erosion surface on the older stiff clays. A wedge of soft clay, thickening toward the harbor (to the southeast) and overlying an erosion surface on the stiff clays, is the interpretation depicted in the cross sections of figures 9, 10 and 11.

Figure 11 is a cross section developed from boring B1A through the USS *Arizona* midship at approximately Frame 83, between the port-side mooring platform adjacent to the Memorial and the starboard-side bitts (mooring posts at the edge (bulwark) of the deck) typically visible above water level. The remains of the upper deck are the present level of the hull in this location.

12 Settlement of the USS *Arizona*, Pearl Harbor, Hawaii

Figure 12 is a depiction of a surface at the base of the preattack undifferentiated sediment, at a subbottom depth of 5 to 6 m. The soft gray clay sampled at boring B2 pinches out or diminishes considerably in thickness between B2 and B1A and between B2 and B3. The “zero isopach trend” area of figure 12 marks the potential trend where the soft gray clay pinches out or thins to insignificant thickness. The trend is guided by the SAIW test results. High velocity SAIW test areas (areas marked “H” in fig. 8) are assumed to contain no B2-type clay,

such as at the bow near boring B3, where clays and coral debris are present beneath the unrecovered preattack and postattack sediment. Low velocity areas (“L” in fig. 8) are located along the port side midship and quarter, near boring B2, and are assumed to contain a significant depth of soft clay. Intermediate velocity areas (“I” in fig. 8) are assumed to contain some lesser thickness of clay. A buried channel margin with steep slopes could explain a thickening of the clay over a short distance, as at the starboard quarter of the USS *Arizona* hull.

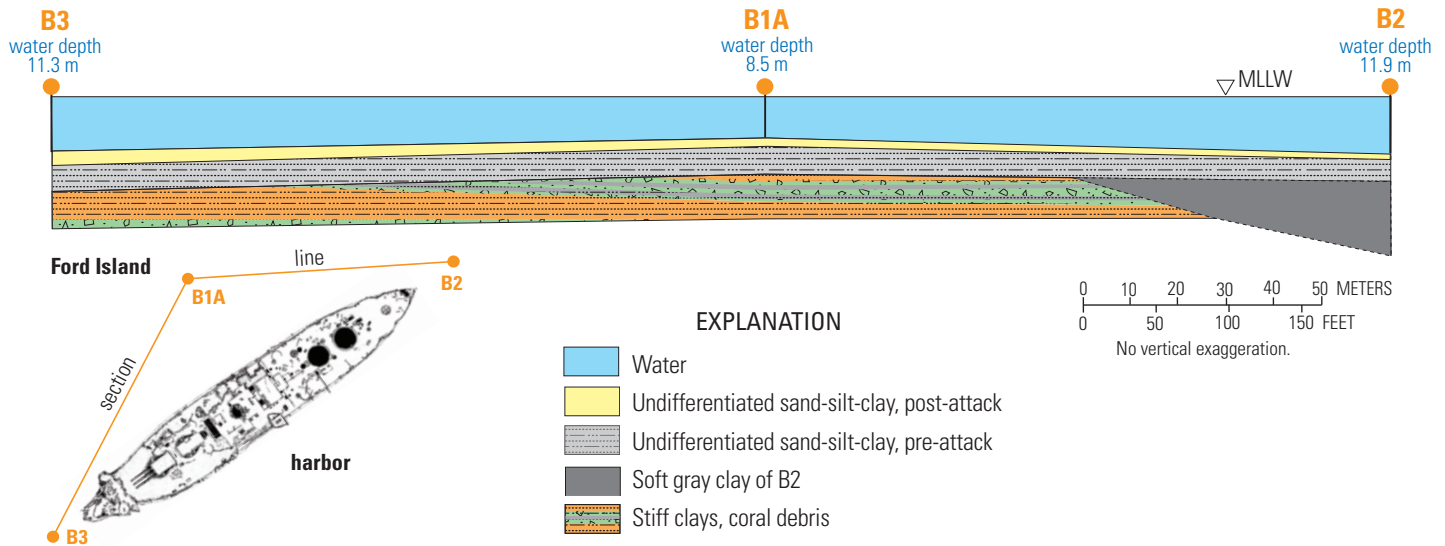


Figure 9. Cross-section of modeled sediment stratigraphy from boring B3 through B1A to B2. The thick, soft gray clay at boring B2 is not present at B3 or B1A and likely pinches out along the lines to B3 and B1A. The boundary between the preattack and postattack undifferentiated sand-silt-clay is speculative. Based on the locations provided by Hirata (2003), the distance from B3 to B1A is 149 m, from B1A to B2 is 130.6 m, and from B3 to B2 is 242.8 m.

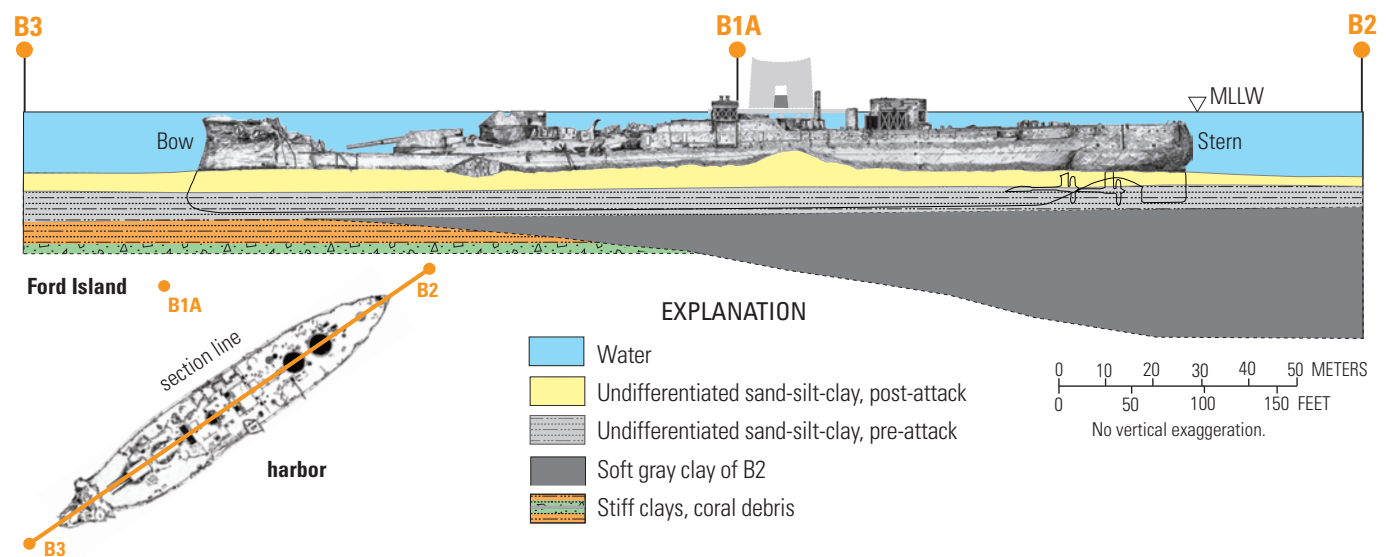


Figure 10. Cross-section of modeled sediment stratigraphy along the axis of the USS *Arizona* between borings B3 and B2. A profile of the USS *Arizona* hull to scale is inserted along the cross-section line. Ship drawing based on a 1984 survey in Lenihan (1989).

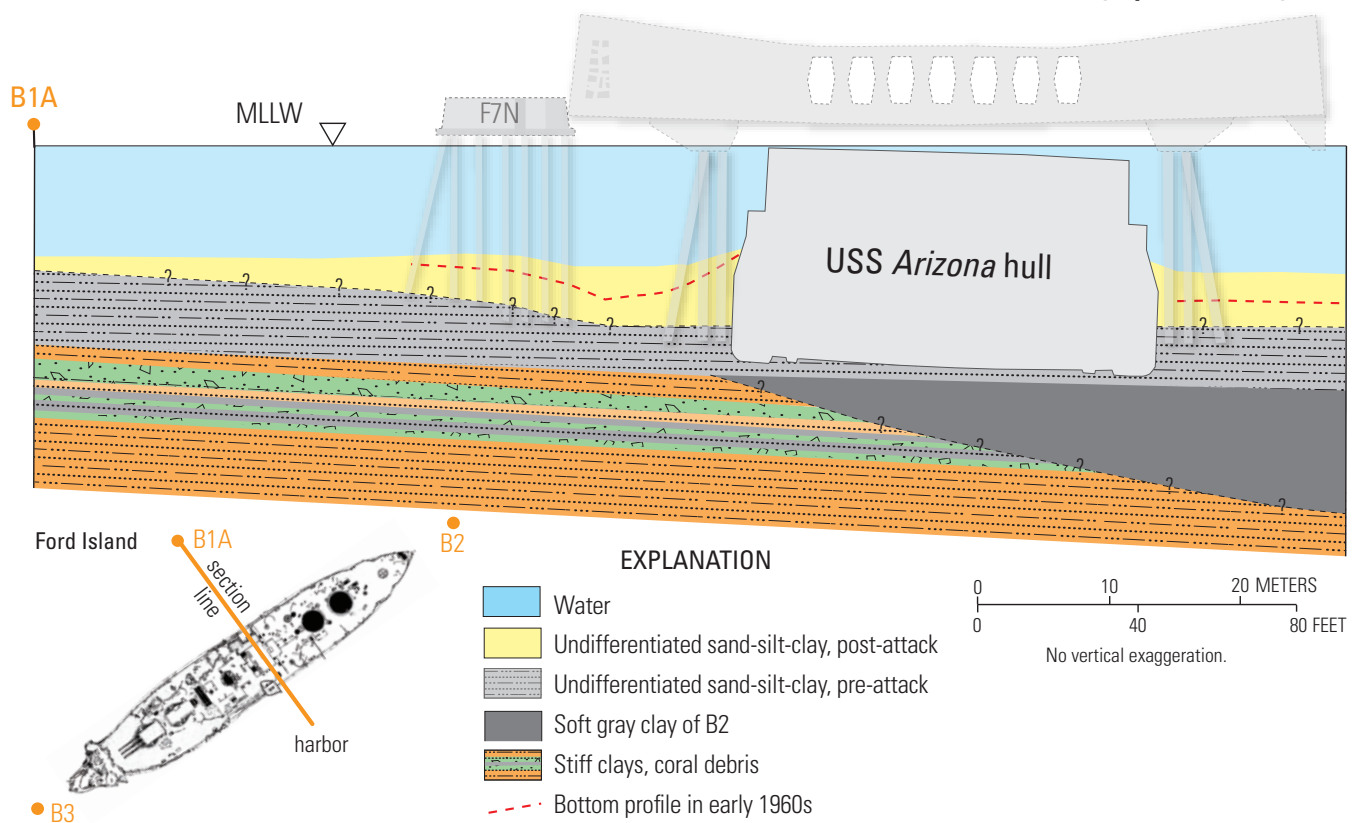


Figure 11. Cross-section of modeled sediment stratigraphy from boring B1A beneath the USS *Arizona* midship at Frame 83 looking northeast toward B2. The distance from B1A to the centerline of the hull is approximately 70 m. USS *Arizona* hull profile adapted from Foecke and others (2010). Profile of the Memorial added for scale. F7N is the Fox 7 north mooring quay.

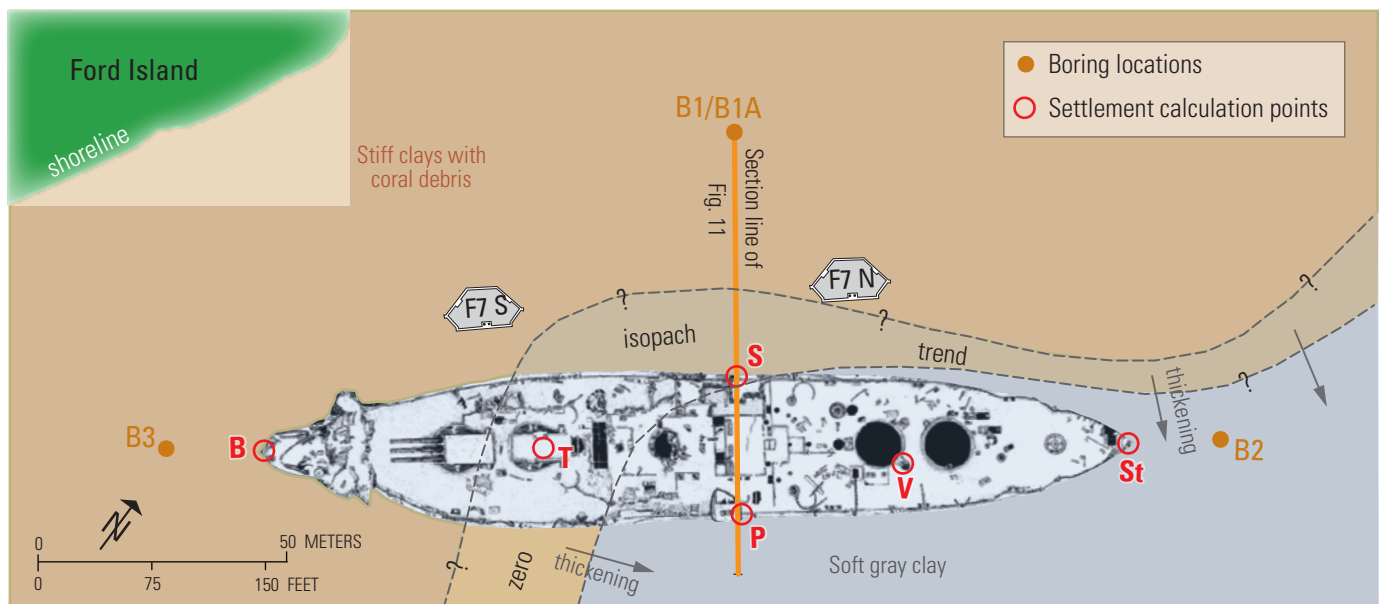


Figure 12. Sketch map showing estimated distribution of the soft gray clay around the USS *Arizona* hull based on the SAIW tests. The zero isopach trend is the estimated location of the soft gray clay pinch-out. There is ≥ 16 m of soft gray clay at boring B2 beginning at a subbottom depth of about 5.3 m. Settlement calculation points B, T, S, P, V, and St are the locations of points shown in tables 7 through 11 and figures 30 and 31. F7N and F7S are the Fox 7 north and Fox 7 south, respectively, mooring quays. Ship drawing adapted from Lenihan (1989).

One version of the stratigraphy beneath the USS *Arizona* dating from the time of the construction of the new memorial is shown in figure 13. The actual results of test borings at the locations of the concrete pile supports were not located in the present study, and it is also not known if the test boring results are incorporated into the depiction in figure 13.

The coral rock as depicted in figure 13 at a subbottom depth of 12 m (40 feet) was not encountered in borings B1A, B2, or B3. A representation of borings B1 and B1A relative to this stratigraphy is shown at the right margin of figure 13. Based on figure 13, the base of boring B2 would have penetrated more than 9 m into the coral rock, but, as already shown, no coral rock was encountered. In addition, SAIW test sites 721 and 722 along the port quarter of the hull (fig. 8) show no indication of significantly rising shear wave velocity at subbottom depths of 15 m.

Reflector C of the 2002 C1-02-HW seismic survey (unpublished memorandum by M. Field and P. Hart, 2002) is considered to be the top of a firm, well-cemented deposit, most likely an eroded limestone or reef deposit. In the area of the USS *Arizona* Memorial, reflector C is located 51 to 55 m below the harbor surface, whereas in figure 13 the interface with the coral rock (that is, the density contrast thought to cause Reflector C) is shown at about 24 m below the surface. The difference between the results of the C1-02-HW seismic survey and the depiction of figure 13 regarding the depth of coral bedrock is not resolved in this study. Several meters of firmly lithified limestone and coral bedrock are exposed in the shore cliff of Ford Island adjacent to the USS *Arizona* Memorial area.

Geotechnical Testing Methods

The USGS Multisensor Core Logger (MSCL)

An early version of the USGS multisensor whole core sediment-logging device, built in Great Britain by Geotek, Ltd. (Serial No. 1), was set up in a temporary field lab in Building 42 on Ford Island (fig. 14) in 2003 to log the cores from the boring operations. Cores were delivered from the coring barge daily and were logged on the same day or placed in refrigerated storage. Capped sediment cores are placed horizontally upon a transport sled and moved by a computer-controlled stepper motor through a frame supporting three sensors. The logging device can sequentially measure core diameter and compression wave (P-wave) travel time to compute P-wave velocity; attenuation of gamma rays from a ^{137}Cs source to compute soil wet bulk density; and magnetic susceptibility of soil particles via a magnetic field loop. Measurements of velocity, density, and magnetic susceptibility are typically taken at 1-cm increments. The transport sled is capable of carrying individual core sections as long as 1.5 m in length. Because of the steel Shelby tube liners, only the bulk density of the sediment could be measured. Scanned cores were kept in refrigerated storage until their shipment to California after the project in late November of 2003.

The USGS developed an Apple HyperTalk™-driven software program called HYPERSCAN to automate the logger system and support a number of scanning options tailored to

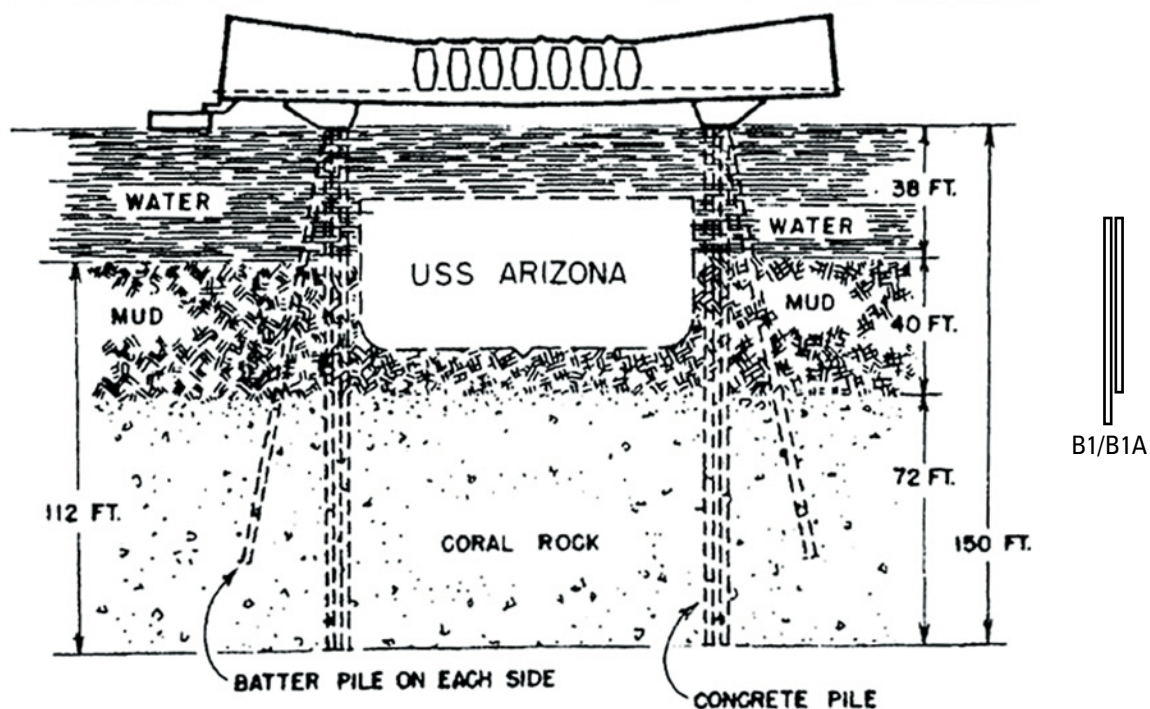


Figure 13. Diagram showing a sectional view of the USS *Arizona* memorial site from the planning or construction stage for the new memorial (Johnson & Perkins, Preis & Associates, 1961). The reason for the low level of the USS *Arizona* deck relative to the water level is unknown. The approximate position of the B1 and B1A borings relative to the stratigraphy is shown at right.

users and the system (Kayen and Phi, 1997; Kayen and others, 1999). The program includes a suite of subroutines for system calibration and permits the sensors to be activated or disabled. For example, at Pearl Harbor, the metal Shelby tube core liners do not allow for measurement of magnetic properties. In this case, the magnetic susceptibility sensor was disabled to increase the efficiency of the system. Computer automation also allows the operator to maintain some physical distance from the ^{137}Cs gamma ray source. During automated scanning, an unsplit sediment core is driven down a track system in user-prescribed increments and a Macintosh computer interrogates sensors. As data enter the computer, the gamma bulk density, P-wave velocity, and magnetic susceptibility are calculated, logged into a matrix data file, and presented in real time on a 3-plot graphics display window.

Wet Bulk Gamma Density

Bulk density is the ratio of the total soil weight to the soil volume. The configuration of our device allows for a core to pass between a scintillation counter and a lead-shielded, sealed, ^{137}Cs radiation source emitting a 1-cm collimated beam of gamma rays. Sediment bulk density (ρ_b) is calculated from the gamma ray attenuation characteristics of the cores according to Lambert's law (Haynes, 2012). For a user-defined time period, the number of gamma decays emitted from the ^{137}Cs source, passing through the core and received at the scintillation detector, is counted.



Figure 14. The USGS multisensor core logger set up in Navy Building 42, Ford Island, during the drilling operations. In this photo, an enameled steel Shelby tube is being scanned. The tube travels along the track from lower right to upper left.

The number of scintillations transmitted from the source to the scintillation counter through air is referred to as the unattenuated gamma count, I_0 . For the case where a homogeneous material of some thickness, d , lies between the ^{137}Cs source and counter, the attenuated gamma ray count, I , can be related to the unattenuated gamma count, I_0 , the material thickness, d , the soil bulk density, ρ_b , and the soil Compton scattering coefficient, μ_s by Lambert's Law:

$$I = I_0 \exp \{-\mu_s \rho_b d\} \quad (3)$$

The bulk density of the soil can be determined as follows:

$$\rho_b = \frac{1}{\mu_s d} \ln \left(\frac{I_0}{I} \right) \quad (4)$$

For whole sediment cores encased in liners, we must account for the influence of the core liner to get an accurate estimation of the soil density. The liner correction accounts for liner attenuation of the gamma-ray beam through absorption and scattering, effects controlled by (1) the liner Compton scattering coefficient, μ_l , (2) liner wall thickness, l , and (3) liner wall density, ρ_l . For sediment contained within a core liner of outer diameter, D , and double-wall thickness, $2l$, equation (2) can be rewritten as:

$$I = I_0 \exp \{-\mu_s \rho_b (D-2l)\} \cdot \exp \{-\mu_l \rho_l 2l\} \quad (5)$$

Equation 5 relates the attenuated gamma-ray count to the partial scattering influences of the liner and soil and can be used to assess the density of material contained within a variety of liner types, both plastic and metal. To determine the bulk density of soil, equation 3 must first undergo transformation to base-e logarithm.

$$\rho_b = \frac{\ln \left(\frac{I_0}{I} \right) - \mu_l \rho_l 2l}{-\mu_s (D-2l)} \quad (6)$$

MSCL Calibrations

Density measurements of soil contained within intact core-liner are calibrated to the known standards of water ($\rho_w = 1.00 \text{ g/cm}^3$) and aluminum ($\rho_{al} = 2.70 \text{ g/cm}^3$). These two standards serve as end-members that fully bound the limits of soil density found at Pearl Harbor. The added advantage of using these materials is that their respective Compton scattering coefficients, μ_w and μ_{al} , are similar to those of soil pore water and soil alumina-silicate particles, although we determine these parameters empirically. To account for the influence of

Table 3. Measured bulk gamma densities of distilled water and aluminum.

[Known values are shown in parentheses]

Density and density statistic	Distilled water	Aluminum
Mean measured density (g/cm ³)	1.004	2.700
(Known density)	(1.00)	(2.70)
Density standard deviation (g/cm ³)	0.010	0.016

the liner, a water-aluminum standard is prepared by inserting a solid-cylinder of essentially pure aluminum (1100 alloy) into an unsplit section of core liner identical to the liner used for soil sampling. The milled aluminum cylinder fills one-half the total length of the “calibration standard” core liner, and distilled water fills the remaining portion. Caliper measurements of the liner diameter and wall thickness are made to determine the travel-path length through the liner and interior space.

During the density calibration, the numbers of scintillations per second are logged for transmission of gamma rays through air to give a measure of I_0 . Similar measurements are made for the “calibration standard” to determine the scintillation count for water-filled liner, I_w , and for aluminum-filled liner, I_{al} . We determine the attenuation ratios for water and aluminum (I_0/I_w and I_0/I_{al}) and solve for the remaining unknowns, $\mu_1\rho_1$ and μ_s , by setting up two simultaneous equations and eliminating one of the variables. For each soil core, we scan the whole-round sections using the same Compton scattering parameters that correct the calibration-standards water and aluminum to their known values of density.

Calibration standards are run repeatedly during testing programs. Typically, to calibrate the sediment-core profiles for density, measurements are made from our calibration standard after every five cores.

After system calibration is complete, soil cores are run through the logger system and calibration-corrected densities and velocities are presented, along with magnetic susceptibility, on a real-time graphics display. Typical run time for driving a 150-cm core through the sensor array is approximately 35 minutes.

MSCL System Calibration Quality Control

Several approaches are taken to assess the quality of our noninvasive measurements of bulk density through a core liner. After extensive use of our system at sea and in our shore-based laboratory, several hundred calibration log files containing 30 or more data points were separated into individual files for water-filled and aluminum-filled core liner. These material-dependent subsets of the calibration files were then used to calculate the mean and standard deviation for the measured density and velocity and compared with the known values for water and aluminum presented in parenthesis (table 3).

The mean value of the calculated and measured density of distilled water was within 0.4 percent of the known value, and the mean value for aluminum was exactly the known value. It was found that the standard deviation for density measurements is on the order of 0.6–1.0 percent of the measured value.

Consolidation Testing for Stress History

Incremental consolidation (“CON”) tests were performed to determine the settlement characteristics and the maximum past stress (σ'_p) experienced by the sediment. Tests were performed with a fully automated and computer-controlled load frame using the traditional incremental loading method of Casagrande (1936). Samples were contained within a sample ring of 3.81 or 6.35 cm diameter and 2.54 cm height in a uniaxially loaded, water-filled cell. A machine calibration was applied to compensate for flexing of the load frame and load cell. Sample material was shaped into a disk for insertion into the sample ring by carving with a razor blade and applying light pressure on the ring around the carved disk.

Samples of the soft gray clay from boring B2 were subjected to a maximum test stress of 686 kPa. The sediment tested from boring B3 was significantly stiffer than that from B2 and was subjected to a higher maximum stress of 3,864 kPa. CON testing could not be reliably performed on much of the coral rubblestone clay of B3 because of the presence of the coarse, hard, fragmental material, which prohibited preparing a suitable sample for the sample ring.

From the consolidation data, the void ratio (e , volume of the voids/volume of the solids) was plotted versus the log of the vertical effective stress. With such a plot, a curve (red line) similar to that in figure 15 is usually produced. The graphical method of Schmertmann (1955) was used to correct the laboratory-determined virgin compression line for the effects of sample disturbance. This allows the creation of the “field virgin compression line.” The slope of this line is the compression index (C_c), the amount of void ratio change for a tenfold increase in vertical stress beyond σ'_p .

Analysis of the test curve proceeds as follows: (1) Identify by eye the point of maximum curvature of the test plot (solid red spot in fig. 15). (2) Draw a horizontal line from the point of maximum curvature. (3) Draw a tangent to the test curve at the point of maximum curvature. (4) Bisect the horizontal and tangent lines. (5) Extend the laboratory virgin compression line through the bisector; the stress at the intersection defines the maximum past stress σ'_p . (6) Identify a point on the laboratory virgin compression line at $0.42 e_0$. (7) Identify a point at the intersection of σ'_p and e_0 . (8) Draw the line between points 6 and 7; this defines the field virgin compression line. The compression index, C_c , is the change in void ratio for one log cycle of the field virgin compression line.

The in-place overburden stresses, σ'_{vo} , for borings B2 and B3 were determined using the depths of the recovered cores and the MSCL gamma density for each logged depth increment. Densities not considered representative of undisturbed sediment, as described below, were eliminated

from the calculation. By dividing the maximum past stress σ'_p by the calculated in-place overburden stress σ'_{vo} , the overconsolidation ratio (OCR) is obtained. An OCR of 1.0 indicates normally consolidated sediment. For OCR of less than 1.0, the sediment has not yet fully consolidated to the in-place overburden stress, whereas for OCR greater than 1.0 the sample is considered to be overconsolidated.

Measurements of undrained shear strength of sediment were made with a RocTest™ model G-200 fall cone apparatus. Cone penetration depths using several different cone masses are listed in table 4.

Geotechnical Testing Results

A plot of the gamma density for each of the cores recovered from the borings is shown in appendix A, and physical properties of the tested sediment are listed in table 4. The top and bottom of each density plot have been variably trimmed to delete low densities caused by coring disturbance. In a few cases, other low densities due to cracks or other voids, where obvious, have also been deleted. MSCL density in table 4 is the average gamma density of the test interval as determined by the multisensor core logger. Lab density is calculated from the mass of the sample before consolidation testing divided by the volume of the space within the sample ring. The lab density is commonly slightly less than the MSCL density because the test sample may not fully fill the sample ring before testing.

Certain cores from borings B2 and B3 (for example, 9.15 to 13.7 m in B3, appendix A) exhibit repeating patterns in their density characterized by lower density overlying higher density. These patterns appear to be due to coring disturbance and (or) entraining material sloughed from the boring walls.

The low-density sections, considered to be not representative of undisturbed sediment, are highlighted in red on the density plots in appendix A. The entire contents of one B3 core (10.7–11.4 m) were extruded and revealed to be soft, dark brown, sandy clay, without obvious intermixing of other materials, corresponding to the low-density part of the plot. This contrasted with very stiff, higher density, and presumably undisturbed, dark brown sandy clay in the lower part of the tube.

The results for 14 CON tests performed on sediment samples from borings B2 and B3 are tabulated in table 5. The consolidation test plots for each test are given in appendix B.

The combined MSCL, fall cone, and CON test results are consistent for each of the two clay sedimentary sections examined. The soft, gray clay from boring B2 has gamma densities from 1.29 to 1.59 g/cm³, shallow 60-gram fall cone penetrations, and OCRs from 1 to 1.9. The low OCRs indicate that the section is normally consolidated. In contrast, the stiff brown clay from B3 has gamma densities from 1.85 to 1.99 g/cm³, low fall cone penetrations with a much higher (400 g) cone mass, and OCRs between 12 and 22, indicating that the sediments are overconsolidated.

Figure 16 shows OCR values versus depth for the clay samples from the B2 and B3 CON test samples. The two clay types are clearly distinguished. The B2 clays trend along normal consolidation (OCR = 1) with depth, whereas the B3 clays are clearly overconsolidated (OCRs above 10).

Overconsolidation of near-surface sediment can be caused by, among other factors, electrochemical bonds, overburden erosion, cementation, or current reworking. Often, overconsolidation is a near-surface phenomenon and is lost at depth. The high OCRs of B3 clays are suggestive of erosional removal of an overlying sedimentary column.

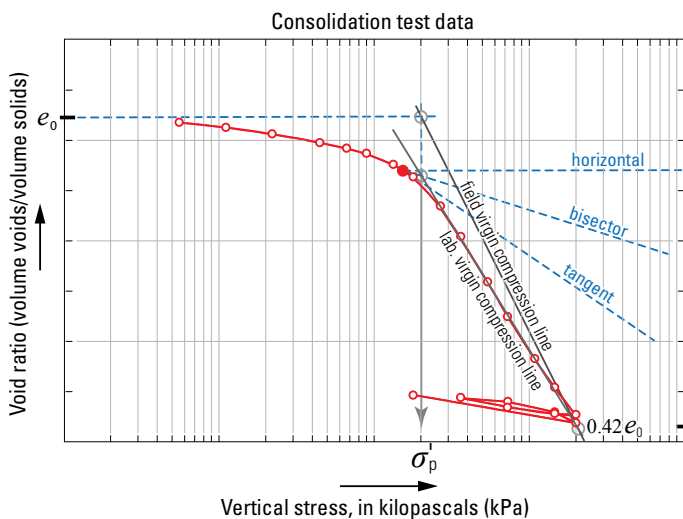


Figure 15. Graph showing ideal consolidation test plot with applied analysis of Casagrande (1936) and Schmertmann (1955). The solid red curve is the consolidation test result. See text for explanation.

Recent Measurements at the USS Arizona

Measurements were made on March 4, 2008, to determine the tide-corrected elevation of points on the USS Arizona hull, to calculate the tilt of decks or other structures, and to measure the dimensions of structures. Heights of features above or depths below the water level and the local time were recorded for determining the tide-corrected elevations of various points on the USS Arizona hull. Conditions on the harbor the morning of March 4 were calm and ideal for making measurements relative to the water level. In this report, the term elevation is used to describe the vertical position of a structure relative to a datum (that is, MLLW). Height is used to describe a dimension of a structure or the position of a surface or point relative to a water level (for example, vent top or bulwark height above the water level). Differential real-time kinematic (RTK) Global Positioning System (GPS) measurements were made around the hull at most of the points where water-level measurements were made. Present tide-corrected elevations of structures will serve

Table 4. Lithology and measured physical properties of samples from USS *Arizona* borings B2 and B3 for consolidation tests.

[MSCL, U.S. Geological Survey multisensor core logger. --, no data or not determined]

Boring	Depth interval		Lithology	Test interval, cm	MSCL gamma density g/cm ³	Lab density g/cm ³	Fall cone penetration, mm (mass, in grams)
	Meters	Feet					
B2	5.34–6.10	17.5–20	soft clay	85.6	1.45	1.48	4.4 (60)
	8.38–9.15	27.5–30	soft clay	65.8–68.3	1.47	1.40	6.0 (60)
	9.90–10.7	32.5–35	soft clay	86.3–88.8	1.48	1.51	3.8 (60)
	10.7–11.4	35–37.5	soft clay	62–64.5	1.48	1.46	3.0 (60)
	12.2–13.0	40–42.5	soft clay	88.1	1.40	1.45	2.8 (60)
	13.0–13.7	42.5–45	soft clay	87.5–90.0	1.41	1.42	5.1 (60)
	13.7–14.5	45–47.5	soft clay	85.8–88.3	1.28	1.29	8.3 (100)
	14.5–15.2	47.5–50	soft clay	87.3–89.8	1.29	1.30	3.1 (60)
	16.0–16.8	52.5–55	soft clay	86.3–88.8	1.37	1.41	6.0 (100)
	16.8–17.5	55–57.5	soft clay	87.3–89.8	1.51	1.40	3.0 (60)
	17.5–18.3	57.5–60	soft clay	86.2–88.8	1.53	1.48	5.8 (100)
	18.3–19.1	60–62.5	soft clay	66.4–68.9	1.52	1.50	2.7 (60)
	19.1–19.8	62.5–65	soft clay	88.5	1.52	1.53	3.2 (60)
	20.6–21.3	67.5–70	soft clay	76.5–79.0	1.58	1.58	2.8 (60)
B3	3.66–4.57	12–15	sand	86.5–89	1.85	1.84	--
	9.15–9.91	30–32.5	stiff clay	80.9–83.7	1.98	1.88	2.7 (400)
	9.91–10.7	32.5–35	stiff clay	78.5–81	1.99	1.87	2.4 (400)
	10.7–11.4	35–37.5	stiff clay	82.6–85.4	1.95	1.88	3.0 (400)
	11.4–12.2	37.5–40	stiff clay	77.1–79.6	1.96	1.85	2.8 (400)
	12.2–13.0	40–42.5	stiff clay/coral debris	78.5–81	1.69	1.58	4.5 (400)

to anchor the base of the settlement and tilt trends derived for the preceding years. The dimensions of structures also serve as a reference for scale in older photographs. The locations of measured points with calculated elevations relative to mean lower low water (MLLW) at Honolulu Harbor are plotted in figure 17. Efforts were made to measure from the original deck margin, the top of the bulwark, as much as possible. Two measurements on the midship starboard side are at the higher, outer hull edge (−0.12 m) and at a lower, flat surface (−0.38 m) within the hull edge. The height difference between these two points is 0.26 m, which corresponds to the estimated height of the bulwark derived from photographs (though perhaps only coincidentally, given the uncertainty of what the lower flat surface represents).

At the shoreline of the Pearl Harbor-USS *Arizona* Memorial headquarters, we set up a differential GPS base station over benchmark AM2 (UTM coordinates, zone 4 easting 609906.148; northing 2363086.479; ellipsoid height 17.00 m, WGS84). The RTK-GPS survey control was obtained by using a pair of continuously operating Topcon Hiper+™ geodetic-quality, dual-frequency (L1/L2) GPS receivers. One

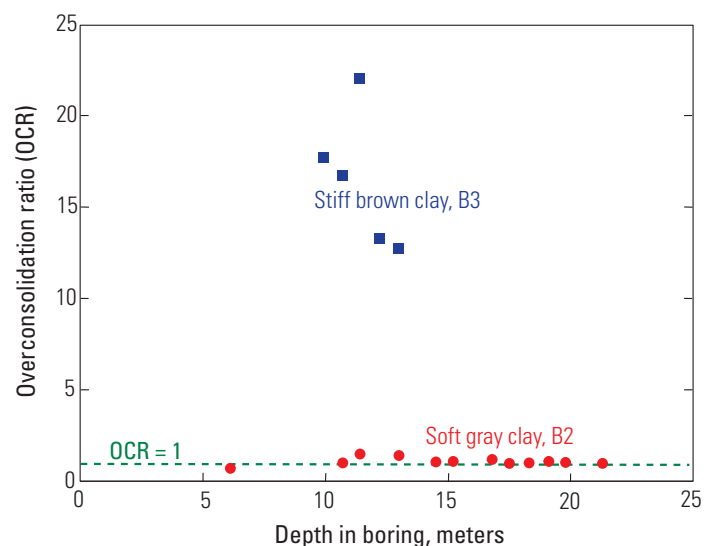
**Figure 16.** Graph of overconsolidation ratio (OCR) versus subbottom depth for clay-rich samples from Borings B2 and B3. Sample CON-212 from B3, composed of sand, is not shown.

Table 5. Consolidation test results for samples from the USS *Arizona* borings.

[kPa, kilopascals; OCR, overconsolidation ratio; C_c , compression index; C_v , coefficient of consolidation; e_0 , initial void ratio. Quality is a qualitative term to describe the distinctiveness of the slope break in the plot of void ratio vs. effective stress for determining the maximum past stress]

Boring	Core depth, m	Test interval, cm	Max. past stress, kPa	Calculated effective stress, kPa	OCR	Excess stress, kPa	C_c	C_v	e_0	Quality	Test number
B2	5.34–6.10	86.1–88.6	30.3	43	0.7	13.3	1.21	1.70E-04	2.68	fair	CON-246
	9.90–10.7	86.3–88.8	63	63	1	0	0.96	1.70E-04	2.50	poor	CON-202
	10.7–11.4	62–64.5	100	65	1.5	35	1.65	4.00E-04	2.80	very good	CON-247
	12.2–13.0	70.9–73.4	100	71.6	1.4	28.4	1.53	2.80E-04	2.92	good	CON-249
	13.7–14.5	85.8–88.3	80	77	1.04	3	2.67	7.80E-04	4.69	fair/poor	CON-206
	14.5–15.2	82.3–84.8	85	79	1.08	6	2.50	8.60E-04	4.34	good	CON-204
	16.0–16.8	86.3–88.8	101	83.4	1.2	16.6	2.00	4.00E-04	3.18	excellent	CON-207
	16.8–17.5	87.3–89.8	84	87	0.97	–3	1.18	1.50E-04	2.49	fair	CON-200
	17.5–18.3	86.2–88.8	90	90.6	1	–0.6	1.23	1.40E-04	2.51	very good	CON-199
	18.3–19.1	66.4–68.9	102	93	1.1	9	1.40	1.20E-04	2.48	excellent	CON-251
	19.1–19.8	85.1–87.6	100	97.4	1.03	2.6	1.08	2.10E-04	2.38	fair	CON-248
	20.6–21.3	76.5–79.0	104	104	1	0	0.84	2.30E-04	2.03	good	CON-252
B3	3.66–4.57	86.5–89	85	31	2.8	54	0.28	3.50E-04	1.05	poor	CON-212
	9.15–9.91	80.9–83.7	1,400	79	17.7	1321	0.32	3.10E-04	1.01	good	CON-245
	9.91–10.7	78.5–81	1,440	86	16.7	1354	0.25	8.50E-04	1.02	fair	CON-216
	10.7–11.4	82.6–85.4	2,040	93	22	1947	0.54	1.50E-04	1.01	fair	CON-244
	11.4–12.2	77.1–79.6	1,320	99	13.3	1221	0.28	4.40E-04	1.07	poor	CON-214
	12.2–13.0	78.5–81	1,330	105	12.7	1225	1.1	2.00E-05	1.99	poor	CON-215

receiver was mounted to a 2-m reference pole and operated as a roving receiver (rover). This second GPS unit was set up over benchmark AM2 and operated as a fixed base station located within 1.2 km of the vessel. The fixed base station set up directly over the project benchmark was also used to gather a static OPUS (Online Positioning User Service of the National Geodetic Survey) file used to compute a solution that was within 1 cm of the published coordinates for AM2. We used a common reference system (WGS84) and a common vertical datum (NGVD 1988) for measurements.

Data collected by the rover were differentially corrected against errors computed at the base station position and transmitted in real time using a PacificCrest™ FM-frequency broadcast radio on a government frequency. Rover receiver RMSE accuracy was always subcentimeter during our survey. On the vessel, survey positions were measured around the perimeter of the USS *Arizona* along the starboard and port sides using an extension on the 2-m rover pole to reach greater depths on the hull where necessary. A diver was used to place and secure the base of the extension pole in position. All GPS data points are plotted in figure 18 and listed in table 6.

The elevation of the points relative to the MLLW datum is calculated by subtracting 0.26 m from the mean sea level (MSL) elevations. The MSL of the Ford Island Ferry Dock and Honolulu tide stations are 0.26 and 0.25 m, respectively.

In figure 19, the present tilts across the hull of the USS *Arizona*, across turret 2, and across barbette 3 are shown. Transverse deck tilts in part *A* are determined from the tide-corrected deck elevations in figure 17 and GPS elevations across the distances between measuring points. On the basis of GPS measurements at the bow and stern, the axis of the hull is oriented 54.3° east of north. Drawings for the USS *Arizona* in Stillwell (1991) and Friedman and others (1978) show the decks constructed flat fore to aft, which can also be observed in suitable photographs of the ship. The ship section in Foecke and others (2010) shows a transverse camber to the principle decks. The tilt of 0.3° from midship (Frame 83) forward to the bow is at the approximate level of the original upper deck, the two points being separated by a large collapsed area. In part *B* of figure 18, tilts were calculated from the height above and below the water level of the forward and aft corners of the top edges of turret 2.

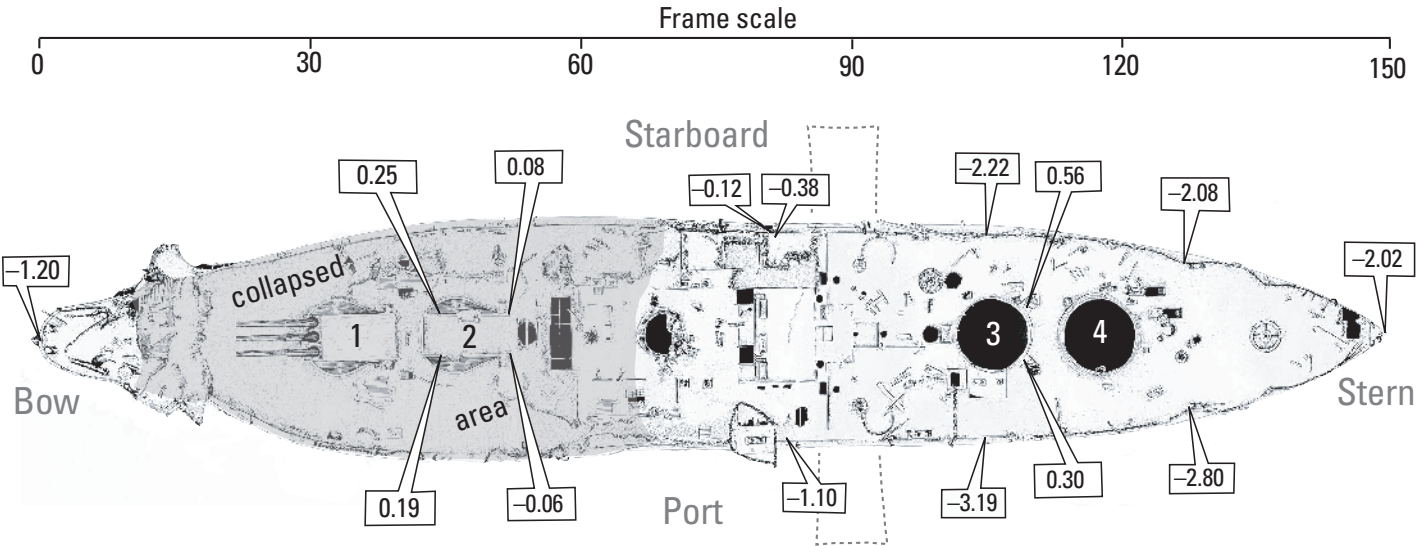


Figure 17. Diagram showing present tide-corrected elevation of points along the USS *Arizona* hull measured March 4, 2008, in meters relative to Honolulu Harbor MLLW. Elevations are based on smoothed, verified, 6-minute tide data. Frame scale alongside hull is for reference. One frame has a length of 4 feet (1.22 m). Numbers 1 to 4 are turret and barbette locations. Location of the Memorial structure is shown by the dashed border near midship.

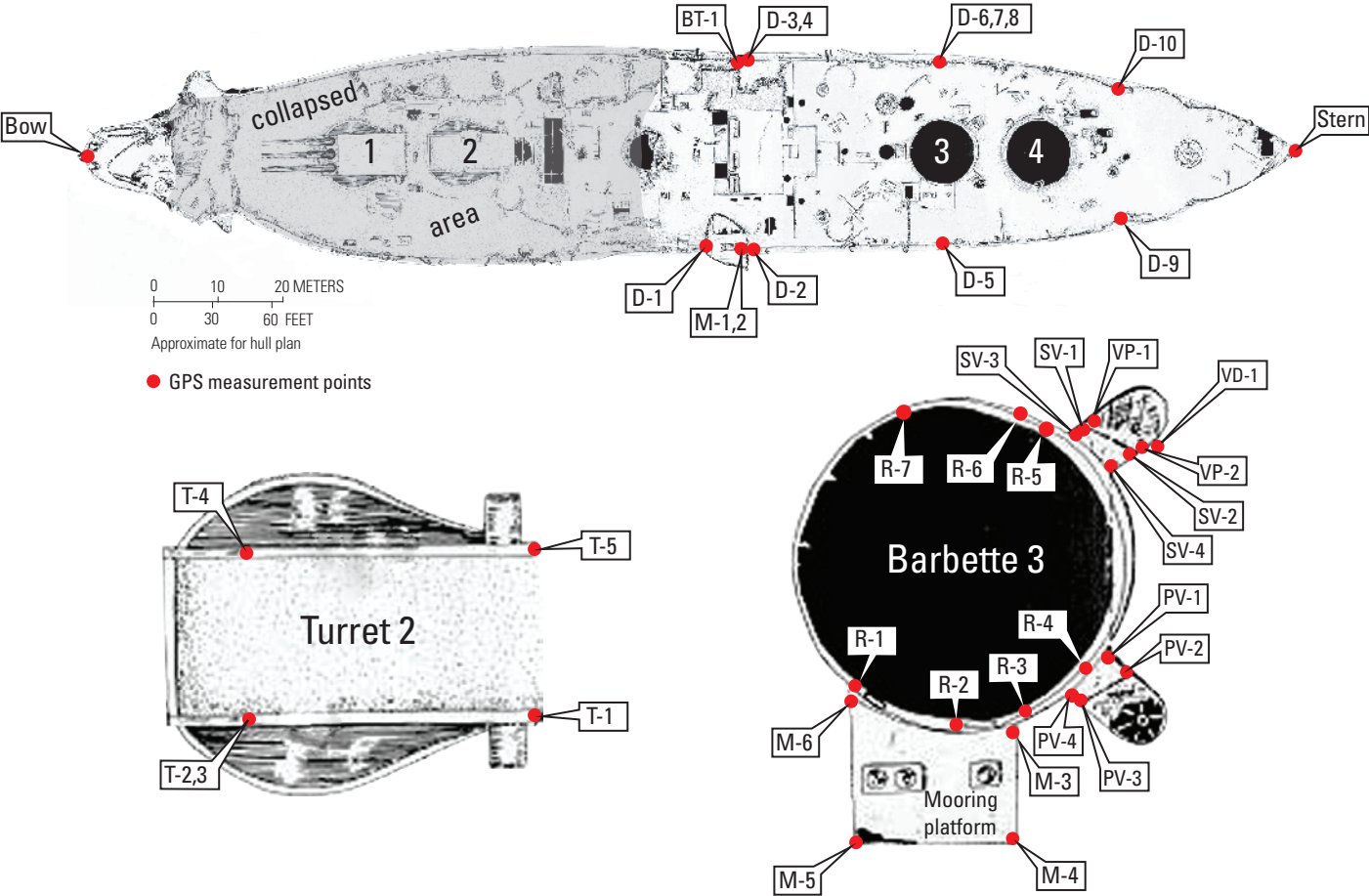


Figure 18. Diagram showing Global Positioning System (GPS) measurement points and ID numbers on the USS *Arizona* hull. ID numbers and structure names are listed in table 6.

Table 6. Global Positioning System (GPS) measurements on the USS *Arizona* hull and attached structures.

[Location IDs are shown in figure 18; MSL, mean sea level; MLLW, mean lower low water]

Struture	Location ID	Easting (m)	Northing (m)	Ellipsoid height (m)	~MSL(Geoid03 NAVD88) height (m)	~MLLW height (m)
AM2 Arizona Memorial benchmark		609906.148	2363086.479	17.00	1.31	1.05
Bow half-round (av. of 2)	Bow	608776.072	2362830.289	14.78	-0.91	-1.17
Turret 2 port aft corner	T-1	608827.562	2362865.659	15.89	0.20	-0.06
Turret 2 port forward 1	T-2	608820.439	2362860.042	16.14	0.45	0.19
Turret 2 port forward 2	T-3	608820.657	2362858.666	16.19	0.50	0.24
Turret 2 starboard forward	T-4	608817.167	2362864.795	16.26	0.57	0.31
Turret 2 starboard aft	T-5	608824.881	2362870.068	16.01	0.32	0.06
Midship port deck 1 (av. of 2)	D-1	608859.250	2362873.987	14.77	-0.92	-1.18
Midship port deck 2 (av. of 2)	D-2	608864.024	2362877.160	14.83	-0.86	-1.12
Midship port mooring plat. top 1	M-1	608864.037	2362877.112	18.72	3.03	2.77
Midship port mooring plat. top 2	M-2	608864.033	2362877.173	18.75	3.06	2.80
Midship starboard deck 1	D-3	608848.021	2362899.725	15.61	-0.08	-0.34
Midship starboard deck 2	D-4	608848.011	2362899.330	15.64	-0.04	-0.31
Midship starboard aft bitt top	BT-1	608847.573	2362898.701	16.39	0.70	0.44
Barbette 3 rim 1	R-1	608879.229	2362900.795	17.67	1.98	1.72
Barbette 3 rim 2	R-2	608882.465	2362901.449	17.65	1.96	1.70
Barbette 3 rim 3	R-3	608884.047	2362903.070	17.69	2.00	1.74
Barbette 3 rim 4	R-4	608884.704	2362905.718	17.77	2.08	1.82
Barbette 3 rim 5	R-5	608880.576	2362910.157	17.96	2.27	2.01
Barbette 3 rim 6	R-6	608879.658	2362910.139	17.97	2.28	2.02
Barbette 3 rim 7 (av. of 2)	R-7	608876.488	2362908.635	17.97	2.28	2.02
Barbette 3 port vent top NW	PV-1	608885.057	2362906.583	16.33	0.64	0.38
Barbette 3 port vent top NE	PV-2	608886.068	2362906.009	16.29	0.60	0.34
Barbette 3 port vent top SE 1	PV-3	608885.321	2362904.744	16.24	0.55	0.29
Barbette 3 port vent top SE 2	PV-4	608884.994	2362904.938	16.25	0.56	0.30
Barbette 3 port mooring plat. N	M-3	608884.075	2362902.339	16.62	0.93	0.67
Barbette 3 port mooring plat. E	M-4	608886.009	2362899.369	16.57	0.88	0.62
Barbette 3 port mooring plat. S, steel	M-5	608882.131	2362896.640	16.42	0.73	0.47
Barbette 3 port mooring plat. W	M-6	608879.231	2362900.613	16.66	0.97	0.71
Barbette 3 strd. vent top NW	SV-1	608881.086	2362910.881	16.51	0.82	0.56
Barbette 3 strd. vent top NE	SV-2	608882.334	2362910.997	16.51	0.82	0.56
Barbette 3 strd. vent top SW	SV-3	608881.149	2362910.490	16.51	0.82	0.56
Barbette 3 strd. vent top SE	SV-4	608882.576	2362909.984	16.48	0.79	0.53
Barbette 3 strd. vent projection W	VP-1	608881.210	2362911.120	14.69	-1.00	-1.26
Barbette 3 strd. vent projection E	VP-2	608882.462	2362911.167	14.67	-1.02	-1.28
Barbette 3 deck at strd. vent	VD-1	608882.675	2362911.311	13.81	-1.88	-2.14
Barbette 3 port deck	D-5	608887.568	2362893.910	12.73	-2.96	-3.22
Barbette 3 starboard deck 1 (av. of 2)	D-6	608872.476	2362917.534	13.69	-2.00	-2.26
Barbette 3 starboard deck 2	D-7	608873.042	2362916.722	13.63	-2.05	-2.31
Barbette 3 starboard deck 3	D-8	608872.630	2362917.318	13.71	-1.97	-2.23
Barbette 4 port deck (av. of 2)	D-9	608907.025	2362912.327	13.04	-2.65	-2.91
Barbette 4 starboard deck (av. of 2)	D-10	608895.394	2362929.155	13.94	-1.75	-2.01
Stern deck (av. of 2)	Stern	608922.812	2362935.677	13.92	-1.76	-2.02

Settlement of the USS *Arizona* as Determined from Historical and Recent Photographs

A photographic record of the USS *Arizona* through time was compiled and analyzed to construct settlement trends for several points on the USS *Arizona* hull and to determine elevations and tilt of structures. This process involves the measurement of the heights of features above the water level and correcting the heights to a tidal datum. This requires the use of dated photographs in which useful shadows can be measured to determine the local time of day and from this to determine the tide level at that time. The elevation of reference points on the hull are calculated relative to MLLW and can be followed through time to determine the magnitude and rate of the change.

Photographs were obtained from military and Navy archive Web sites, the USS *Arizona* Memorial Museum Archives in Hawaii, the Submerged Resources Center of the National Park Service, and other sources found through keyword searches on the Internet.

The ideal photograph is one that:

1. is given a date that indicates the date of the scene in the photograph (it is not always known with certainty what the date for any photograph may represent—for this report, the dates are assumed to be the date the photograph was taken, unless it can be established otherwise),
2. shows a clear view of the feature of interest, and
3. contains sufficient shadow detail so that an estimation of local time can be made. A long shadow that extends across a mostly horizontal structure, as well as viewed from above, provides the least ambiguous indication of trend or azimuth. In contrast, a low-angle or horizontal view introduces considerable foreshortening and measurement error.

Supporting evidence for the date of a photograph is sought as much as possible. This also means that what would otherwise be a very useful photograph can be rendered much less useful by the lack of a date or shadows or both (see, for example, fig. E-6). Other photos can be suitable if water levels or heights can be reasonably transferred to a feature that is not visible in the scene. Difficulty in discerning water levels due to shadows, reflections, shades of gray in old black and white photographs, and viewing angles also hinder interpretations.

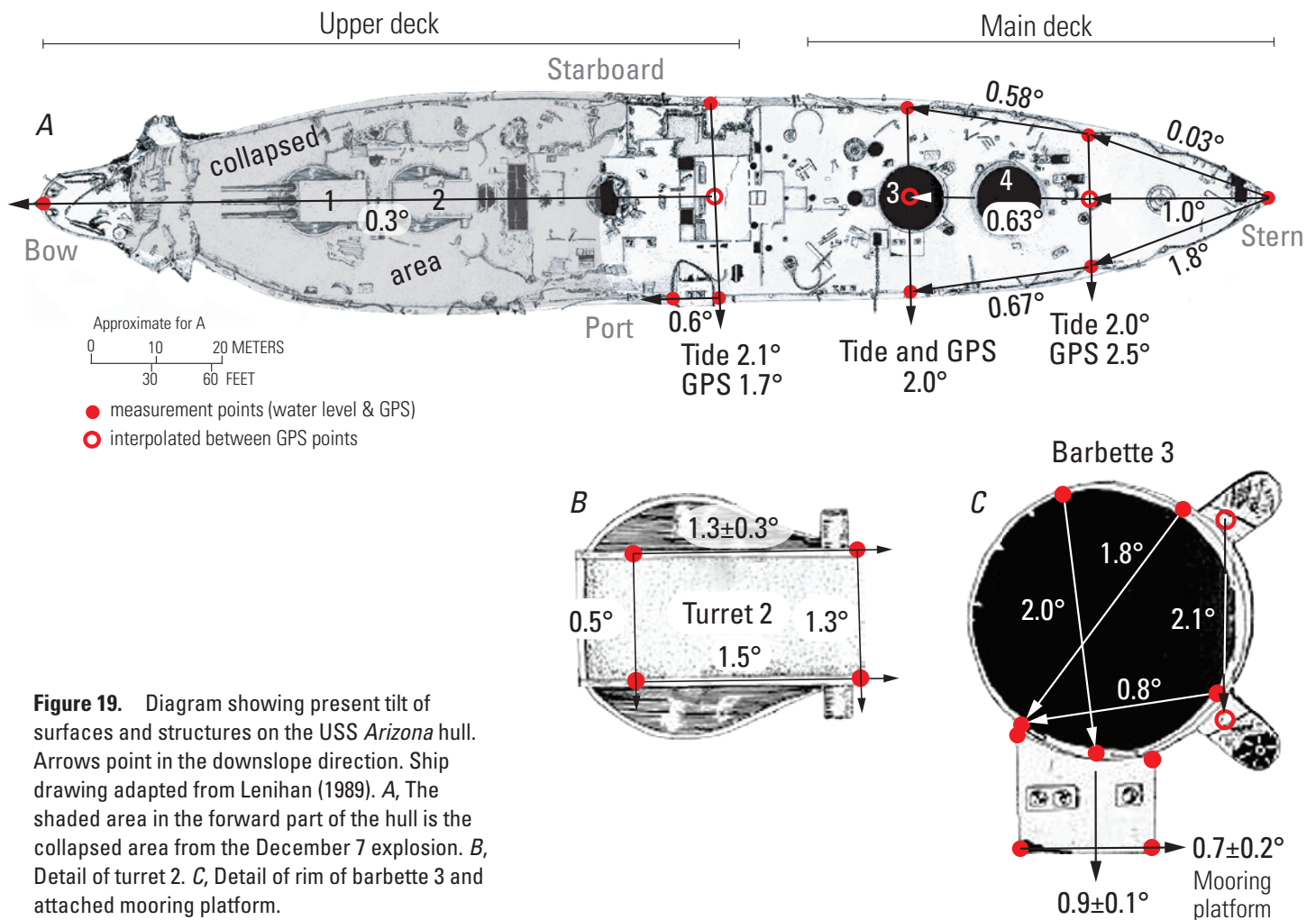


Figure 19. Diagram showing present tilt of surfaces and structures on the USS *Arizona* hull. Arrows point in the downslope direction. Ship drawing adapted from Lenihan (1989). A, The shaded area in the forward part of the hull is the collapsed area from the December 7 explosion. B, Detail of turret 2. C, Detail of rim of barrette 3 and attached mooring platform.

Also, the proportions of a structure can change slightly from one photo to another possibly as a result of distortions during photo development or later manipulation into an electronic form. The known or estimated dimension of a structure as close to the feature of interest as possible provides a dimensional scale in each photo. When a time cannot be estimated because of a lack of shadows, a tide level at the middle of the daylight hours, usually 12:30, is used along with appropriate range bars.

Interpretation of the photographs is guided by several observations and assumptions:

1. The axis of the ship, and thus all parallel structures, is oriented 54.3° east of north, as determined by GPS. Measurements off Google Earth produce an orientation of 54.5° . This is an approximately 3° divergence from the line of "Fox" mooring quays on the northeast side of Ford Island.
2. The Memorial structure is oriented 90° to the ship axis, giving the long axis of the Memorial an azimuth of 144° .
3. The main 14-inch guns were oriented parallel to the axis of the ship at the time of the attack. This appears to be the case as seen in the few vertical photographs available.
4. The optical rangefinder projections on turrets 3 and 4 are assumed to be oriented 90° to the longitudinal axis of the turrets. These features produce useful shadows in photos from December of 1941. The turrets were later rotated toward Ford Island and then removed during the salvage phase.
5. Measurements of features on the hull and attached structures were made on March 4, 2008, for use as scale in photographs and to establish present-day values for the tide-corrected elevations of the hull.

The National Oceanographic and Atmospheric Administration's (NOAA) Solar Position Calculator at <http://www.srrb.noaa.gov/highlights/sunrise/azel.html> (last accessed March 5, 2013) was used to determine the local time at the moment the photograph was taken. The coordinates used in the calculator for the USS *Arizona* are lat $21^\circ 21' 54''$ N., long $157^\circ 57'$ W., which is the location given for the USS *Arizona* Memorial in Wikipedia. Certain shadows in photographs can be related to the orientation of the ship to determine the sun azimuth. The apparent shadow orientations are plotted on a diagram of the ship, and, using a protractor or software tools, the angle between the shadow and the axis of the ship is measured and added (in most cases) to the azimuth of the ship (54.3°). In photographs taken following the construction of the Memorial, shadow orientations are plotted on a satellite photo showing the Memorial structure, and measurements are made relative the orientation of the Memorial. In this case, the flagpole shadow on the roof of the Memorial structure commonly provides a very useful indicator of sun azimuth in photographs. Using the Solar Position Calculator on the date of the photograph, iteration with different times is done to match the sun azimuth produced by the calculator with the sun azimuth calculated from the plot. Sun azimuth is generally easier to measure than elevation, although in some cases the

sun elevation can be estimated and substituted for the azimuth or used as further verification that a reasonable azimuth has been determined. Some dated photographs obtained from various sources on the Internet with an assigned date and (or) time deviate significantly from others within the same time period. This can arise, in part, from tourists neglecting to properly set the date and time in their cameras when they travel and from photo-sharing Web sites capturing incorrect time and date tags.

When the date and local time for the photograph are known, the tide level for that time can be determined from historical tide records. The NOAA Tides and Currents Web site at <http://tidesandcurrents.noaa.gov/> (last accessed March 5, 2013) was used to access verified, hourly, historical tide data. Tide elevations for fractional hours are calculated by linearly interpolating within the hourly data. The closest station to the USS *Arizona* with an extended record is the Honolulu station (station ID No.1612340) located in Honolulu Harbor, 6.75 km from the USS *Arizona*. A temporary station was located at the Ford Island Ferry Dock in Pearl Harbor (station ID No.1612404). This station, about 1 km from the ship, recorded data from January 29, 1987, to March 22, 1987. A comparison of the two stations during their period of contemporaneous operation (fig. 20) of 1,261 hours shows that the Ferry Dock site has a mean hourly tidal elevation 1.1 cm higher than the Honolulu Harbor station, with a standard deviation of 0.022 m. An analysis of the tidal cycles in this period shows the Ferry Dock station has a mean hourly elevation 0.71 cm higher during flood tides and 1.53 cm higher during ebb tides.

No verified hourly tide data are available at the NOAA Tides and Currents Web site for the Honolulu Harbor gage from January 20, 1962, through December 4, 1967. Two dates fall within this time period (figs. E-17 and F-9). In lieu of verified data, predicted tide levels can be found at the University of South Carolina WWW Tide and Current Predictor at <http://tbone.biol.sc.edu/tide/tideshow.cgi> (last accessed March 5, 2013). Comparison between verified and predicted tide data for other dates typically reveals that verified data differ from the predicted values. Proxies for the two 1962 dates were compiled by averaging the May and June verified hourly tide levels for 1959, 1960, 1961 (three years before 1962), and for 1968, 1969, and 1970 (three years after 1967). The mean hourly difference between the predicted and verified heights for the six 2-month periods is 0.03 m with a 2-sigma (twice the standard deviation) of 0.084 m.

The Salvage Diary for Pearl Harbor (in the Industrial Department War Diary Collection, Naval Historical Center, Washington, D.C.; available at http://www.nps.gov/valr/historyculture/upload/War_Diary1-2.pdf, last accessed March 19, 2013) for the period March 1, 1942, through November 15, 1943, contains daily accounts of the salvage activities at each ship, including the USS *Arizona*. Photos from two dates examined fall within the time line of the diary and are discussed further in a later section of this report. These photos depict distinctive events that can be identified in the diary and indicate a deviation from the dates imprinted in the photos.

Results of Photograph Analysis

The results of the photographic analysis are summarized in tables 7 and 8. Appendixes E, F, G, and H contain thumbnail versions the photographs examined and the details involved in the interpretation of each one. A quality designation has been assigned to each photo and interpretation to reflect various degrees of uncertainty or limitations of usefulness. The calculated elevations in these appendixes are not adjusted for sea level rise. Tables 7 and 8 also contain tide-based elevations of structures measured on March 4, 2008, one of which has an accompanying photo in appendix E. These March 2008 measurements did not require the observation of sun azimuth or elevation.

Six symmetrically arranged points on the hull were identified (locations in fig. 12) for measuring the movement of the USS *Arizona* hull through time. Photographic depiction of these areas is not consistent; photos of the port side of the hull, facing the open harbor, are far more common than those of the starboard side. Also, the bow and stern disappeared below water during or soon after the attack. One distinctive feature, a vent attached to the port side of barrette 3 (figs. E-1 to E-30), has remained visible and survived almost unchanged since the sinking. The top of this structure is a point for settlement calculation, and the size of its opening is an important source of scale in many photos. Recent measurements in 2008, however, reveal that the vertical dimension of the opening is larger than during the early years, possibly from the loss, by corrosion or detachment, of part of the metal plate of the structure. The opening within an identical vent on the starboard side of the turret retains its original size, being 0.74 m high and 1.27 m wide. Two other areas on the ship, the port and starboard midship areas, between frames 78 and 83, have sufficient exposure through time to develop settlement timelines.

The stern disappeared below the water surface and is not seen again beyond December of 1941. The remains of turret 2 are visible above the water surface today, depending upon the

tide level. There are many years between 1945, approximately the end of the salvage phase, and the present for which no useful photographs were found.

The top of the bulwark along the upper deck on the port and starboard sides is the reference point for height determinations. The bulwark at the starboard side at the present time is mostly intact, and its upper edge seems to be near the original condition, retaining a few stubs of the railing posts (fig. G-8). At the port side, aft of the midship mooring platform, the bulwark appears variably degraded (fig. F-12), but is regarded as close to the original height, and no adjustment was determined or applied for consistency with early photographs.

Figure 21 shows a compilation of port-side rangefinder shadows on turrets 3 and 4 and the calculated times derived from the position of the shadow on the face of the turrets. Sun azimuths in these cases were calculated by measuring the shadow positions on the face of the turret, plotting a vertical view of those positions on a diagram of the turret and measuring the angle between the sunlight ray and the ship axis.

Other sources of information can be used to support a calculation of date or time and can justify assigning a higher quality designation to some of the dated photos. Any features or events that add identifiable content to a photo that can be verified from other sources are useful. For example, all photos showing the *Arizona* burning vigorously identify them as dating from December 7, 1941. The arrival of the USS *Missouri* at its new berth in Pearl Harbor is a well-documented event (fig. E-27), as well as ceremonies on the 50th anniversary of the attack (fig. E-25), both of which add identifiable content to the images. The very low tide visible at the starboard side of the USS *Arizona* on June 3, 2000 (fig. G-8), corresponding to tide levels in the historical record, adds support for this date. The submarine rescue vessel USS *Widgeon* (ASR-1) was on the harbor during December 7, 1941, following the attack (fig. E-2). Deck logs for the *Widgeon* obtained from

Figure 20. Graph of hourly elevation difference between the Ford Island Ferry Dock and the Honolulu Harbor tide stations through their period of simultaneous operation from January 29, 1987, to March 22, 1987. The red line is the mean elevation of Ford Island relative to Honolulu Harbor.

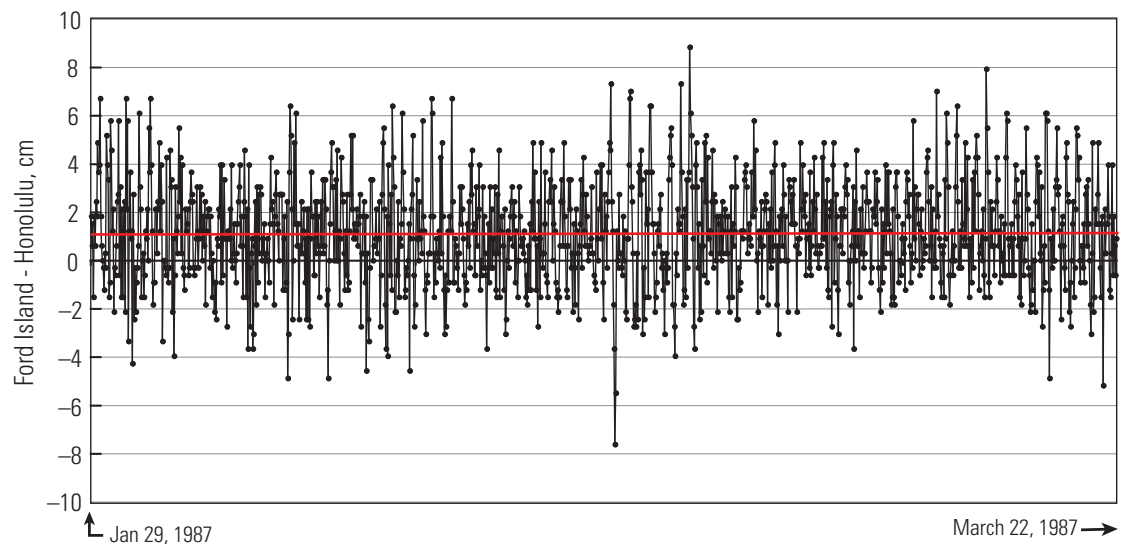


Table 7. Summary of information from and about photographs examined in appendix E for data points for the USS *Arizona* barbette 3 vent top settlement line.

[Calculated structure elevations are not sea-level-rise adjusted; MLLW, mean lower low water. Quality designations are defined as follows: A, direct measurement by authors of water levels and times; B, photographs with corroborating evidence to support the date; C, date is considered reliable; D, photograph has limitations due to lack of date or shadows or limited resolution; E, significant difficulties exist in photo interpretation using the given date of the photo. --, no data or not determined; times with * are assumed midday times—see appendix figures for these dates]

Date	Structure elevation, meters MLLW	Local time	Tide elevation, m MLLW	Sun azimuth	Sun elevation	Day	Quality
Barbette 3 port side vent (V)							
Dec 7, 1941	3.00±0.08	10:21	0.19	144	--	1	B
Dec 7, 1941	2.65±0.06	13:29	0.07	201	--	1.1	B
Dec 8, 1941	2.37±0.1	13:30	0.07	201	--	2	B
Dec 9, 1941	2.25±0.06	11:00	0.28	154	--	3	B
Dec 12, 1941	2.06±0.05	11:55	0.25	170	--	6	C
Dec 12-Feb 17	1.95+0.15/-0.17	13:30?	--	200?	--	7-72	D
Feb 25, 1942	1.48+0.1/-0.15	12:30*	0.06-0.21	--	--	81	D
June 8, 1942	1.59±0.06	12:25	0.36	40	--	184	C
Jul 17, 1942	1.46±0.1	8:45	0.07	--	36	223	C
Sep 30, 1942	1.28+0.23/-0.08	12:30*	0.18-0.49	--	--	298	D
Mar 21, 1943	1.28±0.07	8:14	0.14	99	--	469	D
Apr 20, 1943	1.34±0.04	13:03	0.34	219	77	500	E
May 4, 1943	1.32+0.04/-0.07	11:41	0.1	114	--	514	E
Nov 25, 1944	1.19±0.07	8:28	0.19	123	25	1,085	E
June 12, 1950	0.75±0.1	11:00	0.21	80.8	69	3,110	C
May 31, 1958	0.59±0.05	7:03	-0.19	72	--	6,020	B
May 29, 1962	0.54±0.14	9:35	0.08	81	50	7,113	C
May 17, 1969	0.50±0.1	7:00-11:00	-0.03-0.05	--	--	10,023	D
Apr 7, 1978	0.60±0.03	11:38	0.18	135	--	13,271	E
Oct 1, 1981	0.39±0.02	10:11	0.39	124	--	14,544	C?
May 1, 1986	0.39±0.02	13:11	0.12	240	--	16,217	C
Feb 23, 1987	0.37±0.03	8:48	0.01	112	--	16,515	C
Mar 1, 1989	0.36±0.02	7:49	0.16	103	11	17,252	C
Dec 4, 1991	0.39±0.02	10:37	0.16	148	--	18,260	C?
Dec 7, 1991	0.35±0.03	7:51	0.51	119.5	--	18,263	B
Mar 8, 1993	0.35±0.05	8:02	0.13	102	--	18,720	C
Jun 22, 1998	0.33+0.08/-0.03	8:41	-0.13	76	--	20,286	B
Jun 3, 2000	0.32±0.05	10:30	-0.1	--	65	21,364	C
Nov 18, 2004	0.33±0.03	9:30	0.74	132	--	22,992	C
Mar 4, 2008	0.30±0.01	Average of 4 direct measurements by authors				24,194	A

Table 8. Summary of information from and about photographs examined in appendixes F, G, and H for data points for the port and starboard midship hull, turret 2, bow, and stern of the USS *Arizona*.

[Calculated structure elevations are not sea-level-rise adjusted; MLLW, mean lower low water. Quality designations are defined as follows: A, direct measurement by authors of water levels and times; B, photographs with corroborating evidence to support the date; C, date is considered reliable; D, photograph has limitations due to lack of date or shadows or limited resolution; E, significant difficulties exist in photo interpretation using the given date of the photo. The March 4 measurements for turret 2 refer to the four highest corners of the turret. --, no data or not determined; times with * are assumed midday times—see appendix figures for these dates]

Date	Structure elevation, meters MLLW	Local time	Tide elevation, m MLLW	Sun azimuth	Sun elevation	Day	Quality
Port side midship deck (P)							
Dec 7, 1941	1.02±0.08	10:21	0.19	144	--	1	B
Dec 7, 1941	0.84±0.05	13–15:00	0.07	192–223	--	1.1	B
Dec 12, 1941	0.37±0.03	11:39	0.26	165	--	6	C
Feb 17, 1942	–0.05±0.06	13–15:00	0.1–0.21	--	43–54	73	C
Jul 17, 1942	–0.31±0.05	8:45	0.07	--	36	223	C
Sep 30, 1942	–0.38±0.23/–0.08	12:30*	0.18–0.49	--	--	298	D
Sep 20, 1943	–0.44±0.12	15:00	0.3	244	--	653	D
Jan 16, 1945	–0.52±0.61/–0.06	12:30*	–0.03–0.58	--	--	1,137	D
May 29, 1962	–0.96±0.1	9:35	0.08±0.08	81	50	7,113	C
May 30, 1962	–0.94±0.11	9:37	0.01±0.08	--	50	7,114	C
May 1, 1986	–1.07±0.05	13:11	0.12	240	--	16,217	C
Jun 3, 2000	–1.09±0.05	10:42	–0.09	80±5	65	21,364	C
Mar 4, 2008	–1.1	9:37	0.05	--	--	24,194	A
Starboard side midship deck (S)							
Dec 9, 1941	0.94±0.07	11:05	0.27	--	--	3	B
May 6, 1942	0.42±0.1	12:30*	–0.003–0.18	--	--	151	D
Mar 21, 1943	0.37±0.1	8:14	0.14	99	--	469	C
May 31, 1958	0.08±0.07	7:03	–0.19	72	--	6,020	B
May 29, 1962	0.07±0.08	9:35	0.08	81	50	7,113	C
Oct 1, 1981	–0.04±0.03	10:11	0.39	124	--	14,544	C?
May 1, 1986	–0.07±0.03	13:11	0.12	240	--	16,217	C
Jun 3, 2000	–0.09±0.02	10:42	–0.09	--	--	21,364	C
Mar 4, 2008	–0.12	10:18	0.06	--	--	24,194	A
Turret 2 (T)							
Dec 7, 1941	1.23±0.1	13–14:00	0.07	--	--	1.1	B
Mar 4, 2008	–0.06 port aft	9:50	0.053	--	--	24,194	A
Mar 4, 2008	0.19 port forward	10:01	0.054	--	--	24,194	A
Mar 4, 2008	0.25 starboard forward	10:06	0.055	--	--	24,194	A
Mar 4, 2008	0.08 starboard aft	10:08	0.056	--	--	24,194	A
Bow (B)							
Dec 7, 1941	–0.18±0.1	13–14:00	0.07	--	--	1.1	D
Mar 4, 2008	–1.2	10:31	0.07	--	--	24,194	A
Stern (St)							
Dec 7, 1941	1.20±0.13	11:30–13:30	0.07–0.11	--	--	1	B
Mar 4, 2008	–2.02	8:56	0.06	--	--	24,194	A

the National Archives and Records Administration, College Park, Maryland, reveal three short periods of movement on December 7:

10:36 Underway...to assist distressed ships in the harbor.
[first movement after attack]

11:25 Moored port side to U.S.S. CALIFORNIA

13:10 Underway at various courses and speeds to assist distressed ships...

13:35 Moored along side OKLAHOMA

13:50 Underway from along side OKLAHOMA

14:15 Moored alongside CALIFORNIA...

These are the only movements of the *Widgeon* on December 7, and, according to the logs, movement does not take place again until late December 10. The calculated time of $13:29 \pm 7$ minutes for photo PR-52 (fig. E-2) falls within the second period of movement between 13:10 and 13:35.

The sea level trend for the period of record of the Honolulu Harbor gage, beginning in 1905, is available at <http://tidesandcurrents.noaa.gov/>. The trend shows a seasonally adjusted rising sea level with a rate of 1.5 ± 0.25 mm/year. Sea level rise (SLR) over the period from 1941 to 2008 has the effect of producing an apparent excess in settlement magnitude when using historical tide records and is not negligible, amounting to a rise of 0.1 ± 0.02 m. Water level elevations at the Honolulu Harbor gage are based on the NGVD (National Geodetic Vertical Datum) of 1929. Calculations of settlements from tidally adjusted structure

elevations are adjusted to the present epoch using this rate of rise, scaled from 0 in 2008 to -0.1 m for all photos prior to January 16, 1945. Tables 9 and 10 contain recalculated structure elevations adjusted for SLR.

Three semilog settlement plots based on the SLR-adjusted structure elevations from tables 8 and 9 are derived for three locations on the ship: the barbette 3 port-side vent top (fig. 22), the port-side midship (fig. 23), and the starboard-side midship (fig. 24). The structure elevations were regressed from December 9, 1941, to March 4, 2008, and yield the linear trends and equations on the plots. This retrospective, photo-based method of elevation determination, using the commonly available photos found for this report, begins to lose an ability to discern a clear trend beginning in the 1980's, as can be seen in the inset of figure 22. On the basis of these photos, it is not known if the settlement trends of figures 22, 23 and 24 remain linear in recent decades.

The timelines are most complete for the barbette 3 vent and the port-side midship, where resolution is sufficient within the first three days after the sinking to show that movement was nonlinear. On December 7, following the sinking, movement of the barbette 3 vent (figs. E-1 and E-2) and midship port-side (figs. F-1 and F-2) are rapid enough to reveal noticeable movement over a 3-hour time period. A portion of a description of events following the attack illustrates rapid movement of the USS *Arizona*. Aviation Machinists Mate, First Class D.A. Graham, as recorded in

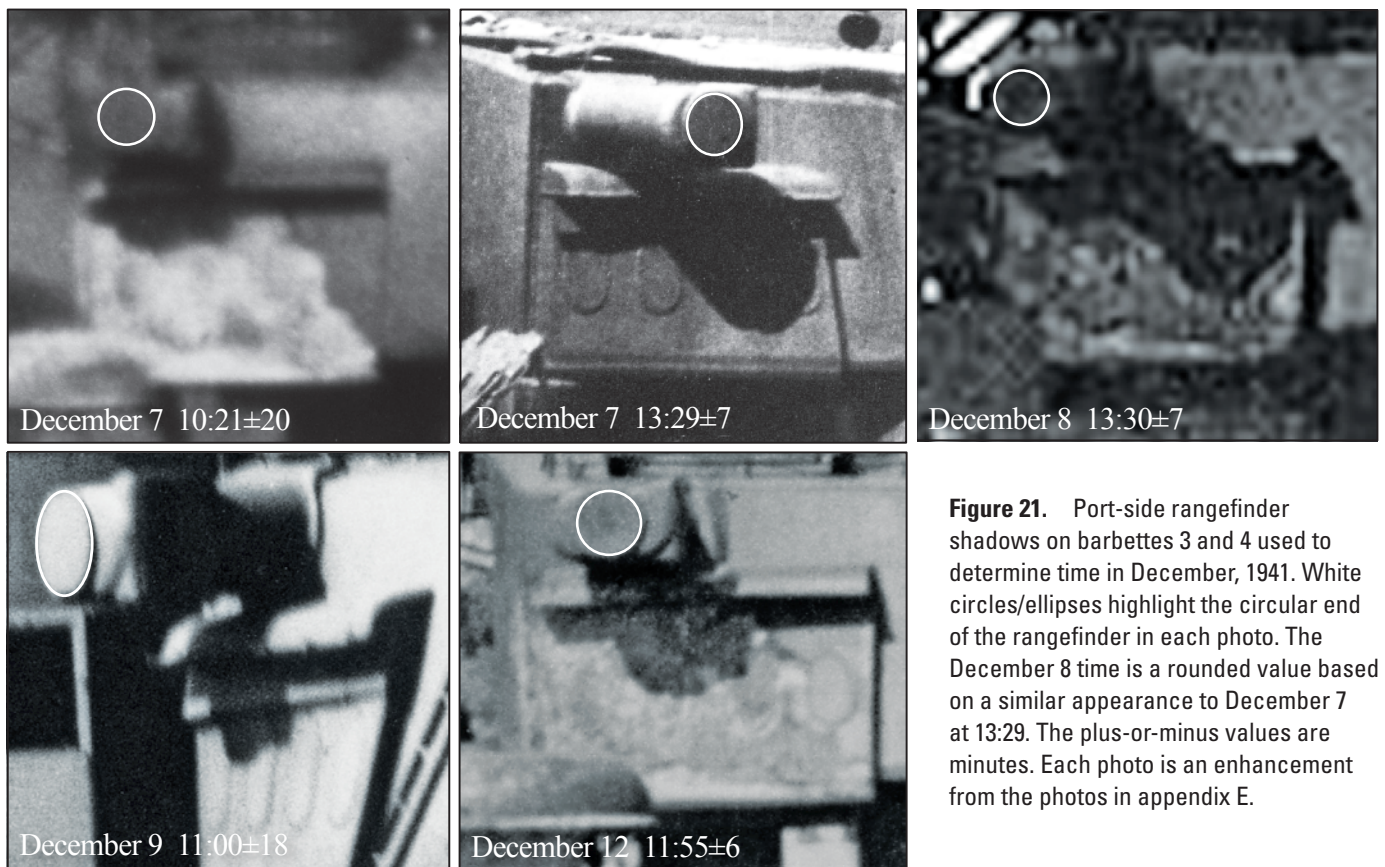


Figure 21. Port-side rangefinder shadows on barbette 3 and 4 used to determine time in December, 1941. White circles/ellipses highlight the circular end of the rangefinder in each photo. The December 8 time is a rounded value based on a similar appearance to December 7 at 13:29. The plus-or-minus values are minutes. Each photo is an enhancement from the photos in appendix E.

Table 9. Calculated elevation of the USS *Arizona* barbette 3 vent top adjusted for sea level rise (SLR) relative to the current epoch (1983–2001) at the Honolulu Harbor station.

[MLLW, mean lower low water]

Date	Structure elevation, meters MLLW	Years before Mar 4, 2008	Applied adjustment, meters	SLR-adjusted elevation, meters MLLW
Barbette 3 port side vent (V)				
Dec 7, 1941	3.00±0.08	66.28	−0.1±0.02	2.90±0.08
Dec 7, 1941	2.65±0.06	66.28	−0.1±0.02	2.55±0.06
Dec 8, 1941	2.37±0.1	66.28	−0.1±0.02	2.27±0.1
Dec 9, 1941	2.25±0.06	66.28	−0.1±0.02	2.15±0.06
Dec 12, 1941	2.06±0.05	66.27	−0.1±0.02	1.96±0.05
Dec 12–Feb 17	1.94+0.15/−0.17	66.18	−0.1±0.02	1.84+0.15/−0.17
Feb 25, 1942	1.48+0.1/−0.15	66.06	−0.1±0.02	1.38+0.1/−0.15
June 8, 1942	1.59±0.06	65.78	−0.1±0.02	1.49±0.06
Jul 17, 1942	1.46±0.1	65.67	−0.1±0.02	1.36±0.1
Sep 30, 1942	1.28+0.23/−0.08	65.47	−0.1±0.02	1.18+0.23/−0.08
Mar 21, 1943	1.28±0.07	65.00	−0.1±0.02	1.18±0.07
Apr 20, 1943	1.34±0.04	64.92	−0.1±0.015	1.24±0.04
May 4, 1943	1.32+0.04/−0.07	64.88	−0.1±0.015	1.22+0.04/−0.07
Nov 25, 1944	1.19±0.07	63.31	−0.1±0.015	1.09±0.06
June 12, 1950	0.75±0.1	57.76	−0.09±0.015	0.66±0.1
May 31, 1958	0.59±0.05	49.79	−0.08±0.015	0.51±0.05
May 29, 1962	0.54±0.14	46.80	−0.07±0.01	0.47±0.14
May 17, 1969	0.50±0.1	38.82	−0.06±0.01	0.44±0.1
Apr 7, 1978	0.60±0.03	29.93	−0.05±0.01	0.55±0.03
Oct 1, 1981	0.39±0.02	26.44	−0.04±0.01	0.35±0.02
May 1, 1986	0.39±0.02	21.85	−0.03±0.005	0.36±0.02
Feb 23, 1987	0.37±0.03	21.04	−0.03±0.005	0.34±0.03
Mar 1, 1989	0.36±0.02	19.02	−0.03±0.005	0.33±0.02
Dec 4, 1991	0.39±0.02	16.26	−0.02±0.005	0.37±0.02
Dec 7, 1991	0.35±0.03	16.25	−0.02±0.005	0.33±0.03
Mar 8, 1993	0.35±0.05	15.00	−0.02±0.005	0.33±0.05
Jun 22, 1998	0.33+0.08/−0.03	10.71	−0.02±0.005	0.31+0.08/−0.03
Jun 3, 2000	0.32±0.05	7.75	−0.01	0.31±0.05
Nov 18, 2004	0.33±0.03	3.29	−0.01	0.32±0.03
Mar 4, 2008	0.30±0.01	0	0	0.30±0.01

the Reports by Survivors of the Pearl Harbor Attack (<http://www.history.navy.mil/docs/wwii/pearl/survivors2.htm>), reported:

Assisted by a seaman from #4 turret, we rendered the bow line around and cast her [the USS *Vestal*, at 8:45] off. Then getting the small life raft on #3 turret barbette port side off and over the port stern, the water and oil being on deck, and the ship settling fast, we got orders to embark in the motor boat at the starboard stern quarter, Lieutenant Commander Fuqua and a few others still being aboard.

The ship was settling noticeably according to this observer on the deck approximately 40 minutes after the explosion that sank the USS *Arizona*. An additional observation of movement is described in Camp (2006), where marines escaping the burning ship some time after the explosion were in danger because of 6-inch diameter mooring lines attached to an F-7 mooring quay becoming taut and breaking.

A continuation of this rapid movement is measurable from 10:21 a.m. (photo PR-54A), approximately 2 hours and 11 minutes after the explosion, to 13:29 (photo PR-52), when the barbette 3 vent settled an additional 0.35 m. This early rapid movement is likely the result of decreasing buoyancy of the ship as air is expelled and the settling of the hull into the softest upper part of the harbor sediment. The total measured movement of the barbette 3 port-side vent top is 2.6 m, 50 percent of which had taken place within 2 months of the sinking.

The bow area of the USS *Arizona* is visible in a few photographs dating from December of 1941. Approximately the first 10 frames of the bow survived the attack relatively intact, but the deck may have never been above the water level after the attack. The view in figure H-1 shows the bow covered by shallow water. Another photo of lesser quality from December 7 (not included in this report) with the ship burning vigorously

shows the bow area with a similar appearance, that is, the deck is below the water surface.

Photographs from December 7 show the stern of the USS *Arizona* emergent above the water level; figure H-3 shows the stern approximately 1.2 m above the surface. Photograph #NH83064 dated December 9, 1941 (shown as a thumbnail in fig. 32), and possibly taken at the same time as PR-66 (fig. E-4), shows the stern just barely above the water level and is the last dated photo found in which the stern is visible.

Early Tilt of USS *Arizona* Decks

Photographs from four dates during the 6-day period following the sinking of the *Arizona* show that the aft decks of the ship were rapidly tilting longitudinally and settling vertically. These movements are reflected in the nonlinear, upper-elevation end of the settlement trends of figures 22 and 23. Some transverse tilt change probably occurred during this time also, but is not as obvious or easy to determine, because of the lack of suitable photographs.

A major disruption in the structure of the USS *Arizona* hull occurs near the former location of the toppled foremast. Forward of the foremast the hull is largely collapsed, whereas aft of the foremast there is a transitional zone of collapsed and tilted decks that merges into the inclined decks of the largely undamaged aft half of the hull. The longitudinal slope of the USS *Arizona* main and upper decks on December 7, 1941, at 10:21, aft of the collapsed foremast area, as measured from the tilt of the top edge of barbette 3 in PR-54A (fig. E-1), is approximately 2.6° forward. The tilt of the vertical leg of the main mast at this time is 3° forward. A later photo (fig. E-2), with an estimated time of 13:29, shows a longitudinal tilt of the main deck of about 2.2°, perhaps slightly steepened by the viewing angle.

The longitudinal deck tilt is reduced to about 1.3±0.1° forward on December 12, 1941, in PR-16A (fig. E-5), and the main mast tilt is 1.8° forward at this time. The approximately 0.4° difference between the deck and main mast tilts is measureable

Table 10. Calculated elevation of USS *Arizona* structures adjusted for sea level rise (SLR) relative to the current epoch (1983–2001) at the Honolulu Harbor station.

[MLLW, mean lower low water]

Date	Structure elevation, meters MLLW	Years before Mar 4, 2008	Applied adjustment, meters	SLR-adjusted elevation, meters MLLW
Port side midship bulwark (P)				
Dec 7, 1941	1.02±0.08	66.28	-0.1±0.02	0.92±0.08
Dec 7, 1941	0.84±0.05	66.28	-0.1±0.02	0.74±0.05
Dec 12, 1941	0.37±0.03	66.27	-0.1±0.02	0.27±0.03
Feb 17, 1942	-0.05±0.06	66.08	-0.1±0.02	-0.15±0.06
Jul 17, 1942	-0.31±0.05	65.67	-0.1±0.02	-0.41±0.05
Sep 30, 1942	-0.38±0.23/-0.08	65.47	-0.1±0.02	-0.48±0.23/-0.08
Sep 20, 1943	-0.44±0.12	64.50	-0.1±0.02	-0.54±0.12
Jan 16, 1945	-0.52±0.61/-0.06	63.17	-0.1±0.02	-0.62±0.61/-0.06
May 29, 1962	-0.96±0.1	46.80	-0.07±0.01	-1.03±0.1
May 30, 1962	-0.94±0.1	46.79	-0.07±0.01	-1.01±0.1
May 1, 1986	-1.07±0.05	21.85	-0.03±0.005	-1.1±0.05
Jun 3, 2000	-1.09±0.05	7.75	-0.01	-1.1±0.05
Mar 4, 2008	-1.1	0	0	-1.1
Starboard side midship bulwark (S)				
Dec 9, 1941	0.94±0.07	66.28	-0.1±0.02	0.84±0.07
May 6, 1942	0.42±0.1	65.87	-0.1±0.02	0.32±0.1
Mar 21, 1943	0.37±0.1	65.00	-0.1±0.02	0.27±0.1
May 31, 1958	0.08±0.07	49.79	-0.08±0.015	0.00±0.07
May 29, 1962	0.05±0.05	46.80	-0.07±0.01	-0.02±0.05
Oct 1, 1981	-0.04±0.03	26.44	-0.04±0.01	-0.08±0.03
May 1, 1986	-0.07±0.03	21.85	-0.03±0.005	-0.1±0.03
Jun 3, 2000	-0.09±0.02	7.75	-0.01	-0.1±0.02
Mar 4, 2008	-0.12	0	0	-0.12
Turret 2 (T)				
Dec 7, 1941	1.23±0.1	66.28	-0.1±0.02	1.13±0.1
Mar 4, 2008	0.12	0:00	0	0.12
Bow (B)				
Dec 10, 1941	-0.18±0.1	66.27	-0.1±0.02	-0.08±0.1
Mar 4, 2008	-1.2	0	0	-1.2
Stern (St)				
Dec 7, 1941	1.20±0.13	66.28	-0.1±0.02	1.10±0.13
Mar 4, 2008	-2.02	0	0	-2.02

and consistent in both the PR-54A and PR-16A photos. The 0.9° change in tilt over the length of the USS *Arizona* from the foremast to the stern from the afternoon of December 7 to December 12 would move the stern about 1.7 m lower, below the surface of the water, though no photographs showing the stern area during the rest of December 1941 were found.

Calculations of the early transverse deck tilt after the sinking of the USS *Arizona* can be derived from two photographs from December 9, 1941, which show the USS *Navajo* and USS *Tern* spraying water on the port side of the ship. Photograph PR-66 of the port side is shown in figure 25 and photo 80-G-32609 of the starboard side in figure 26.

These photographs show pairs of mooring bitts located just aft of turret 4 at about frame number 128. The bitts are assumed to be 0.69 ± 0.01 m in diameter, as measured from the existing midship starboard bitts. On the port side the visible bitt top is estimated to be 0.10 ± 0.02 m above the water level. The time is estimated to be 11:00 from figure E-4. On the starboard side (fig. 26), the bitt tops are estimated to be 0.25 ± 0.03 m above the water at a nearly equivalent time and tide level. The beam at this point is 20.5 m (GPS 2008; 18.5 m from ship drawing). The height difference between the bitt tops results in a deck tilt of $0.4 \pm 0.1^\circ$ to port.

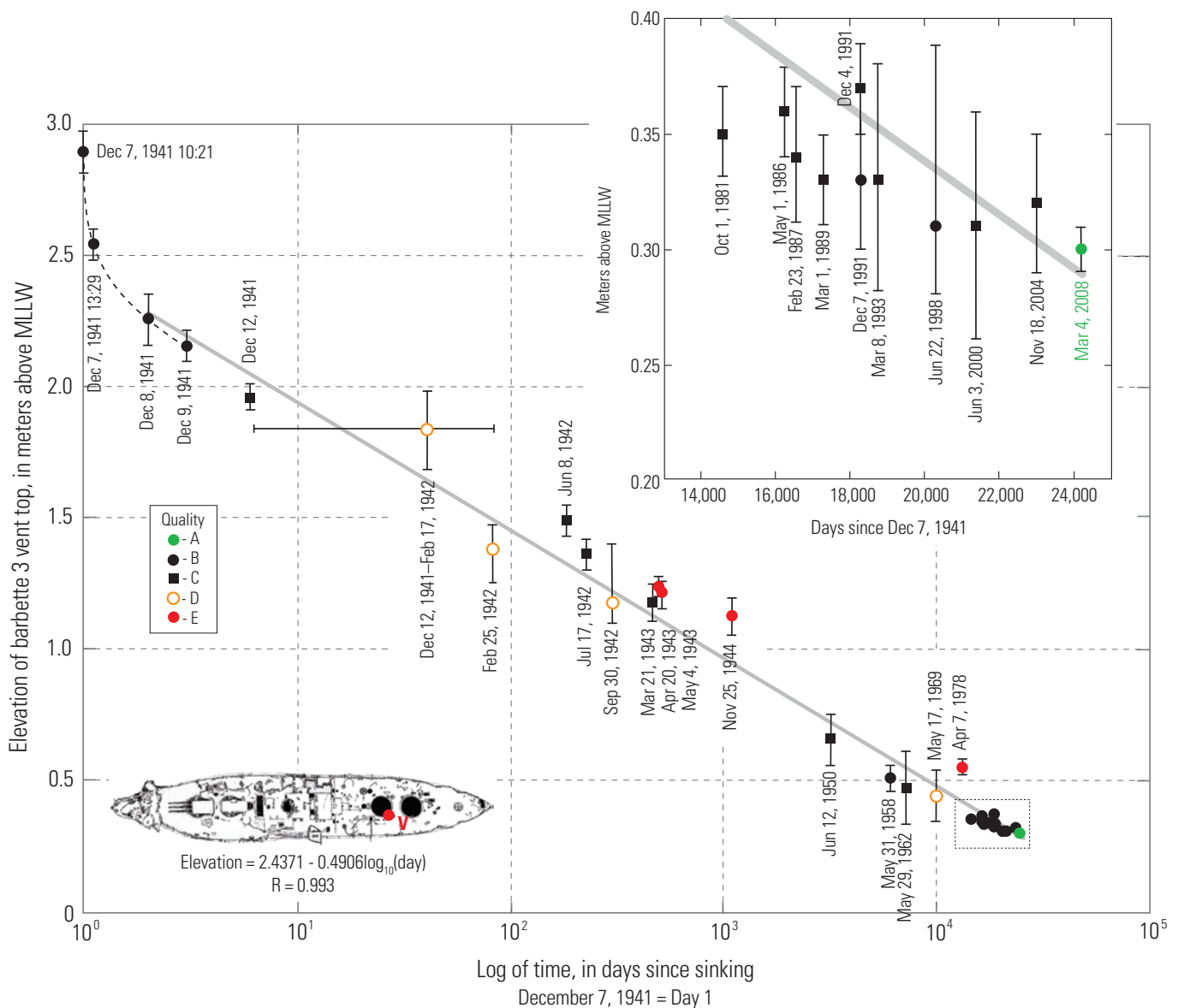


Figure 22. Settlement plot showing elevation of the USS *Arizona* barrette 3 vent top versus time from December 7, 1941 (day 1) to 2008. Elevations are adjusted for sea-level rise. Quality designations are defined in table 7. Enlargement shows settlement line and data points from 1981 to 2008 on a linear scale.

Figure 23. Settlement plot showing elevation of the USS *Arizona* midship port-side deck edge versus time. Elevations are adjusted for sea-level rise. Quality designations are defined in table 7.

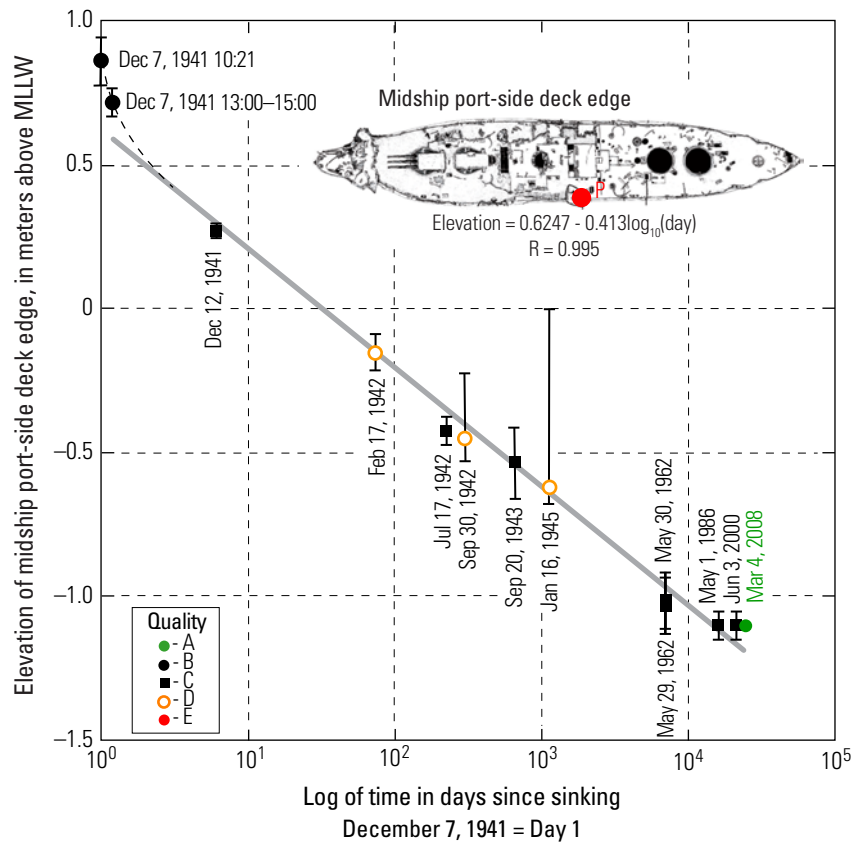
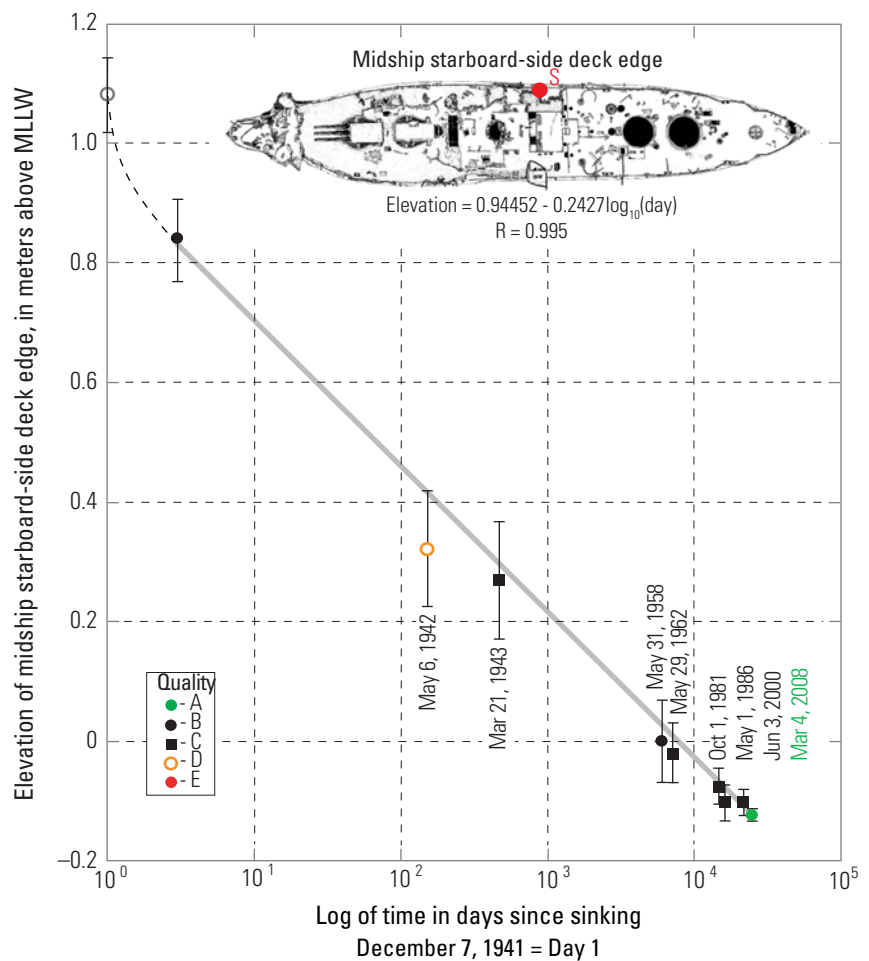


Figure 24. Settlement plot showing elevation of the USS *Arizona* midship starboard deck edge versus time. Elevations are adjusted for sea-level rise. A projected elevation back to a time of 10:21 on December 7, 1941 (day 1), is indicated by the open gray circle at an elevation of $+1.14 \pm 0.1$ m MLLW. Quality designations are defined in table 7.



In figure 27 the water level at the port and starboard vents on barbette 3 on December 9, 1941, is compared. These areas are also visible in the two photos that were used in figures 25 and 26. A structure closest to the water line, a horizontal projection housing a fan at the base of the vertical part of the vents, is visible above the water line. The vent opening height provides scale to show that the flat top of the vent projection is 0.14 ± 0.05 m above the water on the port side and 0.2 ± 0.04 m above the water on the starboard side. It is estimated that there is little time difference between the two photos, as explained in a following section. The horizontal distance between the vents is approximately 6.2 m, resulting in a port tilt of $0.55 \pm 0.5^\circ$.

The present transverse tilt of the USS *Arizona* deck at barbette 3 is 2° to port (fig. 19). This represents an increase of about 1.5° since the sinking on December 7, 1941. The present tilt of the mooring platform at barbette 3 is about 0.9° to port. If the platform is assumed to have been constructed level at the beginning of 1945, 0.6° of deck tilt to port occurred during the first four years after sinking. The final 0.9° of tilt for the deck and platform occurred during the 63 years from 1945 to 2008.

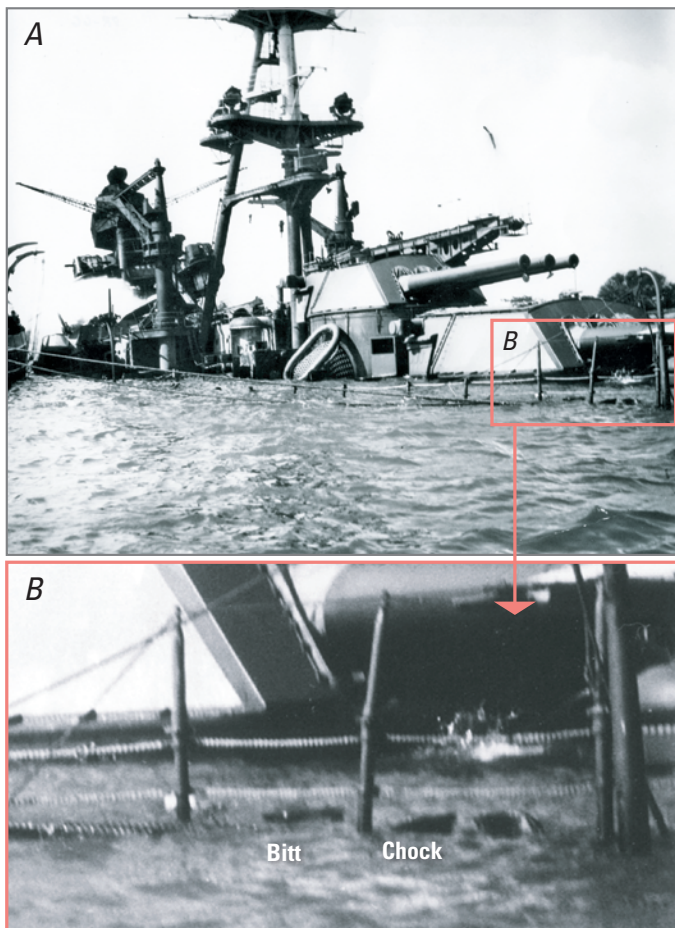


Figure 25. Mooring bitts at the port aft side of the USS *Arizona*. A, Photograph PR-66 dated December 9, 1941. B, Enlargement of area outlined in A, showing the top of one bitt and chock located just aft of turret 4. Only one bitt of a pair is clearly visible.

Changes at Turret 2

During the explosions that destroyed the forward magazines of the USS *Arizona*, turret and barbette 2 dropped about 7 m vertically (Friedman and others, 1978) relative to the surrounding deck structure as this forward part of the ship collapsed. The upper edges of the turret, with the guns and top removed during the salvage phase in 1943, have remained near the water level to the present day and are one of a few readily visible reference points surviving. A photo from the early afternoon of December 7, 1941, (fig. H-2) shows the top of turret 2 above the water line and is the basis for the earliest elevation estimate. Other photos (fig. 28) show the turret resting in a basically level position in the days following the explosion. The top edge of the turret as viewed from the starboard side on December 9, 1941 (fig. G-1, full-size



Figure 26. Mooring bitts at the starboard aft side of the USS *Arizona*. A, Photo 80-G-32609 taken on December 9, 1941 (Stillwell, 1991), as shown by the Navajo and Tern at the port side, as in figures 19 and E-4. This is Photo 3 in figure 32. B, Enlargement of outlined area in A. Two bitts are visible just aft of turret 4, opposite the pair of bitts on the port side. The apparent edge of the deck at the bitts may be a boat boom attached near the chock; the dark edge is too high relative to the bitt tops to be the top of the bulwark. A similar boom is present on the port side and can be seen extended in the full size photo PR-52 (fig. E-2).

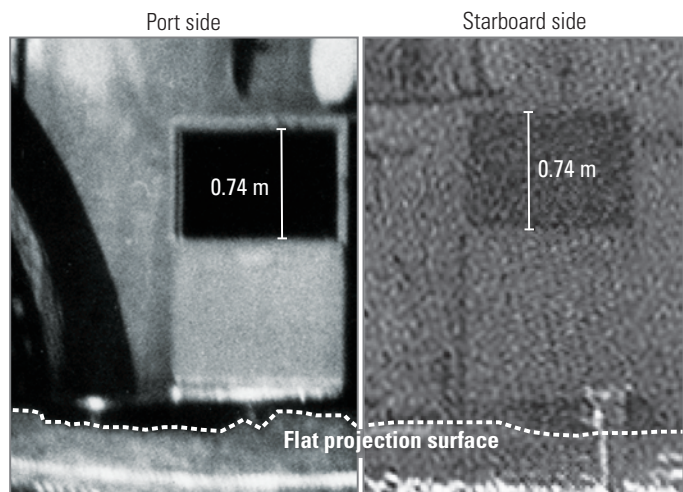


Figure 27. Port and starboard vents on barbette 3 of the USS *Arizona* on December 9, 1941. The dashed line is the water line and the flat surface of the projection is above the water line on both sides of the ship. Port side photo is PR-66; see figure 25A for wider view. Starboard side photo is 80-G-32609; see figure 26A for a wider view.

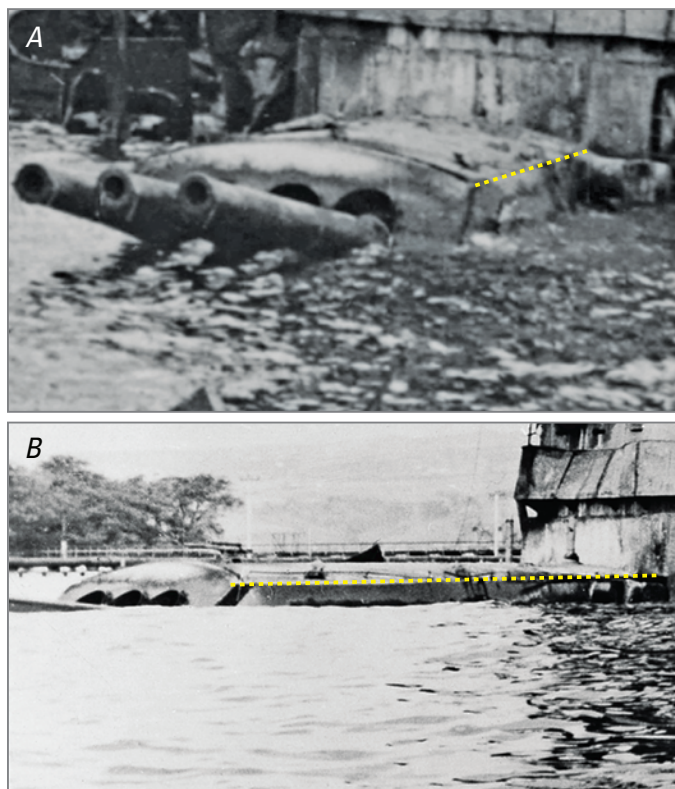


Figure 28. Turret 2 of the USS *Arizona* in December 1941, showing a basically level position of the turret. Dashed lines in both A and B mark the upper edge of the port-side turret face. A, A portion of photo NH 63918, dated December 10, 1941. B, A portion of undated photo BuAer650393 obtained from the National Park Service Submerged Resources Center. BuAer is the former Bureau of Aeronautics.

version) also indicates an essentially level position. Aft of this position, the ship had a low forward slope of about 2.6° early on December 7, indicating that the turret tilted slightly aft with respect to the rest of the hull during its collapse. A tilt of the turret to aft and port is already evident in a photograph dated February 17, 1942 (not included in this report), and this movement follows the general trend of tilt evolution that occurred in the hull aft of the turret.

A more recent view of turret 2 is shown in figure 29. Measurements taken on March 4, 2008, reveal that the four corners of the turret (table 8) have an average tide-corrected elevation of 0.12 m MLLW. The settlement of the turret since December 7, 1941, based on this average height amounts to 1.22 m. The maximum settlement is 1.37 m at the port aft corner; the minimum settlement is 1.06 m at the forward starboard corner.



Figure 29. Views of the top edges of turret 2 during a very low tide in 2000. The top of the turret and guns were removed in 1943. A, The turret as viewed from the USS *Arizona* Memorial toward the bow. The rangefinder projections are visible at the breech (near) end of the turret. The port tilt between the two forward ends measures about 0.5° ; the port tilt across the aft ends measures 1.25° . A portion of photo DN-SC-02-05621, dated June 3, 2000 from www.defenseimagery.mil/. B, The turret as viewed from the port side looking toward Ford Island, with the aft tilt visible. The port side edge has an aft tilt of about 1.5° ; the starboard side about 1.3° . A portion of photo DN-SC-02-05620, dated June 3, 2000, from www.defenseimagery.mil/. The tilts were determined from measurements made on March 4, 2008.

Table 11. Reference elevations on the USS *Arizona* hull, settlement components and rates.

[MLLW, mean lower low water; IVP, initial vessel penetration. The sea-level-rise (SLR)-adjusted elevation is the elevation of the structures at 10:21 on December 7, 1941. Latest 10-year period is 1998 to 2008, and the rates are calculated from the regression formulas. --, no data or not determined]

Structures	Earliest observed elevation, m MLLW		Method	Reference elevations, SLR-adjusted 10:21 Dec 7, MLLW	IVP Dec 7 10:21 to Dec 9, meters	Consolidation Dec 9 to present, meters	Settlement		Latest 10-year avg. consolidation rate, mm/yr
							Total structure, meters	Long-term rate, cm/year	
Bow (B)	-0.18±0.1	Dec 10	Estimated	-0.1±0.1	0.5 est.	0.6	1.1±0.15	1.7	--
Turret 2 (T)	1.23±0.1	13–14:00 Dec 7	Estimated	1.31±0.1	0.5	0.7	1.22±0.11	1.8	--
Port midship (P)	1.02±0.08	10:21 Dec 7	Observed	0.92±0.08	0.45	1.55	2.02±0.1	3.0	2.9
Starboard midship (S)	0.94±0.07	11:05 Dec 9	Calculated	1.14±0.11	0.3	0.95	1.26±0.15	1.9	1.7
Barbette 3 vent (V)	3.00±0.08	10:21 Dec 7	Observed	2.90±0.08	0.75	1.85	2.6±0.1	3.9	3.5
Stern (St)	1.2±0.1	11–14:00 Dec 7	Calculated	2.09±0.13	1.5	2.6	4.11±0.15	6.2	--

Characterization of USS *Arizona* Settlement

The observed settlement of the USS *Arizona* can be subdivided into two components: a rapid and early, nonlinear component and a long-term, linear component. The nonlinear component begins the moment the ship impacted the bottom after the explosion. It is best documented by the barbette 3 vent settlement trend (fig. 22), which begins at 10:21 on December 7, about 2.2 hours after the explosion, and ends on or about December 9 as the settlement trend begins to become linear. We refer to this period of time and settlement as the initial vessel penetration (IVP). During the IVP the ship is penetrating the uppermost and softest part of the sediment column and physically displacing material as it sinks into the bottom. The linear component proceeds from approximately December 9 and continues to the present time. This phase of settlement is characterized by normal consolidation processes as the increased stress on the sediment column slowly expels pore water, decreasing the void ratio and decreasing the sediment volume.

Calculation of Reference Elevations

The late morning (10:21 hours) of December 7, 1941, approximately 2.2 hours after the explosion, is the beginning of the photographic record of settlement and the earliest determination of elevation on the USS *Arizona* hull. Two structures are observed at this time: the barbette 3 vent and the midship port-side bulwark as seen in figure E-1. The relatively rapid movement observed in the hours following the attack at these two points certainly also occurred at all points on the hull; the documentation of such movement is lacking because of the absence of suitable photographs. For purposes of settlement magnitude and rate comparison between six selected points on the hull (see table 11), adjustments have been derived for the other four measurement points to create the earliest reference elevations of structures on the ship. The elevation at the midship starboard

side is calculated from the early transverse tilt of the USS *Arizona* as derived in a preceding section. It is estimated that the ship had a maximum initial port tilt of about 0.5°. The height difference across a beam of 27.5 m brings the starboard midship bulwark 0.24 m above the port side at 10:21 hours. For the stern, which is not seen in the earliest photographs, the longitudinal deck tilt of 2.6° as observed at 10:21 on December 7 (fig. E-1), projected 44 frames (54 m) from turret 3, creates an added height of about 0.8 m above the elevation calculated in figure H-1. For the bow and turret 2, 0.18 m is added to their earliest observed elevations. This is the amount of observed movement at the midship port side from 10:21 to about 13:30 on December 7 and is the basis for the “estimated” method in table 11. The resulting SLR-adjusted reference elevations are tabulated in table 11.

Discussion of Initial Vessel Penetration and Settlement

Table 11 contains estimated IVP settlements derived from the reference elevations for six structures around the USS *Arizona*. The full magnitude of the IVP is speculative and requires knowledge of the depth profile along the Fox 7 mooring quay prior to the December 7 attack. The photographic record captures only part of these settlements.

With limited photographic evidence, and with the previously cited depth of water, drafts, and calculated floating height of the decks above the water line as constraints, one version of the IVP history can be compiled. This version assumes a uniform water depth at the Fox 7 mooring quay of 13.7 m, as cited in Friedman and others (1978). At about 8:10 on the morning of December 7, the USS *Arizona* exploded and sank in 13.7 m of water. The bow deck, which had been floating about 6.6 m above the water surface was, by 13:30, 5.3 hours after the explosion, below the water surface, and the keel at the bow had settled about 3 m into the harbor mud. The midship port-side bulwark at the upper deck, the same level as the bow deck, by 10:21 was about 0.8 m above the water and had penetrated about 1.9 m into the harbor mud. Nearly 2 m of

penetration at the midship starboard-side is necessary also to keep the ship at its low initial port tilt. The stern deck at 10:21 is projected to be about 2.1 m above the water line. The base of the rudder is about 14 m below the deck; therefore, at a water depth of 13.7 m, the rudder and propellers may not have contacted the bottom by this time.

The 2–3 m of IVP in the forward part of the ship within hours of the sinking may be considered extraordinary. An alternate possibility is that the harbor bottom at Fox 7 was not actually flat, but instead sloped to the southwest and was deeper at the bow, which could result in significantly less IVP. In that case the early forward tilt of 2.6° of the aft decks at 10:21 on December 7 could be, at least in part, a reflection of deeper water at the bow as the ship rests on the bottom. The IVP cannot be as tightly constrained as in the former case where the water depth along the ship is considered constant. Examination of sounding records from before and during the salvage operations would distinguish amongst these possibilities.

Any amount of IVP requires displacement of a significant volume of bottom sediment from below the ship. A report by Lt. M.L. McClung, serving as Assistant Salvage Engineer, issued after the attack, describes the damage to the USS *Arizona* (full report in Murphy and Russell, 2008). Part of this report reads:

The soundings taken before and after Dec. 7, 1941, indicate that mud has been deposited on both sides of the ship abeam of turrets No. 1 and No. 2. A reasonable opinion of the cause of this deposit based on experience in submarine rock excavation is that this deposit came from under the ship or the water displaced by the explosion brought the mud when it returned.

A speculative condition is that the bottom of the ship between approximately frames 20 and 70 may have ruptured in the explosion, allowing some sediment to be accommodated within the lower part of the hull. During the salvage operation, the hull from frame 70 forward was examined from the mudline inboard 3 m from the turn of the bilge, in an effort to find torpedo damage; however, the condition of the flat bottom of the hull beyond the areas examined is not known (Paine, 1943).

At 10:21 on December 7, photographic evidence begins. By 11:00 on December 9 the barbettes 3 vent top had settled an additional 0.75 m, concluding the IVP phase, the upper nonlinear settlement in figure 22. It is during this time that linear consolidation of the harbor sediment below the USS *Arizona* hull begins. Settlement magnitude at the bow during this time period is uncertain because the bow is submerged and is not visible, but it is estimated in table 11. The aft (main) deck had a forward tilt of about 2.6° at 10:21 on December 7. This tilt decreases with time and the stern disappears below the water surface probably between December 9 and 12. The tilt of the intact aft decks decreases with time as the stern settles as a result of consolidation of the wedge of deeper, soft harbor sediment underlying the aft half of the hull. The hull, which initially had just a slight tilt to port, perhaps 0.5°, begins to tilt increasingly to port with the passage of time. The bow currently rests in 11 to 12 m of water, and the base of the bow is about 6.5 m below the harbor bottom. In addition, the

accumulation of sediment around the hull since 1941 has increased the burial depth. The top of the rudder is near the mud line in recent times, as depicted in the drawings from Lenihan (1989).

The resulting adjusted total structure settlements and long-term settlement rates from table 11 are plotted in figure 30. In figure 30A, arrows at the measured structures represent the estimated relative proportions of IVP and normal consolidation. In figure 30B, the port and starboard midship settlements and rates are bisected to derive values at the axis of the hull and place these points on a trend comparable to the barbettes 3 vent and stern. Those three points form a linear trend that demonstrates that the aft half of the hull is moving as an intact, rigid body. The figure also shows the damaged and variably collapsed section of the hull between frames 10 and 70. This area is loosely subdivided into explosion and collapse zones, the collapse zone being aft of the magazine areas. The vertical highlighted zones correspond to areas where rigid connectivity of the hull is questionable. The hull in the explosion zone contains a known large crack at frame 30, 37 m from the bow, identified during the salvage phase (Murphy and Russell, 2008).

In figure 31 the total settlements are plotted together with the resultant tilt vectors calculated from the estimated transverse and longitudinal tilt changes. The tilt change of turret 2 resembles the trend of the aft half of the hull, the main difference being that the turret has not settled vertically to a great extent, and the position of the stern can be estimated from the changes at turret 2. The aft tilt of the top edges of turret 2 of about 1.4° (fig. 29), developed from December 1941 to the present, projected over the hull length of 102 frames (124 m) to the stern, amounts to a height change of 3.03 m at the stern. If the vertical height change of 1.22 m of the turret is added to 3.03 m, a total vertical change of about 4.25 m would be indicated for the stern. This is comparable with the total movement of the stern during this time period (4.11 m, table 11) as estimated by other means. Turret 2 clearly became detached from the supporting structure around it during the explosion and collapse, but it is evidently nestled within a deeper structure that may be moving with the aft part of the hull.

Consolidation of Sediment Under Stress Exerted by the Hull of the USS *Arizona*

This section addresses the potential for normal consolidation processes to affect the orientation and elevation of the USS *Arizona* through time, with respect to the seafloor and the waterline. The three borings around the vessel indicate that the vessel rests upon highly variable sediment. The settlement potential of the vessel is greater toward the stern and toward the port side. Stiffer sediments observed at boring B1A off the starboard side midship may act to reduce settlement of the vessel there and may amplify tilting toward the bay and may also enhance differential settlement beneath the vessel that can result in hull stresses that deform the underbody of the vessel. The larger settlements toward the stern and increasing port tilt correspond with the observed orientation of the vessel. Because the actual thicknesses of clay beneath the hull were

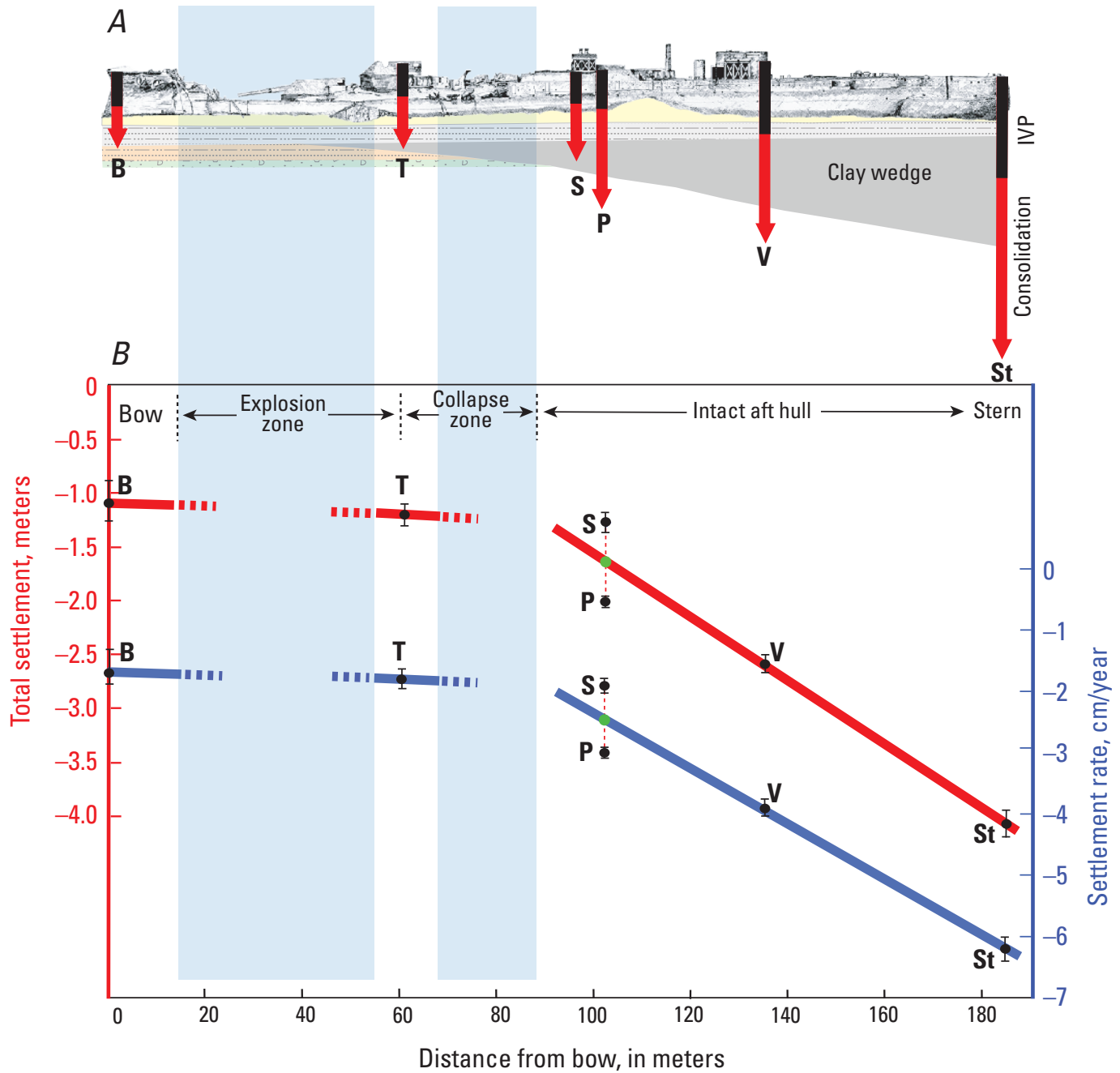


Figure 30. Total structure settlements and long-term settlement rates for structures on the USS *Arizona*. Total settlements are computed from 10:21 on December 7, 1941, the beginning of the postexplosion photographic evidence. A, Diagram showing side view of hull, with vertical arrows proportional to the total structure settlement values in table 11. Black component is initial vessel penetration (IVP); red is normal consolidation. B, Graph of total settlements and rates plotted along the ship axis. Vertical blue shading highlights sections of the hull and corresponding breaks in the settlement trends indicating where continuity of the hull is unknown. B is the bow; T, turret 2; P, port midship side; S, starboard midship side; V, barbette 3 port-side vent; St, stern

not measured and are unknown, calculations of the possible extent of consolidation cannot be done. Instead, we apply the measured properties of the clay recovered from boring B2 to scaled versions of the B2 stratigraphic column to reproduce the observed consolidation settlement and therefore estimate the thickness of the clay wedge beneath the aft part of the hull.

The full weight displacement of the vessel, assumed here to be the vessel weight on December 7, 1941, was approximately 37,600 short tons. The total density of steel and its buoyant density in seawater are 7.85 and 6.82 g/cm³, respectively; thus the submerged weight of the vessel beneath the waterline is approximately 33,000 tons (30.5x10⁶ kg, or 30,500 metric tons). The length and beam, at the waterline, of the vessel are 185 m and 29.6 m, respectively, and we estimate the area of the flat bottom of the vessel to be 4,300 m². Thus the effective stress of the vessel acting on the seafloor directly beneath the centerline of the vessel is approximately 30.5x10⁶ kg/43x10⁶ cm², or 0.71 kg/cm² (~71 kPa). This stress level is equivalent to approximately 9 m of deposited sandy sediment with a bulk density of 1.8 g/cm³.

Settlement Analysis

A preliminary analysis of the vertical consolidation of sediment beneath the vessel assumes that the hull is a rigid mat that is uniformly loading the ground beneath the centerline of the vessel. The initial void ratio (volume of the void space /volume of the solid particles) of the soil deposit can be estimated from the core sediment logger profiles, assuming a grain specific gravity for the solid particles, and from the initial state and consolidation characteristics of the consolidation test samples. Table 5 lists the initial void ratio estimates for each of the Shelby Tube soil samples tested, and the individual test

results are presented in appendix B. Based on the observation of normal consolidation (overconsolidation ratio, OCR ~ 1.0) in all the test samples, the void ratio (e) and full consolidation under an additional load of 0.71 kg/cm² is computed as follows:

$$e = e_o - C_c \text{ LOG } \{P/P_o\} \quad (7)$$

Here, C_c is the compression index and P is the effective overburden stress of the overlying soil (P_o) plus the added stress of the vessel pressure on the seafloor (assumed to be 0.71 kg/cm²). The fine-grained portion of the sediment column, susceptible to the majority of the settlement, was subdivided into individual layers represented by the Shelby tube sample taken within it. These layers have variable incremental thicknesses (H_{inc}), depending on the sampling depths. We compute the individual layer settlement as:

$$\Delta H_{inc} = H_{inc} \times (e_o - e)/(e_o + 1) \quad (8)$$

The total consolidation ΔH at three points beneath the vessel is derived as the sum of the incremental consolidations (ΔH_i), or $\Delta H = \sum \Delta H_i$, and is shown in table 12.

In table 11 we estimated the consolidation component of the total settlement at the port midship, barbette 3, and stern locations to be approximately 1.6, 1.9, and 2.6 m, respectively. Projecting clay thicknesses of about 14 m at the port midship location, 16 m at barbette 3, and 22 m at the stern can reproduce these settlements.

This slow process of consolidation followed the abrupt initial impact of the vessel on the seafloor and plastic shear deformation of the softest near-surface mud. The thickness of this surface mud layer at the time of sinking of the vessel is

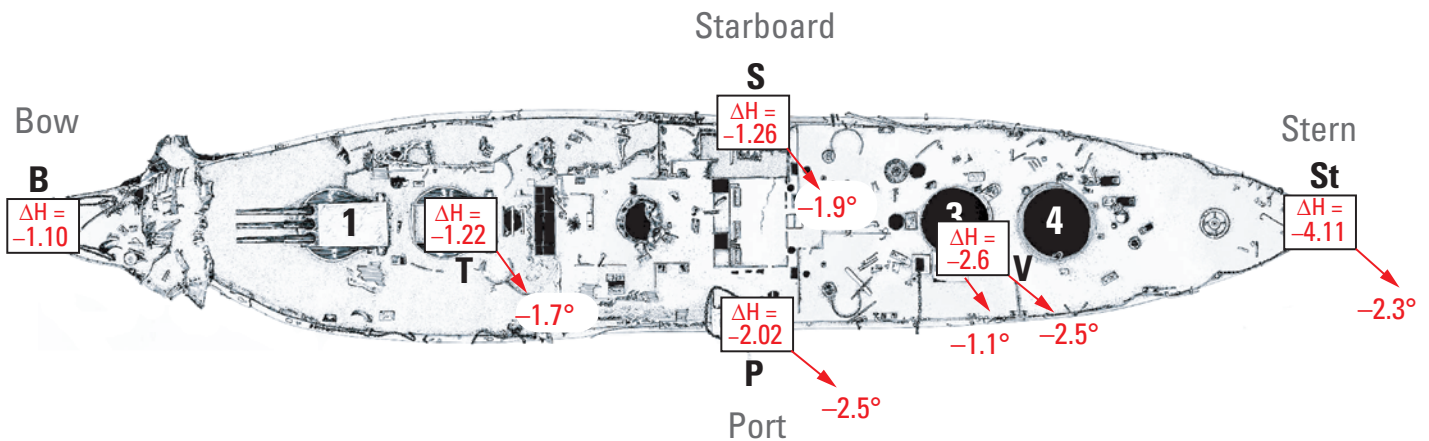


Figure 31. Sketch plan of the USS *Arizona* hull, showing total settlements (ΔH) and tilts from the morning (10:21) of December 7, 1941, to 2008. Settlement values (initial vessel penetration plus consolidation) in meters at the measured structures are shown in boxes. Tilt change vectors are the resultant of longitudinal and transverse components from the morning of December 7, 1941, except for the barbette 3 mooring platform (-1.1°), which is from January 1945, and for the starboard midship deck (-1.9°), which is from December 9, 1941. Negative sign on tilt vectors indicates a downward direction.

Table 12. Calculation of settlement from analysis of sediment samples from boring B2 near the hull of the USS *Arizona*.

[Layers A to F are layers of sediment with properties derived from the associated CON test results; Depth is the cumulative depth of the increment thicknesses; Hinc, incremental thickness; Δh , calculated settlement of each increment]

Layer	Port Midship			Barbette 3			Stern			CON Test number
	Depth (m)	Hinc (m)	Δh (m)	Depth (m)	Hinc (m)	Δh (m)	Depth (m)	Hinc (m)	Δh (m)	
A	2.45	2.45	0.33	3.36	3.36	0.45	6.10	6.10	0.81	CON-246
B	3.21	0.76	0.08	4.20	0.84	0.08	7.17	1.07	0.11	CON-202
C	6.26	3.05	0.41	7.55	3.35	0.45	11.44	4.27	0.57	CON-249
D	7.02	0.76	0.09	8.39	0.84	0.10	12.51	1.07	0.12	
E	7.78	0.76	0.10	9.23	0.84	0.11	13.58	1.07	0.14	CON-206
F	9.30	1.52	0.19	10.91	1.68	0.21	15.71	2.13	0.27	CON-207
G	10.06	0.76	0.07	11.75	0.84	0.07	16.78	1.07	0.09	CON-200
H	10.82	0.76	0.07	12.59	0.84	0.07	17.85	1.07	0.09	CON-199
I	13.11	2.29	0.21	15.11	2.52	0.23	21.05	3.20	0.29	CON-248
J	13.87	0.76	0.05	15.95	0.84	0.06	22.12	1.07	0.08	CON-252
Total settlements $\Delta H = \Sigma$			1.60			1.83			2.57	
Δh (m)										

unknown. The consolidation of the underlying layers would need years or decades to complete before full consolidation and equilibrium were reached with the new loads. The tilt of the vessel seaward is likely due to the seaward-thickening wedge of fine-grained sediment. The soil borings indicate that the stern overlies a large wedge of soft, fine-grained sediment capable of large settlements, whereas the bow is founded on stiffer, denser, and high-velocity (V_s) deposits of sandy silt and silty sand, with less clay near the surface. Consolidation modeling indicates that this sediment variability has resulted in the stern settling to a much greater extent than the bow.

Estimation of Time of December 9, 1941, Photographs

This section describes the process by which a time estimation was obtained for a historical photograph. A version of Photo NH 97383, dated December 9, 1941 (fig. G-1), obtained from <http://www.navsource.org/archives/01/39b.htm> (last accessed March 29, 2013), is the source for the earliest observation for the elevation of the midship starboard side of the USS *Arizona* and is therefore an important photograph. The description of the photo states that the USS *Tern* is on the opposite side of the USS *Arizona*, spraying water on the still-hot wreckage. There are no useful shadows in the photo and the time is unknown. Deck logs from the USS *Tern* state that it was present at the port side of the USS *Arizona* between 14:30 on December 8 and 12:35 p.m. on December 9, when the fire had been put out and the *Tern* departed.

A clue to the time of the photograph can be obtained by piecing together a timeline as shown in figure 32. A series of

photographs, not all of which are fully identified or, as far as known, from the same photographer, can be assembled into a sequence taken by a hypothetical photographer moving around the USS *Arizona* during the morning of December 9, 1941.

The sequence begins with Photo 1 (PR-66, fig. E-4) taken near the USS *Arizona* stern at an estimated time of 11:00±18 minutes, based on the rangefinder shadows on turrets 3 and 4. Photo 2 (#NH83064) was taken from a position beyond the stern. As can be seen in a number of photos dated December 9, the USS *Navajo* and USS *Tern* are tied up to the port side of the USS *Arizona* spraying water in the final phase of extinguishing the fire.

In Photo 3 (<http://www.historylink101.com>) in figure 32, also identified as G-80-32609, the photographer, still near the stern, has moved to the starboard side of the ship. The *Navajo* is still spraying water, and in the distance is a group of people that we have interpreted to be just about to enter a small boat adjacent to the starboard side of the USS *Arizona*. As seen in the full photos, a shadow on the aft face of turret 3 is in an identical position as the same shadow in Photo 1. The common shadow and water spraying activity provide a link between the port and starboard side photos 1 and 3.

Photo 4 (<http://www.pearlharbormemorial.com>) was taken from a different position closer to the small boat and shows the people continuing to enter the small boat.

Photo 5 (<http://www.navsource.org/>) shows all people in the small boat and the USS *Navajo* and USS *Tern* in the background still aside the *Arizona* spraying water (see also fig. G-1 for a wider view). The photo was taken from behind the Fox 7 north mooring quay on the Ford Island side. The middle of the small boat is approximately at Frame 83 of the *Arizona*. Deck logs from the *Tern* indicate that it departed from the USS *Arizona* at 12:35 (<http://www.history.navy>).

mil/docs/wwii/pearl/ph118.htm), which would be the latest possible time for the photo. We estimate the time of the photo to be $11:05 \pm 18$ minutes on the basis of the time it might take for the group of people to enter the boat and the photographer to travel along the starboard side the USS *Arizona*.

The assumed time difference between Photos 1 and 5 creates no significant tide-level difference for calculations derived from Photo 5. This exercise provides support for assigning a time to photo NH 97383 (Photo 5) that is very close to that derived for PR-66 (Photo 1).

Discussion of the Barbette 3 Settlement Line and Selected Photos

The barbette 3 settlement line (fig. 22) is anchored early and late by a number of what are considered to be reliably dated photos. The sequence of four photos from December 7 through 9, 1941, form a coherent trend, and the photos contain identifiable events or conditions in a chronology that

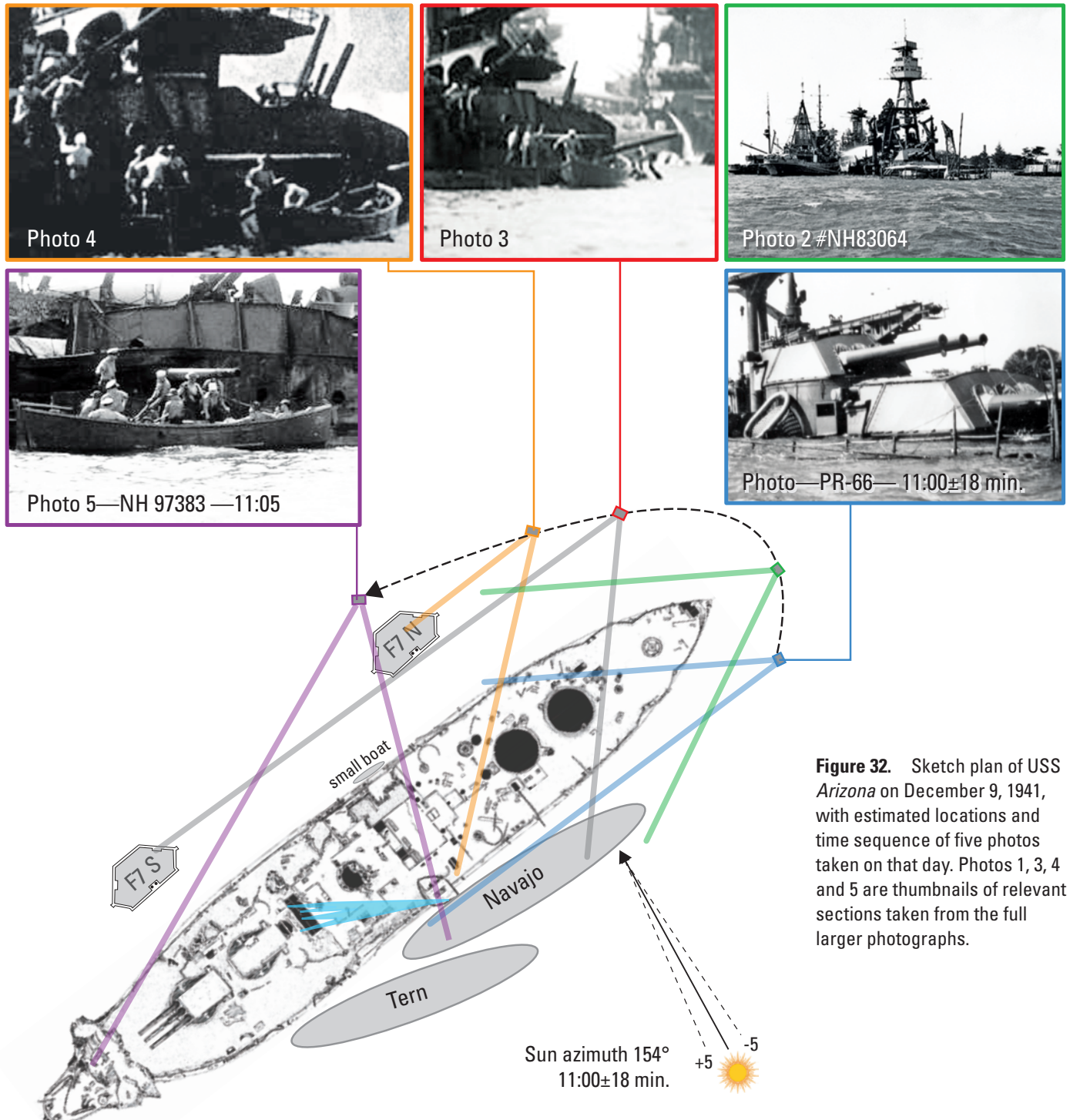


Figure 32. Sketch plan of USS *Arizona* on December 9, 1941, with estimated locations and time sequence of five photos taken on that day. Photos 1, 3, 4 and 5 are thumbnails of relevant sections taken from the full larger photographs.

can be verified. The December 12 photo continues this trend, but that photo contains no distinctive features that have been verified independently. In more recent times, photos from the 1980s and 1990s produce a cluster trending to the latest measurement in 2008. The available photos examined between June 1942 and November 1944 form a grouping and trend that plots “high” relative to the linear regression line of figure 22. If a consolidation trend is extended from the December 9 and 12, 1941, points through the 1942–1944 grouping, an offset or change to a steeper slope occurs when the points in the period from 1950 to present are added. This represents an acceleration in the rate of consolidation for which there would be no apparent cause. This 1942–1944 group does not change the total settlement magnitude.

The “high” MLLW-based elevations of this grouping could be due to interpretation difficulties arising from unrecognized, perhaps multiple, subtleties within the photographs, or possibly the date given for the photograph is not the correct date of the scene in the photo. An additional variable may be interpretations that depend greatly upon diagrams of the ship to establish the sun azimuth. These interpretations are contingent upon how well those diagrams portray the structures of the ship, including their relative sizes and locations. Typically, not all of the important parameters can be equally well determined from any given photo. For example, an excellent azimuth may be obtained from a photo that has poor resolution of vent height. The photo of figure E-6 is an example of an excellent photo for determining vent height, but unfortunately there is no date for the photo nor are there any definitive, useful shadows within it.

In this section a few examples involving official military photographs are examined in more detail and highlight the kinds of difficulties that are encountered when interpreting photographs. These photos are photo 6801-44, dated November 25, 1944; photo 2230-43, dated April 19, 1943; and photo 2540-43, dated May 3, 1943. Barbette 3 vent-top elevations calculated for these dates plot as part of the “high” grouping above the settlement line in figure 22. The events depicted in photos dated April 19, 1943, and May 3, 1943, are identifiable in the Salvage Diary.

Photo 6801–44, Dated November 25, 1944

The state of the physical structure shown in this photo (fig. E-14) can be bracketed in time within a 16-month period between photo NASPH#119574, dated September 20, 1943 (fig. F-7), which shows salvage operations underway with a platform still attached to the port side of barbette 3, and photo PH-244-45 (USS *Arizona* Memorial Museum Archives) dated January 16, 1945 (not shown in this report), showing the newly constructed mooring platform added to the port side of barbette 3 that still exists today. Examination of photo 6801-44 took place with a high-quality 6,045 by 4,909 pixel, 600 dpi scan of an approximately 20 by 25 cm black and white print from the USS *Arizona* Memorial Museum Archives. In the photo, a wood stave cofferdam placed around barbette 4 on

May 6, 1943, as part of the salvage operation is still in place. A casual look at the shadows in the photo indicates that this is a relatively early morning time with a low sun elevation.

Figure 33 is a diagram of sightlines and alignment points derived from photo 6801-44 and plotted on a plan of the USS *Arizona* main deck (modified from Stillwell, 1991, p. 372) to determine the location of the camera. For this photo, the location of the camera is needed to refine the point from which the structures are viewed. Crossing sightlines and their convergence to an area rather than a point suggest that proportions depicted in the plan may deviate from what is seen in the photo. An alignment between a point on the hull at the left edge of the photo and a port aft corner of the upper deck (not visible in the photo) helps define a limit to the camera location. The camera must be located aft of this line. Two independent sun azimuths can be derived from the photo (fig. 33). One is obtained by transferring the terminator on the tubular base of the foreground mushroom-shaped vent to the barbette behind it (barbette 3) by the same proportion of illuminated and shadow areas. On the diagram of the ship, a diameter is drawn from the projected terminator location on the outside of the barbette through the center of the barbette. A perpendicular to this diameter is the sun azimuth. This yields sun ray 1 in figure 33 with an apparent azimuth of $123 \pm 3^\circ$. A second sun ray can be drawn on the basis of the wood walkway extending from the top of the foreground mushroom-shaped vent to the hull (fig. E-14) and is not as sensitive to the camera location. The right end of the handrail on the far side of the walkway produces a shadow on the flat port face of the central mushroom-shaped vent just behind the walkway. This alignment yields sun ray 2 with an azimuth of $124 \pm 2^\circ$. An average sun azimuth of 123° with a range of $\pm 3^\circ$ is assumed for the photo.

The sun elevation, measured at various points on barbettes 3 and 4 and the foreground mushroom-shaped vent, is within the range $25 \pm 1^\circ$. Photograph 6801-44 is an example in which the estimated sun azimuth and elevation are measurable and are incompatible with each other for the date given for the photograph. This situation is independent of any calculations of vent height or elevation relative to the barbette 3 settlement line. The barbette 3 port-side vent top is estimated to be 1.0 ± 0.07 m above the water level in the photograph. The SLR-adjusted elevation of the settlement line for the barbette 3 vent on this date is 0.95 ± 0.05 m MLLW based on figure 22 and drops approximately 0.01 m during the timeline of figure 34.

Using the NOAA Solar Position Calculator and the verified hourly tide data, based on the estimated azimuth of 123° for November 25, 1944, the corresponding time, sun elevation, and tide elevation should be 8:28, 19.6° , and 0.19 m MLLW, respectively. The sun elevation is about 5° too low and the tide level approximately 0.19 m too high when compared to the photograph. The tide is rising during the morning of November 25, and greater estimated sun azimuths lead to higher tide levels and greater deviation of the vent top elevation from the settlement line as the morning progresses.

Based on the estimated sun elevation of 25° for November 25, 1944, the corresponding time, sun azimuth, and tide level should be 8:56, 127.1° , and 0.24 m MLLW,

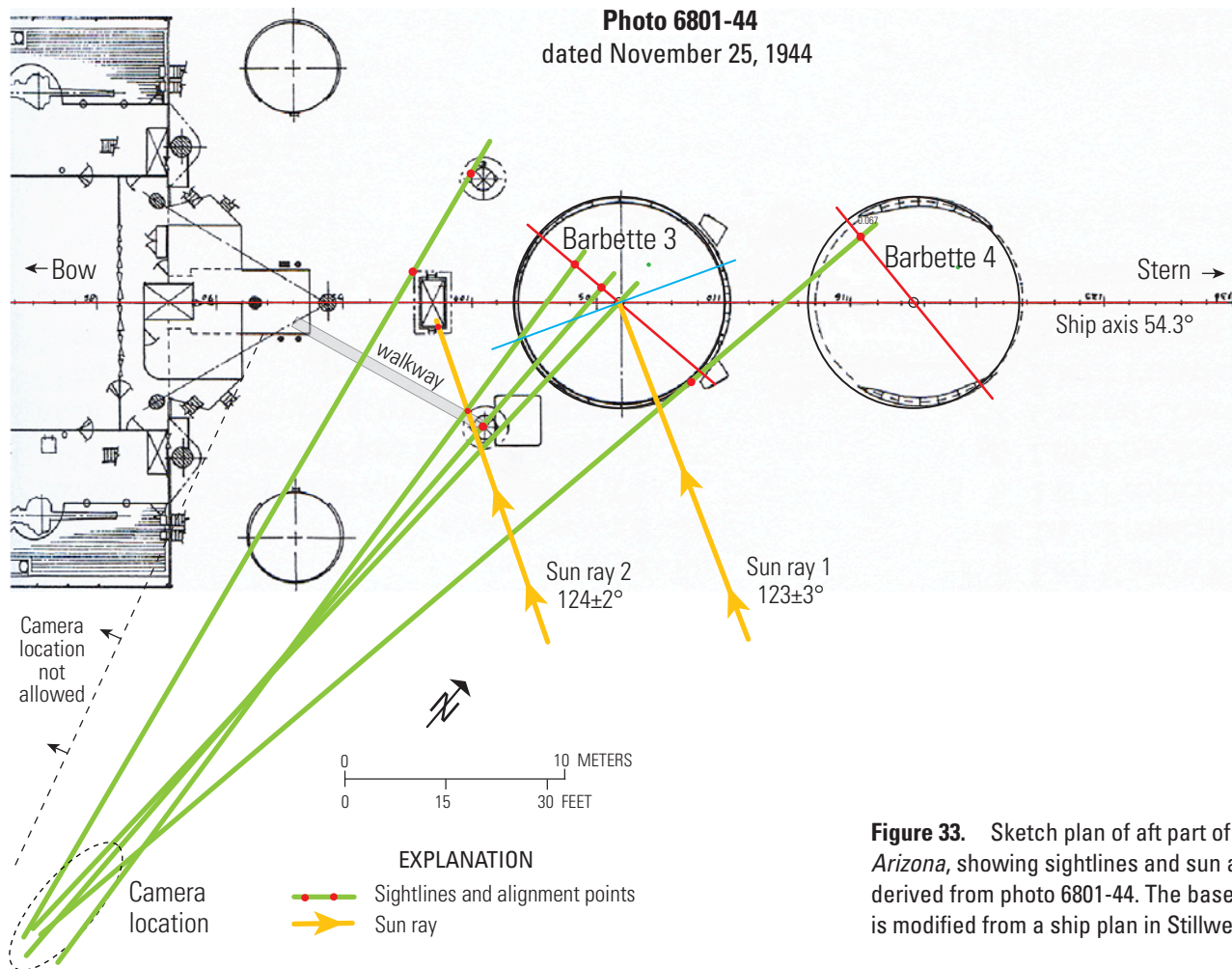


Figure 33. Sketch plan of aft part of USS *Arizona*, showing sightlines and sun azimuths derived from photo 6801-44. The base diagram is modified from a ship plan in Stillwell (1991).

respectively. This sun azimuth is somewhat beyond what has been derived from the photograph and the tide level results in a vent top approximately 0.20 m above the settlement line.

Figure 34 is a graphical compilation of calculations carried out to identify the interrelation of sun elevation, azimuth, tide level, and the barbette 3 settlement line. A range of values is examined that encompasses the likely range of the measured parameters: $\pm 3^\circ$ for the azimuth, $\pm 1^\circ$ for the sun elevation, ± 0.07 m for the height of the vent above the water level, and ± 0.05 m for the elevation of the barbette 3 settlement line.

The process of construction of the diagram is as follows. Based on the azimuth estimation from the photo and using the NOAA Solar Position Calculator, the local time is determined for each day over a range of days around the given date of the photograph when the sun is at the estimated azimuth. For each date, the tide level is calculated from the verified historical tide data at the time determined from the sun azimuth and, for each date, the estimated height of the vent top above the water level in the photo is added to the tide level, then corrected for SLR. This results in the three SLR-corrected, oscillating vent top elevations in figure 34. Also for each date, the associated sun elevation over a range of azimuths is displayed above the

oscillating trends. The solid, gently sloping horizontal red line in the lower part of the figure, with associated elevation range (dashed red lines), is the elevation of the slowly settling vent top for the range of dates shown on the timeline, as determined from the barbette 3 settlement line in figure 22. The barbette 3 settlement line is the elevation trend to which the vent top is expected to conform during the linear consolidation phase of settlement. On this diagram, for any date on the timeline, a vertical line on the plot will link the variables of sun azimuth, sun elevation and vent top elevation expected for that date within the azimuth range shown. Tide levels are obtained from historical, verified, hourly tide level data from the Honolulu Harbor station (ID No. 1612340). The partially irregular forms of the cyclic trends are unmodified, verified tide levels, and their irregularity may be due to local variation of tidal conditions from an ideal sinusoidal tide pattern.

A solution to the vent top elevation discrepancy could involve variations of both the vent height above the water level and the diagram used to analyze the solar azimuth. A lower vent height can be attained by assuming that, at the moment the photo was taken, the trough of a low swell is located at the vent, resulting in excessive apparent height. Alternatively or in addition, the time when the photo was taken may be

characterized by a large deviation of the Pearl Harbor tide level from that recorded by the Honolulu Harbor tide gage. These kinds of deviations were shown in figure 20. The base diagram on which the sightlines and sun azimuths are plotted may contain distortions in the locations and relative sizes of the hull structures that cause a deviation of the estimated azimuth, a situation that is exacerbated by the viewing perspective seen in the photo. Alternatively, the photo may have been assigned a date that was not the actual date the photo was taken, perhaps a result of a delay in the processing of the film or error in annotation of the photograph. In such a case the period of November 11 to 16, 1944, highlighted in red on the settlement line in figure 34, accommodates all of the variables as derived from the photo using the methods of this study.

Photo 2230-43, Dated April 19, 1943

This photograph (fig. E-12) is constrained within a 43-day time period between a preceding photograph dated March 21, 1943 (fig. E-11), and a later one dated May 3, 1943 (fig. E-13). Changes in the structure of the ship due to salvage activities are consistent with this dated photo sequence. The Salvage Diary records indicate that high winds on April 19 delayed the arrival of a 150-ton crane until April 20, when the “upper and middle sections of rotating portion of turret #3” were removed. Photo examination took place with a high-quality 5,680 by 4,580 pixel, 600 dpi scan of an approximately 20 by 25 cm black and white print from the NPS. Photo 2230-43 features a wooden walkway constructed from the top of the starboard-side vent on

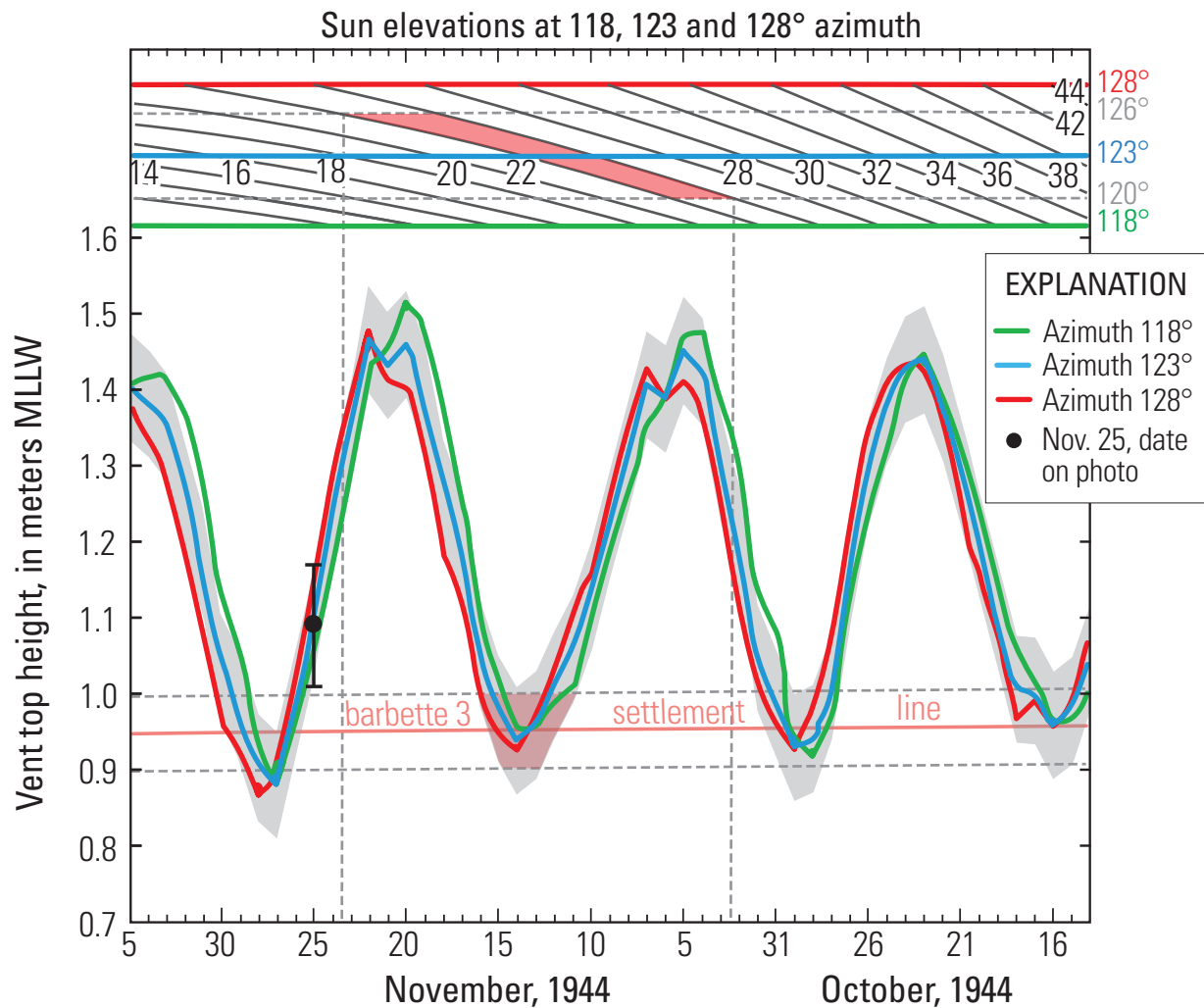


Figure 34. Time plot of sun azimuth, sun elevation, and elevation of the barquette 3 port-side vent top, illustrating solar-tide calculations for photograph 6801-44 (fig. E-14), dated November 25, 1944. The November 25 position of the vent top at a sun azimuth of 123° is shown by the solid black point. The vent top is 1.0 ± 0.07 m above the water level for these calculations. The red highlighted area along the barquette 3 settlement line corresponds to the sun azimuth and elevation values derived from the photo.

barbette 3 along the starboard end of turret 4, which has been rotated toward Ford Island.

The conditions visible within the photo allow for a good estimate of the sun azimuth and thus of the time of the photo. Figure 35 is a diagram of sightlines and alignment points derived from photo 2230-43 and plotted on a plan of the USS *Arizona* main deck to determine the location of the camera. As can be seen in other photos and as depicted in figure 35, turret 4 is not at right angles to the ship axis. The sightlines confirm the camera location, which can also be inferred from the scene in the photo, where the view is directly down the starboard handrail of the walkway.

The port handrail of the walkway adjacent to the starboard side of turret 4 (fig. E-12) casts a shadow on the walkway that is almost directly beneath the handrail. The geometry of this situation is such that, with the sun in the general direction of the bow, when the shadow is directly beneath the handrail, the azimuth of the handrail will be the sun azimuth. The sun is probably within a minute of reaching this orientation, since the sun azimuth is changing at a rate of about one degree per minute, indicating that, for this date and time period, the sun azimuth is a very sensitive indicator of time and tide level. The azimuth of the handrail is estimated to be $219 \pm 2^\circ$. The port-facing edge of the starboard vent top on barbette 3 is estimated to be 1.00 ± 0.03 m above the water level; the primary scale for this determination is the 1.52-m height difference between the vent top and the barbette rim.

Photo 2236-43 dated April 19, 1943 (not shown in this report), taken some moments after photo 2230-43, presumably the same day, shows the upper part of turret 3 removed from

the barbette and hanging over a barge at the port side of the ship. The view is toward the port-side vent of barbette 3, which is largely, but not completely, obscured in shadow below a walkway. This photo seems to confirm the height of the barbette 3 vent top as being at least 1 m above the water. Examination of the height of the barbette 3 starboard-side vent above the water level in photo 2230-43, allowing for the estimated port tilt of the hull, also confirms the height of the port-side vent top.

Although determination of the sun azimuth is straightforward, the sun elevation in photo 2230-43 is more elusive. The sun elevation is high, and an estimate can be made using the configuration of the supports for the handrail and the shadows on their horizontal projections. Because of uncertainties in the lumber dimensions, the elevation is estimated to fall within the range of 77° to 81° . The maximum elevation for the date of the photo is 79.75° at 12:30. The estimated sun azimuth and elevation are, within estimation ranges, compatible for this time and the date of the photograph. The sun elevation is not used for calculations involving this photo, the azimuth being a much more sensitive indicator of time.

Figure 36 is a diagram, as constructed for photo 6801-44, that displays the interrelations of the measured variables relative to the settlement line. At an azimuth of 219° , corresponding times and tide levels for April 19 and 20 are: 13:04 and 0.40 m MLLW, and 13:06 and 0.34 m MLLW, respectively. The barbette 3 vent top settlement trend is at an elevation of 1.11 ± 0.05 m MLLW on April 20 and drops about 0.02 m during the timeline of figure 36.

The SLR-corrected vent top elevation for April 19 is 1.30 ± 0.05 m MLLW. This is the open black point in figure 36 plotted above the April 19 date on the time line, and it is about

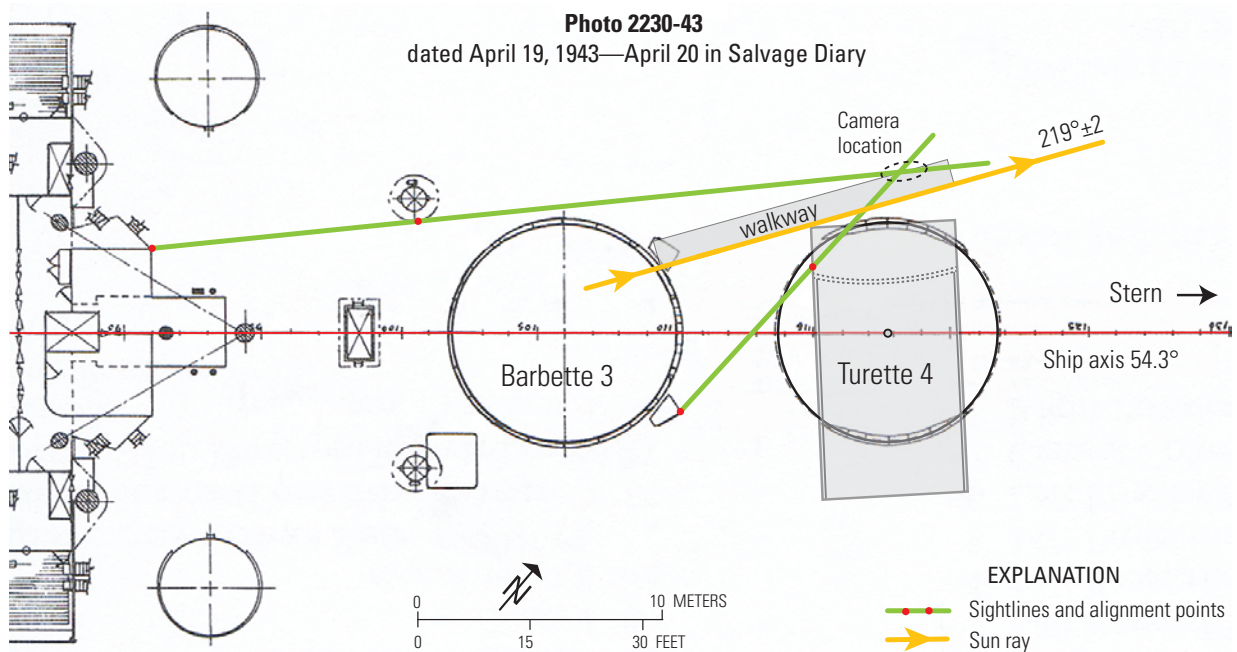


Figure 35. Sketch plan of aft part of USS *Arizona*, showing sightlines and sun azimuth derived from photo 2230-43. The base diagram is modified from a ship plan in Stillwell (1991).

0.19 m above the expected height of the barbette 3 settlement line on this day, as estimated from figure 22. The SLR-corrected elevation for April 20 is 1.24 ± 0.05 m MLLW, the solid black point in figure 36, and this is 0.13 m above the settlement line.

A solution to the discrepancy between the calculated vent top elevation and the settlement line could involve, as for the 6801-44 photo, various combinations of vent height, sun azimuth determination, and tide levels. The sun azimuth for the 2230-43 photo is much more tightly constrained, however, and there are several opportunities to discern the vent height above the water level, which seem to be consistent. As can be seen in figure 36, the date of April 20 from the Salvage Diary plots closer to the settlement line, but uncertainties remain with this photo.

Photo 2540-43, Dated May 3, 1943

High-quality scans of three official military photos dated May 3, 1943, were obtained from the NPS-Submerged Resources Center, and are designated 2538-43, 2540-43, and 2544-43. These photos show the dismantling of a piece of armor on turret 4 and were likely all taken within a short period of time. The Salvage Diary records for May 4, 1943, state: "Removed the 4 side armor plates from turret #4." Like the date offset for the April 19 photo, the event seen in the photo is one day later than the date imprinted on the photo. The reason for this date difference is unknown. Discussion and calculations involving this photo are based on the May 4 date.

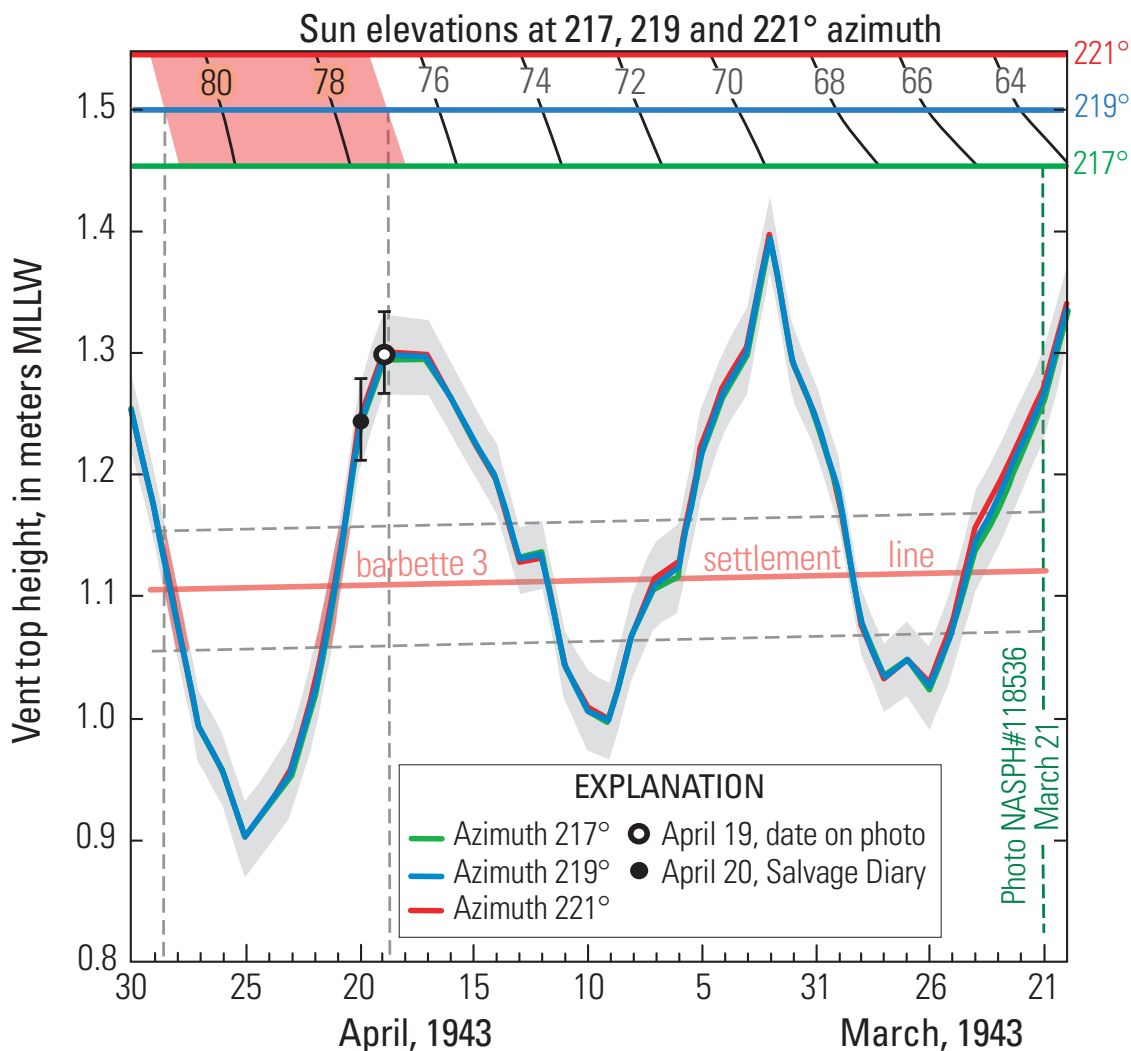


Figure 36. Time plot of sun azimuth, sun elevation, and elevation of the barbette 3 port-side vent top, illustrating solar-tide calculations for the photograph 2230-43, dated April 19, 1943. The solid black point on the vent height trend is the vent top elevation on April 20; the open black point is the April 19 elevation. The red highlighted areas along the barbette 3 settlement line correspond to the sun azimuth and elevation values derived from the photo. Photo NASPH#118536, indicated at March 21, is figure E-11.

Two of the photos also contain within view the port-side vent on barbette 3, and one of these is shown as figure E-13.

The viewing angle and features in the photograph make both the sun azimuth and elevation difficult to measure precisely; however, the sun elevation is high, probably within the range 70° to 80° , as can be seen, for example, from the rivet shadows on the hook block lifting the armor plate, more easily visible in the full-size scan. The maximum sun elevation for May 4 is 84.55° at 12:29. The sun azimuth is estimated to be within the broad range of 104° to 124° , with corresponding ranges of time, sun elevation, and tide elevation for this range of 11:14, 71.5° , and 0.03 m MLLW to 11:56, 80.6° , and 0.14 m MLLW, respectively. In contrast to the difficulty with the sun azimuth and elevation, the height of the barbette 3 vent top above the water level can be accurately estimated at 1.22 ± 0.01 m as determined from photos 2540-43 and 2538-43. The primary scale reference is the 0.74-m-high vent opening. This results in an average vent top elevation of $1.32 \pm 0.04/-0.07$ m MLLW (1.22 m MLLW SLR-corrected). The barbette 3 vent settlement line is at a SLR-corrected elevation of approximately 1.11 ± 0.05 on this date. Using the time and tide level derived from the estimated sun azimuth range, the vent top elevation plots 0.06 to 0.17 m above the barbette 3 settlement trend in figure 22.

A plot similar to figures 34 and 36 was not prepared because the sun azimuth and elevation could not be identified to narrower ranges. At the apparent vent top height above the water level observed in the photos, negative tide levels of approximately -0.06 m or more are required for the vent top elevation to be on the settlement line on May 4, 1943. Tide levels reach a minimum of -0.064 m MLLW on May 4 before about 10:00; however, the sun elevation at these tide levels is less than 55° , incompatible with conditions seen in the photograph. The implication is that there are significant unidentified factors affecting the interpretation of this photo.

Summary and Conclusions

Since sinking on the morning of December 7, 1941, the hull of the USS *Arizona* has been slowly settling lower beneath the surface of Pearl Harbor. Sediment borings and geophysical surveys have identified a varied sedimentary foundation upon which the hull rests. Borings near the bow and starboard side have identified stiff clays and coral debris beneath poorly recovered shallower sediments. In contrast, a boring near the stern contains a thick section of uniform soft clay.

Sediments recovered from the borings were characterized in the lab using multisensor core logger, uniaxial consolidation testing, and fall cone. This testing characterizes dense, overconsolidated clay and coral debris within borings B1/B1A and B3 near the bow and starboard midship, respectively. Boring B2 at the stern contains a continuous sequence of lower density, soft, normally consolidated clay.

Spectral analysis of interface wave testing around the periphery of the USS *Arizona* hull reveals stiff sediment

having higher shear wave velocity (V_s) at the bow and near the starboard quarter and sediment with low V_s velocity along the port quarter. High- V_s sediments are associated with the area of stiff clays; low V_s sediments correlate with the occurrence of soft clay at the stern. The thick sequence of soft clay at boring B2 is modeled to overlie an erosion surface on the stiff clays and form a wedge thickening from midship toward the stern and beyond.

Historical and recent photographs of the USS *Arizona* hull were analyzed to determine the settlement history of the USS *Arizona* hull beginning on December 7, 1941, just 2.2 hours after the explosion that sank the ship. Local time was determined from suitable shadows in dated photographs using sun azimuth and elevation, and from this the elevation of structures on the hull relative to the MLLW tidal datum of Honolulu Harbor was calculated. Settlement trends and hull tilt changes are compiled from the calculated structure elevations. The settlement trends for the USS *Arizona* display two components, an early period of nonlinear initial vessel penetration that ends on or about December 9, 1941, and a long-term, linear trend of normal consolidation that continues to the present.

The early transverse tilt of the *Arizona* from the afternoon of the attack is estimated to be about 0.5° or less to port. The present transverse tilt is about 2° , an increase of 1.5° . The earliest measureable longitudinal tilt of the aft decks is 2.6° forward. The present longitudinal tilt is low, less than 1° , but still forward.

A prephotographic period of initial vessel penetration into the softest upper sediment of the harbor bottom, constrained by water depth and ship dimensions, may have produced as much as 2 to 3 meters of penetration in the forward part of the ship, but these estimated penetrations are scenario-dependent. The estimated settlement of the *Arizona* hull beginning 2 hours after the attack, and adjusted for sea-level rise since 1941, is 1.1 m at the bow, 1.22 m at turret 2, 1.26 m at the midship starboard-side, 2.02 m at the midship port-side, 2.6 m at the barbette 3 port-side vent, and 4.11 m at the stern. The recent rate of settlement of the hull at barbette 3, averaged over the past 10 years, is 3.5 mm per year.

Modeling of the consolidation behavior of the soft clay at boring B2 under the added stress imposed by the USS *Arizona* hull can account for observed vertical settlements by projecting varying thicknesses of the clay beneath the *Arizona* hull. The differential settlement and tilting of the USS *Arizona* hull is a reflection of the varied sedimentary base upon which it rests.

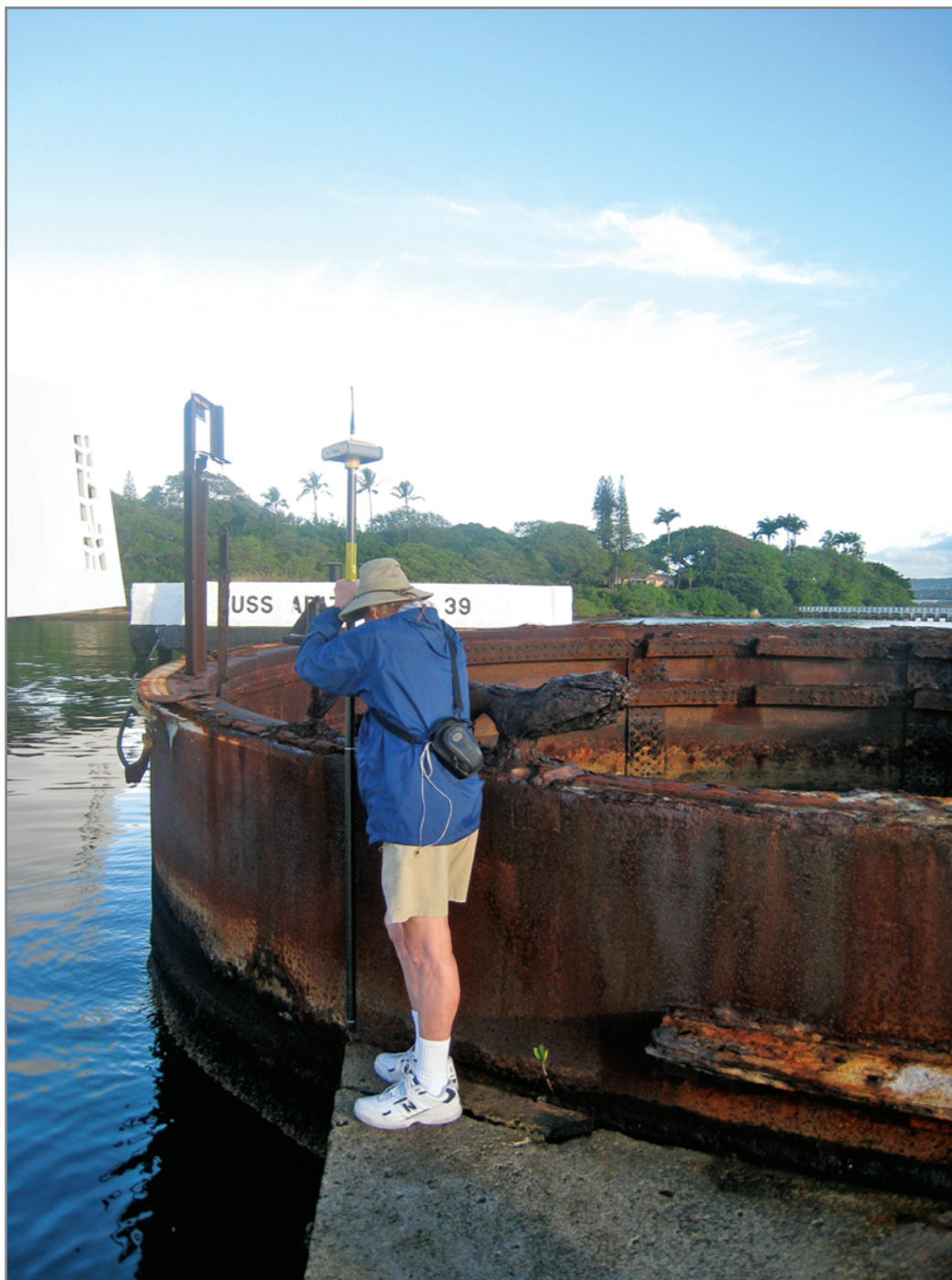
Acknowledgments

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A field assistant making Global Positioning System (GPS) measurements at the USS Arizona on the mooring platform at barbette 3, March 4, 2008. The Memorial structure is on the left.

