MSDL | MARINE STRUCTURES DESIGN LABORATORY

Final Report: Investigation into the Loss of the *H.L. Hunley*

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Abstract: The *H.L. Hunley* carried out the first successful submarine attack in history. However after a successful attack, the submarine disappeared with little evidence has to how it happened. This report documents work on two ONR grants exploring the naval architecture of the submarine. This work was conducted to support high-fidelity underwater explosion modeling of the attack at NSWCCD (not discussed here), but also sheds new light on the final mission and circumstances of the vessel's loss. The vessel's hullform, weights, stability are all discussed, along with model test for the vessel's resistance and potential flooding rates. While the investigation did not reach a firm conclusion the cause of the loss, the results further illuminate the operation of vessel and avenues for further technical study.

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1 Introduction

The night of February 17th, 1864 the seas were calm and the skies were clear, it was the perfect weather the *Hunley's* crew had been waiting for. They departed for USS *Housatonic* with the tide and reached the ship after just a few hours. The crew's mission was to place a lethal charge of black powder on the hull of *Housatonic* and return to shore as quickly as possible. The *Hunley* successfully sank *Housatonic*, making it the first successful submarine attack in history. Having completed the mission, the submarine disappeared into the night, creating a mystery that continues to puzzle the general public for almost 150 years. Many people over the years have tried but failed to recover the submarine themselves and solve this mystery. It was not until August 8th, 2000, when the vessel was finally recovered, and began the preservation process that new details would come to light about exactly how the *Hunley* sank.

A challenge in investigating the loss of the submarine is the lack of basic naval architecture analysis on the vessel. As the recovery and archaeological work has continued, questions about the vessel's operation and potential loss scenarios have become more detailed. To help answer these questions, naval architecture simulation of the vessel's operation become essential. This report outlines initial work on the displacement, trim, stability, propulsion, and damage stability of the vessel. Initially, the methodology followed is outlined in detail. This is then followed by a recap of the historical information that has been gathered on the submarine and its operations. Then a number of potential loss scenarios are outlined, leading to a series of naval architecture investigations. These investigations are presented, followed by conclusions.

2 Methodology

The approach was divided into desk research, field visits, experimental investigations, and computer simulations. A literature review was completed, focusing on historical accounts of the design, construction, two training accidents, and final mission of the *Hunley.* More recent documentation on the discovery, and archaeological investigations was also collected and compared against historical documentation when completing future tasks.

Using the available documentation and archaeological data, a baseline weight estimate was completed using the Expanded Ship Work Breakdown Structure (ESWBS) format. Clear records were kept justifying the calculations to aid in future refinement of the weight estimate. Additionally, point cloud scan data of the hull and internals was used to develop a geometric model of the main hull, ballast system, and key elements of the propulsion system. Completing the weight estimate lead and the vessel geometry allowed a hydrostatics model with internal compartments and tanks to be generated. The model is capable of simulating various flooding and ballast operations through a hydrostatics program. Experimental tests of flooding through damage observed on the vessels, as vessel resistance and propulsion completed the investigations. Based on the investigations, conclusions on the potential scenarios discussed are presented.

3 Background

In order to complete the analysis of how the *Hunley* sank, it is important to understand how the vessel was developed, the events that led up to the attack and historical references that mention the *Hunley*. This section will go through the conception of the *Hunley* to the last known reference of where the *Hunley* was after the attack. This section is a compilation of secondary sources, and is designed to give engineers and Naval Architects a broad overview of the vessel to help place analysis in context. Not all source conflicts or potential interpretations are presented, historically-focused investigations are recommended to read the primary archaeological reports directly. As is standard practice for engineering report, page numbers within sources are not given.

3.1 Historical Context

The *H.L. Hunley* was named after Horace L. Hunley, the principal investor and innovator of the *Hunley*. Horace was deputy collector of customs, as well as a wealthy lawyer and planter. He worked closely with James McClintock and Baxter Watson in the design of the first three Civil War Submarines. James McClintock and Baxter Watson were previously steam engine part suppliers that came up with the idea of an underwater vessel; Horace Hunley joined them in 1861 because he understood the importance of maintaining shipping lanes to Europe [14]. Their first endeavor was the *Pioneer* built in 1861. The *Pioneer* was a 20 foot, three man, hand powered vessel designed to tow a floating torpedo to the target. The vessel had a successful concept test, but was scuttled and later recovered - by the Union Army before being used in the war. The *American Diver* was the next venture in 1862 located in Mobile, Alabama. This vessel was originally planned as a 36 foot steam or electric driven vessel, but the final design was for a crew of five: four to crank and one to steer. The *American Diver* was also designed to tow a torpedo and in 1863 was sent to destroy the Union blockade. However the *American Diver* was too slow to be successful. The submarine ultimately sank under tow in Mobile Bay during a storm. Although there was no loss of life in the loss of the vessel, it was never recovered. The *H.L. Hunley* was the final project of Hunley, McClintock, and Watson. A 40 foot, eight man, hand powered vessel ready to improve upon the previous failures of the team.

The *Hunley* was built in 1863 in Mobile, Alabama. The submarine was shipped by rail to Charleston, South Carolina where she would under go testing. The first test held August 29th left harbor with a new crew of nine. The submarine immediately sank, killing five of the crew members. The reported cause, stated by a surviving member of the flooded submarine, Charles Hasker, was the Officer in charge stepped on the dive plane lever causing the vessel to dive while the hatches were still open [14]. An alternate cause, written into Colonel Charles H. Olmstead's report, was the *Hunley* became entangled in ropes, was drawn to the side and went down [14]. On September 14th, the *Hunley* was salvaged and was readied for additional tests. Between the first and second failure, the vessel did complete several trials successfully returning to port [2]. The second test was held October 15th and departed with a crew of eight, including Horace Hunley. The vessel submerged normally, but after several hours, it was clear that the submarine was not going to resurface. Divers went to recover the submarine and found that it was stuck in the mud bow first at a steep angle. It appeared that Horace Hunley was at the helm when the vessel hit. The reported probable cause was an open valve, that over filled the forward ballast tank and spilled back into the main compartment where it could not be pumped back into the sea [14]. This time the crew had used measures to attempt an escape; The aft tank was pumped dry, and the keel block release bolts had been partially turned. It appeared that six of the crew drowned from the overflow in the forward ballast, while Horace Hunley and Thomas Park tried opening the forward and aft hatches to escape. After the second failure, the vessel underwent maintenance; stuffing boxes were repacked and the compass was replaced [14].

Once the *Hunley* was repaired, additional testing revealed areas of the submarine that could be improved. The towed torpedo configuration proved effective but difficult to control detonation, this provoked the change to the spar configuration around January 10th, 1864 [14]. The crew also discovered that they could be towed a few miles out into the harbor by *David* torpedo boats, then disconnect and go about their mission. Events turned around on January 5th, 1864 when a report was released to the Union Navy from two Confederate deserters that listed the exact details of the *Hunley.* Shortly after, the Union Navy warned all their vessels of a submarine attack, and they responded by placing nets and chains in hope of deterring the *Hunley.* George Dixon, who was now the captain of the *Hunley* moved the *Hunley* from Mount Pleasant to Sullivan's Island. With the current crew configuration, an additional attempt was scheduled for on January 20th. It is unclear if this mission took place and the vessel returned without finding a suitable target, or if bad weather canceled the mission. On February 5th, the final *Hunley* crew was set; William Alexander was called away on business while Wicks returned. Alexander was reportedly replaced by two new recruits. With the crew set, it was time to prove the *Hunley's* worth.

The *Housatonic* was a sloop of war that consistently anchoring around four miles offshore [14]. As one of the closest vessels to the *Hunley's* base, it was either selected as a target or simply emerged as the natural target for the mission. Dixon's plan was to wait for calm seas, then attack, signaling back to shore with a signal, (reportedly a calcium light but no such device has yet been found on the vessel), once the mission was complete. Dixon and his crew began their preparations on the afternoon of February 17th, they had the calm seas they were waiting for, and the time was right to attack the *Housatonic.*

Understanding the context of the *Hunley* is important to determine how the vessel evolved with testing. Elements such as the spar added more additional control of the torpedo, while the compass proved to be prone to breaking under extreme scenarios (having to be replaced at least two times in the life of the vessel [14]). Observing how the vessel previously sank will provide important details about how the *Hunley* sank on the final mission. Knowing that the dive plane lever was sensitive enough to cause the vessel to dive into the ground within seconds if bumped; or an open valve could cause the forward ballast tank to flood over faster than the ballast pumps could handle are both important clues to the behavior of the submarine.

3.2 Timeline

Every witness of the *Hunley* attack on February 17th, 1864 recalls approximately the same events with varying level of detail. This section will combine these accounts to present the entire picture until the *Hunley's* disappearance. At 7:00pm the *Hunley* was loaded pierside and started the journey to the Union blockade [7, 14]. At 8:40pm, the *Hunley* was spotted by the forward lookout of the *USS Housatonic* approximately 400 ft away. A secondary crewman spotted the *Hunley* at 300 ft around 8:45pm. Just before 9:00pm, the *Housatonic* identified the *Hunley* as a threat and the crew was given the order to slip the anchor and fire up the boilers. The reported blast was just before 9:00pm. The *Housatonic* sank between three and five minutes later, settling on the bottom of the harbor at 9:00pm [7]. Colin and Russell the *Hunley* as ramming the *Housatonic* as almost three hours after leaving shore, which would place departure at 6:00pm, but they do not cite a source [5]. Others state that the sinking time as 8:45pm and 9:00pm based on the accounts of different Officers stationed on the *USS Canandaigua*, the vessel to respond to the attack of the *Housatonic* [13]. William Alexander suggests that based on previous operating conditions the *Hunley* ran under the water while surfacing periodically for air replenishment and to navigate [2].

The details of the events that followed are scarce and pieced together from naval court inquiries. The *Housatonic's* crew released two life boats saving most of the crew, while five men are believed to have died in the incident. While the *Housatonic* was under attack, several accounts state that the *Hunley* was under rifle fire until the explosion. One account from Charles Craven, a crewman aboard the *Housatonic*, suggests that a 32 pound gun was loaded and aimed at the *Hunley* but was never fired because of the torpedo blast [14]. It is aslo believed that the sub was too low and close to the vessel for the heavy guns to depress sufficiently to aim at the submarine. The United States Navy Board of Inquiry after the incident, as well as additional crew testimonies, suggests that the *Hunley* was closer to the *Housatonic* than was originally planned. From Sullivan's Island, a report was recorded as having seen the blue light confirming that the vessel's mission was complete and they would be returning [14]. Records also show that the blue light was spotted from the rigging of the *Housatonic* [13, 14]. On February 19th, a report was filed by the Commanding Officer of Sullivan's Island, General Ripley, that they had not heard from the *Hunley* and he fears the vessel was captured or sank. On the same date from the Union side, a report was sent to the Union blockade stating to be weary of similar attacks such as the *Housatonic* [13]. On February 29th, *The Daily Courier* published on that the *Hunley* returned safely. On March 7th, the Union Naval Court of Inquiry released a statement about the sinking of the *Housatonic* but made no reference to what happened to the *Hunley.* On March 10th, the *Hunley* was officially considered lost [13].

Now that the timeline has been established up until the *Hunley* was officially considered missing, historical records will be discussed in order to list any clues leading to the *Hunley's* disappearance.

3.3 Brief Description of the Vessel

Based on the actual vessel remains, the vessel today is becoming better understood. See Appendix A for a brief discussion of several important historical sources, some of which have been proved accurate and others of which are now known to be in error. Additionally, recent work on the reconstruction of the vessel has recently been published [16]. The vessel itself consists of three main regions: a bow section, stern section, and a mid-body region. Overall, the vessel is 40 feet long, 3 feet 6 inches wide, and 4 feet tall. The oval mid-section appears to be formed by adding a flat expansion plate to a circular pressure vessel, with roughly straight bow and stern sections tapering into a large castings, which formed a vertical stem and stern profile. A historical painting of the complete vessel that has proven fairly accurate is shown in Figure 1.

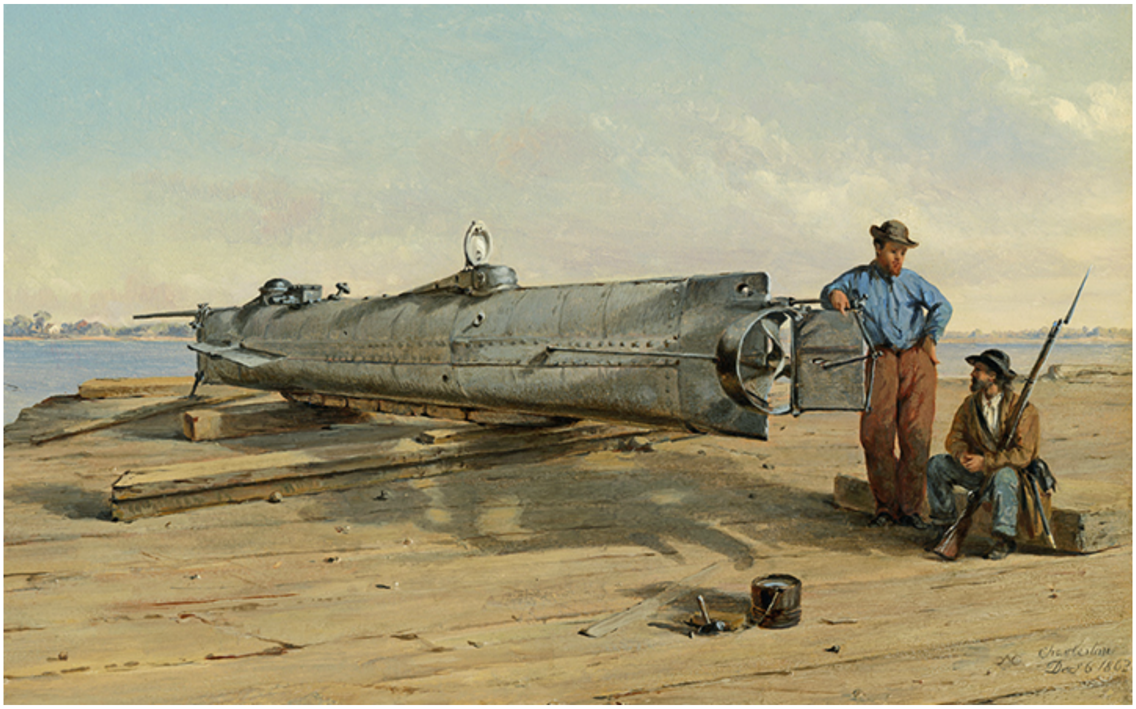


Figure 1: 1863 painting of the vessel by Conrad Chapman

The vessel's structure is reinforced by internal frames, typically split into two half-ovals (presumably for installation) and then pressure fit into the oval midbody. The vessel has numerous appendages:

- Two hatch towers, fore and aft, that served for crew entry/exit, with the forward one also used for conning the vessel. They are approximately circular with portholes for visibility. It is believed each had cutwaters in front of them.
- A snorkel box aft of the fore hatch, which had tubes and a simple mechanism for air exchange without fully surfacing.
- A box keel with detachable ballast weights along the bottom centerline.

- A set of forward dive planes. These were long and narrow plates mounted on a pivot, and their angle could be controlled from within the sub.
- Propeller, propeller shroud, rudder, and supporting brackets and control rod near the stern,

Internally, the vessel features two ballast tanks, one fore, one aft. Each is separated from the main centeral compartment by a partial bulkhead, with space at the top to allow air exchange (and also allow the possibility of progressive flooding into the central compartment). Each was equiped with a fill line, and connected to a pumping system for emptying. Aft of the forward ballast tank was the commander's station, with controls for the dive planes, rudder, and basic instruments. Aft of the commander's station, seven additional crew members were housed along a long crank which turned the propeller. The crew members turned the crank with their arms, and had a small bench to rest against. The crank went through a set of gears, and then exited the vessel aft to turn the propeller. Permanent ballasting was installed throughout, using various sized iron blocks. The combination of the iron ballast and the variable water ballast would allow the vessel fully submerge, or run in a semi-submerged mode with the top of the hull awash and only the hatch towers and snorkel box above the water. The vessel originally was designed to tow a large charge behind it, diving under the target ship and running the charge into the vessel. However, it was modified to use a charge attached to a spar arrangement in front of the vessel, which it would ram into the vessel. This was similar to the setup used by the small David boats, another asymmetric attack vessel employed by the Confederacy [11].

3.4 Features of the Attack Site

In addition to understanding the features of the *Hunley*, the characteristics of the attack site are also important. This section will outline historical accounts of the harbor and weather conditions surrounding the attack.

A report prepared by Executive Officer Higginson of the *Housatonic* suggests what weather conditions the *Hunley* was up against the night of February 17th. He states there was a force 2 North West wind, and the *Housatonic* was anchored in about 28 feet of water. Their relative position was about 6 miles from Fort Sumter and 2.5 miles from Sullivan's Island. From his testimony after the attack he states the *Hunley* was approaching at 3 or 4 knots, targeting just forward of the mizzen mast on the starboard side. He stated the *Housatonic* was attempting to escape, having had the engines fired up and the anchor cable slipped, at which point the torpedo had exploded.

The official report released by the Naval Officers presented with the case of the *Housatonic* lists certain details as follows. They state the *Housatonic* sank around 9pm on February 17th. She was anchored in 27 feet of water, with a bearing that was east south-east about 5.5 miles off the coast of Fort Sumter. The weather was listed as being clear, with bright moonlight and a moderate northward and westward wind, the tide was at half ebb. A floating object was discovered between 8:45pm and 9pm by a lookout stationed on the starboard side, about 75 or 100 yards out that appeared to be a log. The object was listed as having a speed of 3 or 4 knots in the direction of the starboard quarter of the ship. Gun fire was opened on the vessel until the *Hunley* came into contact with the starboard quarter.

Multiple reports suggest that the blue light had been spotted from the *Housatonic* and the troops at Sullivan's Island. The Officer in charge of Sullivan's Island at the time reported that the agreed upon signals had been shown, and they responded by exposing a light on shore that would allow the *Hunley* to return safely. Evidence that the troops could indeed see that far out to sea is provided by McLaurin stating that they could see the commotion of frantic signaling between the blockade vessels.

The pre-disturbance survey completed before recovering the *Hunley* presents important information about the location and orientation of the submarine. The vessel was sitting in approximately 30 feet of water orientated with the bow at 297 degrees relative to magnetic north, which points it almost directly at Sullivan's Island. The *Hunley* was located about 4 nautical miles from the coast of Sullivan's Island, under three feet of sediment. The vessel was canted about 45 degrees starboard. This location is presented in Figure 2.

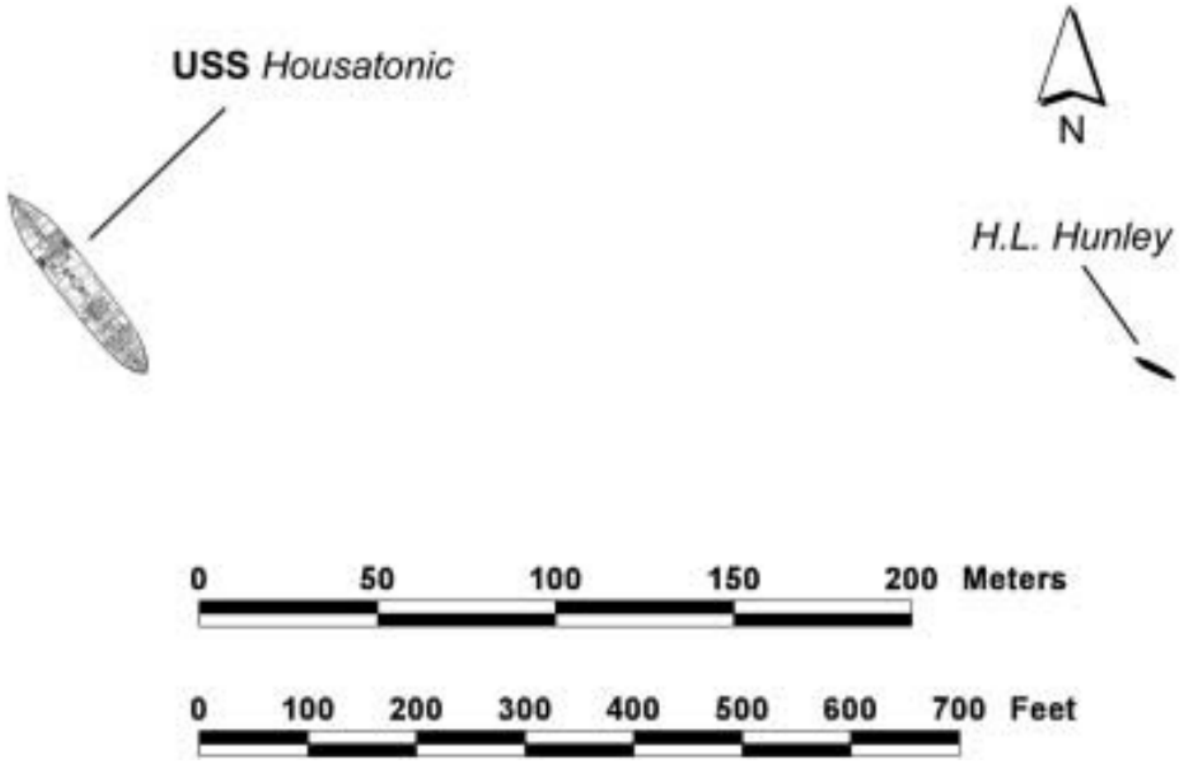


Figure 2: Relative location and orientation of the *Housatonic* and *Hunley*

In addition to the pre-disturbance survey, a site map was completed to help layout the battlefield and how it changed over time. This survey produced four objects: The *Housatonic*, the *Hunley*, the third anomaly which is a buoy, and a fourth anomaly which is an anchor and chain. Figure 3 below presents the layout of objects based on a magnetometer reading.

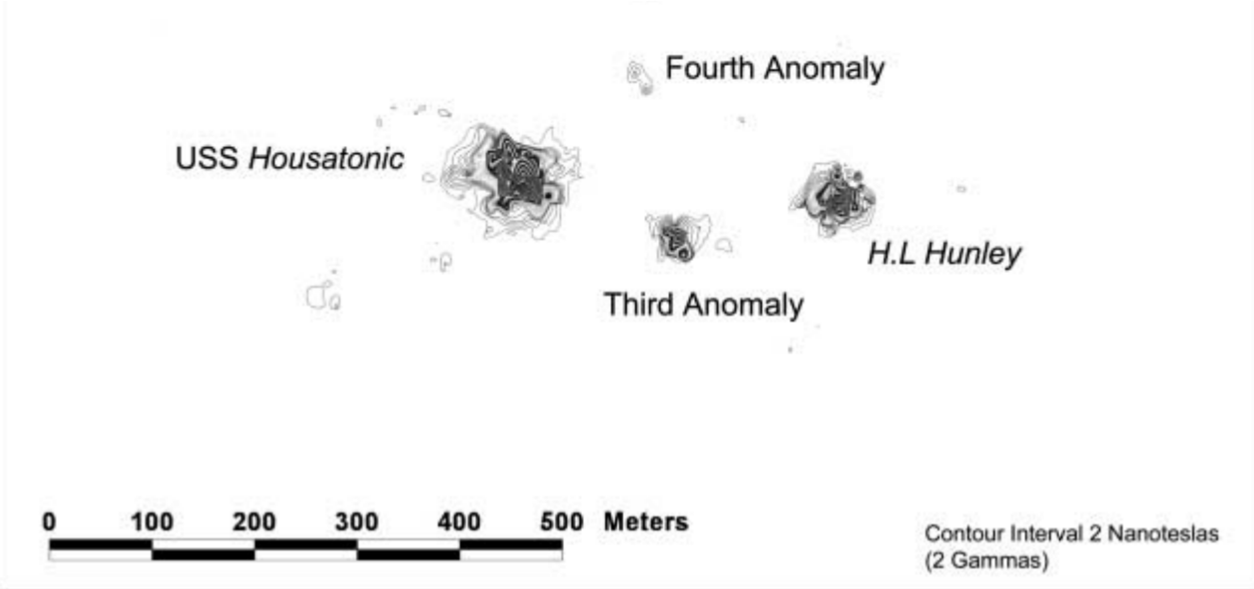


Figure 3: Magnetometer reading of the battle site completed in 1998.

In 1864, nine months after the attack, investigators were instructed to drag an area of 500 yards around the *Housatonic* but found nothing of the *Hunley*. In 1872, the Army Corps of Engineers were contracted to remove the *Hunley* wreck and clear the *Housatonic* wreck to 20 feet below the water line; the *Hunley* was also not found during this mission. A coastal survey also shows a navigation buoy was placed at the location of the wreck (third anomaly in Figure 3). In 1909, the *Housatonic* was again deemed a navigation hazard, and another six feet of hull was removed. Records indicate that the hull was cut down to be even with the seafloor [5]. In 1872, a South Carolina Coast survey shows that a buoy was initially marking the *Housatonic* as a navigation hazard, however when the wreck was cut flush with the seafloor, the buoy was cut as well. When comparing this position to the coastal survey, the buoy was measured as 430 feet away from the *Hunley's* current location, and 915 feet from the current location of the *Housatonic*. The forth anomaly is an anchor with the chain pointing to the *Housatonic*; However, the entire length was not recovered, and it is deemed unrelated to the battle site [5]. In 1877, to control the flow of sediment coming from the river, construction on two jetties was started. These were completed in 1895 ultimately affecting the sediment distribution over the *Housatonic* and *Hunley*. The sediment distribution change timeline is not precisely known, but overall it supports the recovery timeline [5]. Figure 5 presents the relative location of the *Housatonic* and *Hunley* to the jetties and Sullivan's Island, while Figure 4 shows the channel before the jetties were constructed.

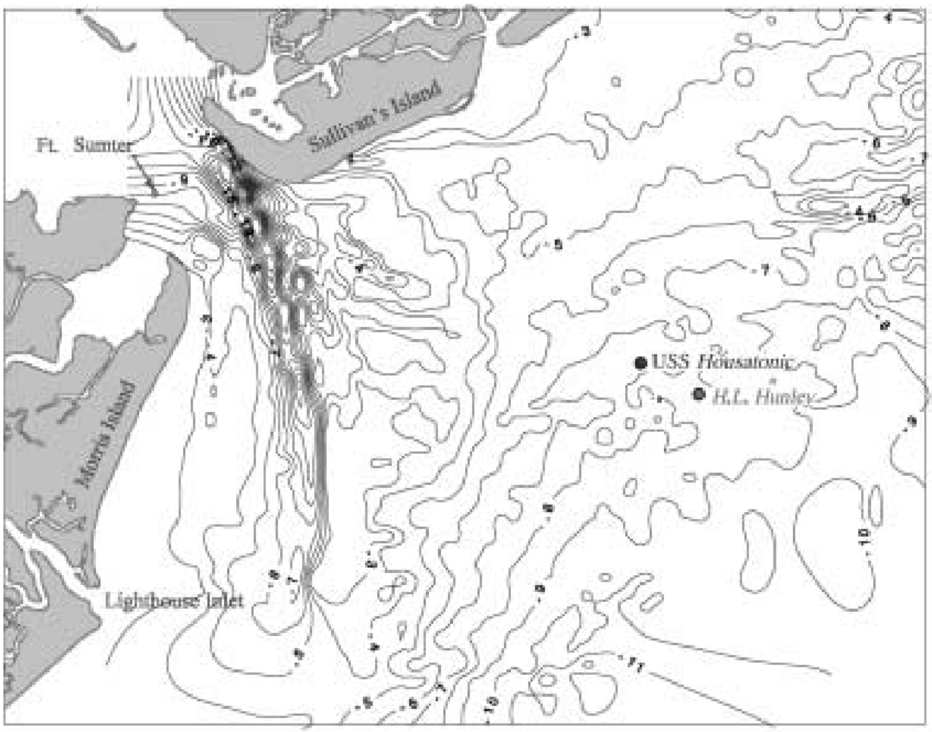


Figure 4: Relative sediment flow presented prior to 1877 when the jetties were constructed

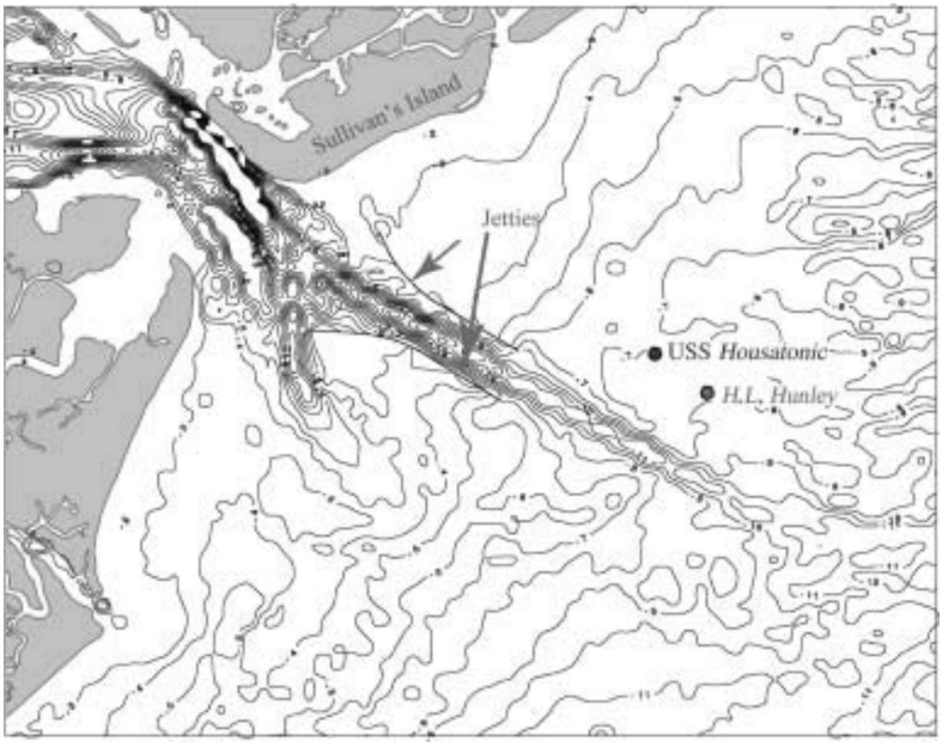


Figure 5: Relative sediment flow presented in 1990

It can be determined from the battlefield survey that the attack was a precision maneuver. Witnesses on the *Housatonic* reported that the *Hunley* changed direction after surfacing, aiming for the vessel's mizzenmast and the vessel's stern with its overhanging counter. It is also possible that the *Hunley's* crew knew the layout of the vessel, and that the weapon storage magazine was located around the mizzenmast, which would cause the most damage if hit properly. The hull had a sharp deadrise which would be in the *Housatonic's* blind spot, giving the crew ample time to place the torpedo. The final resting place of the *Housatonic* and *Hunley* are about 1000 feet apart, with the bow of the *Hunley* pointed 297 degrees, and the *Housatonic* is angled at 316 degrees; Both are pointing towards the general direction of the ebb tide. Two eye witnesses, one crew member of *Housatonic* and one of the response crew reported seeing a blue light signal. However, it is not clear if this was from the *Hunley*, another source, or not related to the action as others did not report the light. If this was the *Hunley*, it would indicate that the vessel was on the surface roughly 50 minutes after the attack. One source [5] makes note that the *Hunley* crew would have to expend significant energy to stay close to the *Housatonic* for 50 minutes after the attack, and mentions that they may have anchored to pass the time. How the crew may have anchored, and the adjustments to the submarine's trim and buoyancy to carry this out are not clear. No anchoring arrangements have been found on the submarine to date, though a small grapple anchor was found near, but not inside or connected to the submarine. The origins, and relationship to the sub, if any, of this anchor are unclear. It could have been carried by the submarine, or may also have been a grapple anchor used to try to locate the submarine after the loss by the Union Navy.

4 Scenarios

To help focus the investigation, a number of potential scenarios for the loss of the vessel were assembled. The scenarios in which the *Hunley* sank have been presented in different sources throughout history. Many scenarios also came about after the *Hunley* was recovered and new evidence was found on the hull.

In 1864, there was very little known about how to properly design a submarine, therefore trial and error was used when designing most of the components of the *Hunley*. This meant several design characteristics that could lead to the *Hunley's* own demise. The first characteristic brought into question is whether or not the vessel was underpowered, and unable to fight the tide back to shore; or if it was inefficient enough that the crew tired too quickly to power the vessel back. Very few historical references show the exact numbers in terms of velocity or range of the vessel, so the scenario looking to be answered is: was the *Hunley* too underpowered to fight the tide, and drifted until it sank? This theory is supported by James McClintock believing the tide was strong, and they drifted for a few hours before ultimately sinking [12].

Most common theories revolve around the *Hunley* being damaged in the attack. Upon recovery of the vessel, a grapefruit sized hole was found in the forward man hatch that could be from the *Housatonic's* counter attack [12]. Was this damage caused by small arms or rifle fire from the *Housatonic*, and was it enough to cause significant flooding of the *Hunley's* hull? The second damage that was uncovered with the recovery, was a sheared pipe for the intake valve of the forward ballast tank. Is it possible to determine when the pipe seperated from the hull fitting, and is the flow through the opening enough to cause the *Hunley* to become unstable and sink? The final evidence that was found upon recovery was a detached rudder sitting beneath the hull. Was the rudder damaged during the attack to the point is was not operable and finally detached when the vessel settled to the sea floor?

Two scenarios were uncovered about the torpedo explosion that may have compromised the vessel, without actually causing any damage to the hull itself. First consists of the vessel's crew being knocked unconscious from the blast. This might have caused them to drift, until natural leaks in the vessel or another source of flooding caused the vessel to sink. The second scenario comes from the blast causing instability in the vessel. Was the blast such that enough water from the ballast tanks made it over the bulkhead to cause dangerous instability and near instantaneous sinking?

The final set of scenarios comes from the *Hunley* surviving the attack, but unable to survive the return journey. The first scenario consists of a successful attack, but upon opening the forward hatch and signaling to shore, a wave came over the hatch and sank the vessel. The second survival scenario was to retreat a safe distance from the attack site, then wait on the sea bed, until it was sufficiently safe to return to shore. While waiting, it is possible the vessel got stuck in the seabed, or the crew died from lack of oxygen. The third scenario consists of the *Hunley* intentionally grounding the vessel to hide the secrets of the submarine from the Union Navy. Finally, A historical report from William Alexander suggests that the attack was successful, but upon trying to retreat the vessel was stuck underneath the *Housatonic*, and dragged to the bottom in the rapid sinking of the vessel [2]. The recovery of the vessel some distance from the *Housatonic* makes this less likely, though the vessel could conceivably have been damaged but managed to escape the sinking site.

The complete list of feasible scenarios gathered are presented in Table 1.

Table 1: List of analyzed scenarios

No.	Description	Notes
1	The *Hunley* was underpowered and unable to fight the tide to shore	Will be investigated by studying resistance and propulsion of the vessel.
2	A grapefruit sized hole in the forward hatch caused significant flooding	Not investigated in current work. Sea was calm and this hole is above the still waterline, so flooding from this hole would have been slow.
3	The sheared ballast pipe caused enough flooding to cause instability and ultimately sinking	Will be investigated along with combinations of scenario 5
4	The broken rudder caused sufficient loss in control that the *Hunley* drifted till it sank	Not investigated in current work.
5	The crew was knocked unconscious from the blast, and drifted until natural leaks or other flooding caused them to sink	Investigated by NSWCCD, explosion alone did not seem to be severe enough to fully disable crew.
6	Significant instability caused by water flooding over the bulkheads from the ballast tanks caused the *Hunley* to sink	Partially investigated
7	Upon signaling a successful attack, a wave came over the forward hatch causing the vessel to rapidly downflood	Not investigated in this work
8	The *Hunley* crew retreated a safe distance and waited on the bottom, dying from asphyxiation	Not investigated in this work
9	The *Hunley* crew intentionally grounded the vessel to hide the secrets of it construction from the Union Navy	Not investigated in this work
10	The *Hunley* was unable to back away from the *Housatonic* after the attack, and was trapped underneath the hull of the *Housatonic*	Not investigated as does not fit with the battlefield archaeology. Possibly combinable with 4, which might have happened after the attack

As the scenario list developed, a few scenarios seemed the most interesting to investigate. Little concrete speed evidence is currently available for the *Hunley*, with archival sources giving top speeds in the 3-5 knot range, but both Alexander and McClintock expressed reservations on the vessel's ability to fight the tide back to shore. Thus, scenario 1 was selected for further analysis. The new discovery of the broken pipe which led to scenario 3 indicated that this scenario would be worth exploring, along side the work of Naval Surface

Warfare Center Carderock in investigating the impact of the blast on the occupants of the submarine. If the blast disabled the occupants, and the vessel drifted while flooding, much of the current battlefield archaeology would be explained. These scenarios were selected because the authors believed at the start of this project that they are among the most likely to explain the sinking and are among those where engineering analysis could produce the most new information. This is not to say that the other scenarios have been completely eliminated. Some scenarios, especially scenario 8, are virtually impossible to disprove at this date given the information that has survived the 150-year plus since the sinking. Thus, the work outlined here focused on gathering information and analysis for discussion of scenarios 1, 3, and 5, with the hope that some of this work will be transferable to other scenario investigations.

5 Analysis

Having chosen three of the most likely scenarios, additional analysis can be completed to discuss the cause of the *Hunley* sinking. This section will outline how drift forcing, powering calculations, and the time to flood analysis was completed to supported the selected scenarios.

5.1 Model Development

Two models were necessary to complete the required analysis: a geometry model, and a hydrostatics model. The geometric model was developed in RhinoCAD and was primarily used for the weights estimation. Relying on accuracy from volume estimation, was critical for parts that currently do not have a recorded weight. The hydrostatics model was completed in General HydroStatics (GHS) and used primarily to determine flooding characteristics and principle hydrostatics.

Early in the process after the recovery of the *Hunley* a laser scan was taken of the exterior and interior of the submarine. The model was developed using primarily the exterior laser scan. The hull surface was fit using least squares of 2D sections at multiple points along the hull, while known measurements were used to set incomplete curvature. Items such as the propeller, which was heavily concreted, relied on sketches from the initial recovery, and best guess curvature based on some of the laser scan data. The final exterior model is shown in Figure 6.

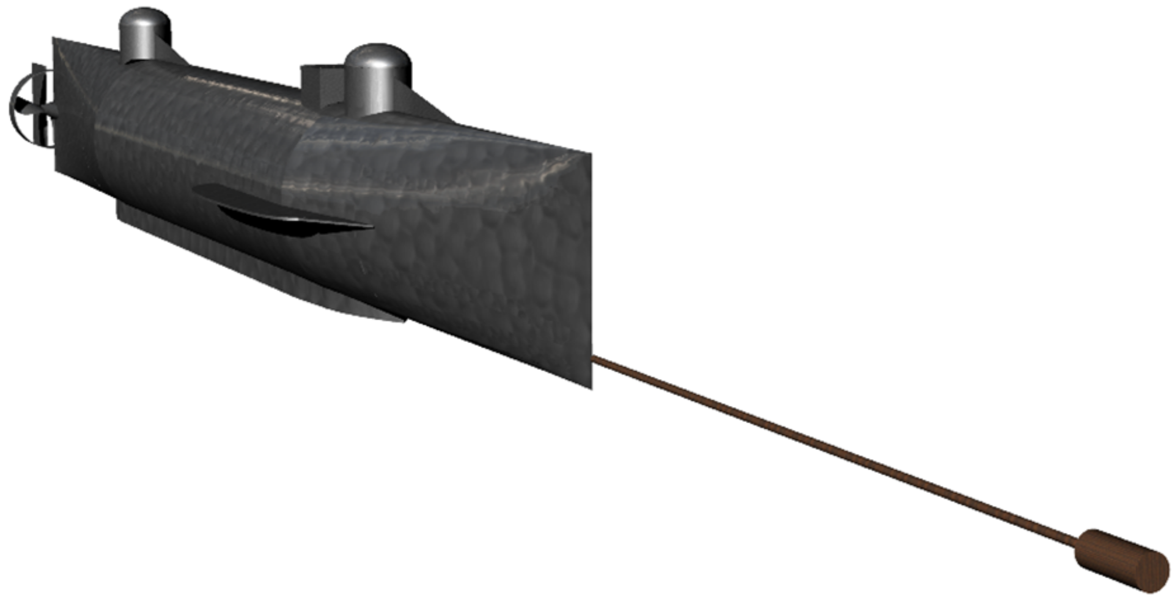


Figure 6: CAD model estimated from laser scan data

Major interior components that have not been removed and weighed were modeled far enough to get a volume estimation and therefore weight. Items such as the crank shaft, and fly wheel are sized to the correct dimensions with assumptions of shape based on recorded pictures. Piping was estimated using small measured sections, and approximated based on hand drawings [15, 8]. Ballast blocks were sized based on the air calculation report provided by Clemson [9], placed based on the laser scan, and corrected for overall geometry.

The Hydrostatics model was completed using the exterior of the geometry model. It does not account for any interior modeling, only the final weight estimate and location of major interior components. The GHS geometry file consists of the outer hull structure, conning towers, snorkel box, bow planes, cutwaters, propeller assembly, rudder, forward and aft ballast tanks, spar, and powder keg. The model geometry omits all vessel particulars that are not relevant in the context of the *Hunley's* hydrostatic characteristics. The final geometry file was discussed with Mr. Brian Thomas, a Professional Naval Architect/Salvage Engineer and GHS expert at the U.S. Coast Guard Marine Safety Center. Figure 7 below presents the final GHS model.

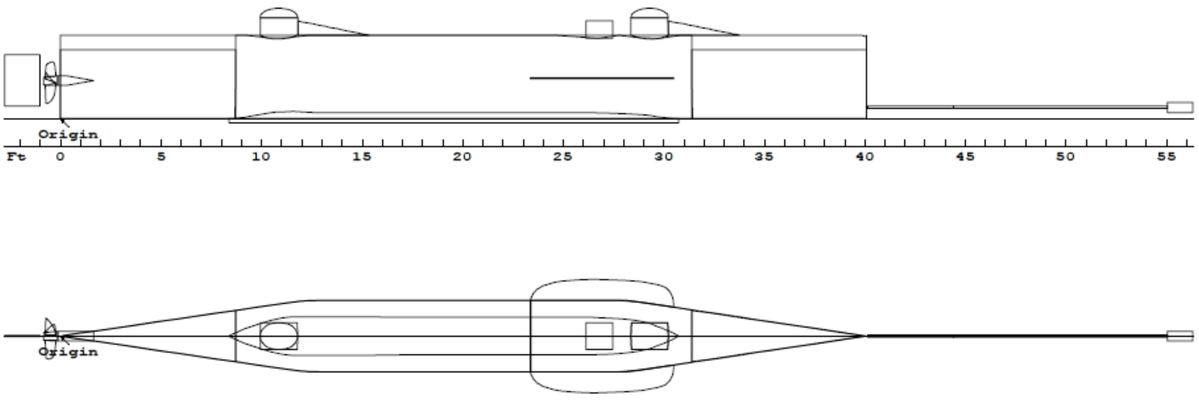


Figure 7: Final GHS model based on exterior geometry

5.2 Weight Estimation

The weight estimation was the first step to determining if the vessel would float appropriately with the displaced volume of the geometry model. Once the vessel has the expected displacement and trimming characteristics, further analysis can be completed. The estimate was completed by stepping through from the largest components such as the hull plating and keel ballast, to the smallest components and recorded using the Expanded Ship Work Breakdown Structure (ESWBS) format.

A sample of plate thickness measurements were used to average the hull thickness to 0.29 inches of rolled wrought iron. The iron density used caused significant variation in weight, so the density was calculated multiple ways. The first was to take the known weights of hull plating [17], and using the model geometry estimate the density, which produced a value of 17.53 slugs per cubic foot. The second was to determine period accurate iron properties based off of the element make up [3] which produced values between 14.82 and 15.11 slugs per cubic foot. The final approximation was to compare the currently accepted standard iron density of 15.04 slugs per cubic foot. Using each of these values, the hull structure weight varied by 17 percent, the chosen value which brought the model into a reasonable ratio of displacement to weight was the average of the iron density completed by the element make up study, with a value of 14.96 slugs per cubic foot. With iron density set, the hull weight was estimated at 5.06 LT. In addition to the exterior shell plating, hatch covers, dive planes and keel block seen in Figure 6, the interior iron components shown in Figure 8 were included as well.

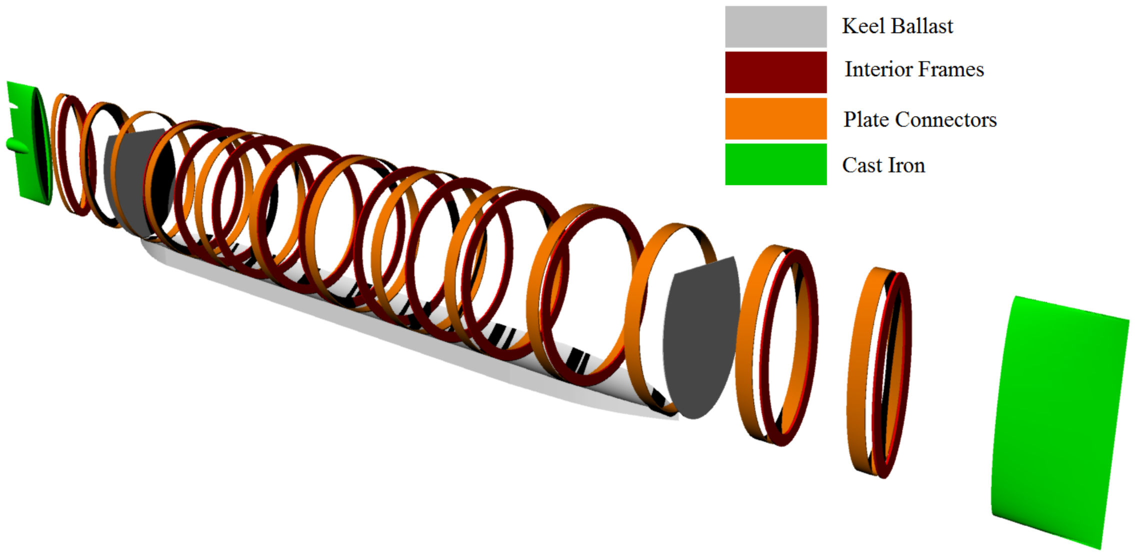


Figure 8: Interior components of hull structure.

The second largest weight was the interior ballast which was known to be made of pig iron. All of the individual blocks were weighed upon removal of the vessel, and recorded along with their overall dimensions [9]. To help verify the selected density of pig iron, the weight and dimensions of the ballast was compared to the 1864 density based on element make up [3]. By completing this, it will also verify the accuracy of iron density previously selected. By element make up, the range of pig iron is between 14.36 and 14.86 slugs per cubic foot. The value calculated from the recorded weight and geometry of the ballast blocks was 14.43 slugs per cubic foot, which is within the expected range. This density comparison was used as only to verify the method used to calculate the weight of the hull. The weight used for the ballast blocks in the estimate are discrete weights taken after the ballast was removed from the submarine and cleaned.

The solid ballast block configuration used in the weight distribution is based on a complete inventory of artifact characteristics developed during excavation. Block locations are based on a three-dimensional laser scan of the interior of the hull; both the inventory and scan were provided by Clemson. The scan was taken with the *Hunley* in its sunken condition with a 45 degree heel to starboard. Given the need to shift the laser-scanned block configuration to fit within the upright computer model, and since it is impossible to know how blocks may have shifted during and after the attack, it was necessary to make assumptions in identifying the transverse and vertical locations of each block. It was assumed that the blocks were largely undisturbed longitudinally as they were held in place by the vessel's framing.

The blocks were arranged according to compartment and weight into four ballast groups: permanent solid ballast in the forward ballast tank, permanent solid ballast in the aft ballast tank, permanent solid ballast in the main compartment, and movable solid ballast in the main compartment. All ballast blocks greater than 70 pounds were considered permanent, as it is improbable that the crew could manually move these blocks once at their stations. In contrast, all ballast blocks 70 pounds or less were considered to be movable, as it is realistic to assume that the crew could move these blocks to adjust the heel and trim of the vessel throughout their voyage. The total weight of the ballast is 2.27 LT. The distribution of weight is shown in Figure 9.

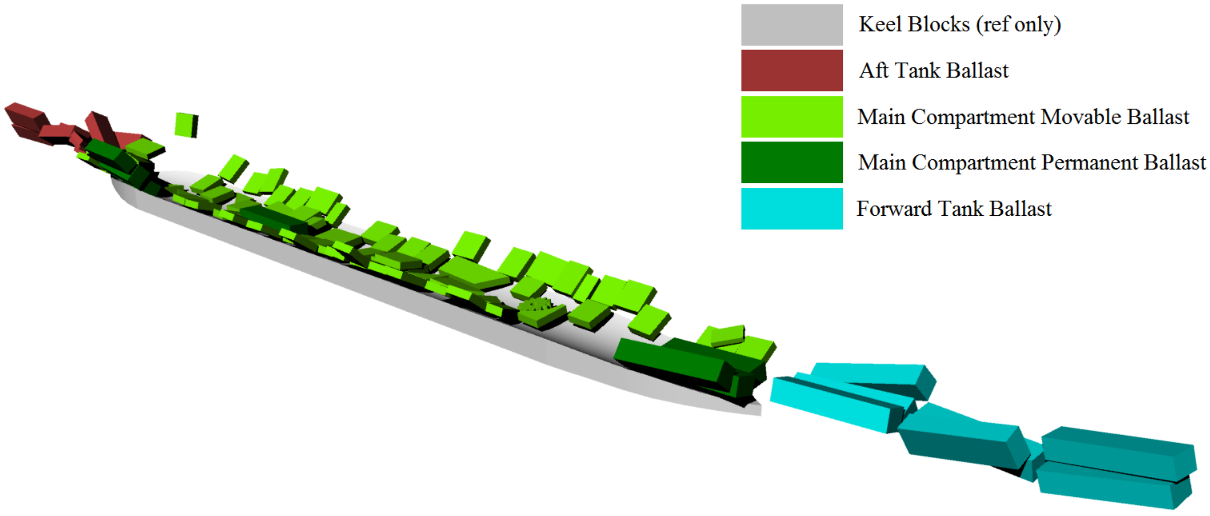


Figure 9: Ballast block arrangement.

The most difficulty in the weight estimate came from the propulsion plant and outfitting systems, because very little documentation existed on these systems. The pipe diameters used for the crank shaft, rudder shaft, and rudder casing were measured from the model, and assumed solid and constant along the entire length. The propulsion plant is a total of 0.45 LT of contributing weight and is presented in Figure 10. The outfitting system consists of only components that have a recorded weight provided in [17]. The contributing weight is 0.11 LT, and is presented in Figure 11.

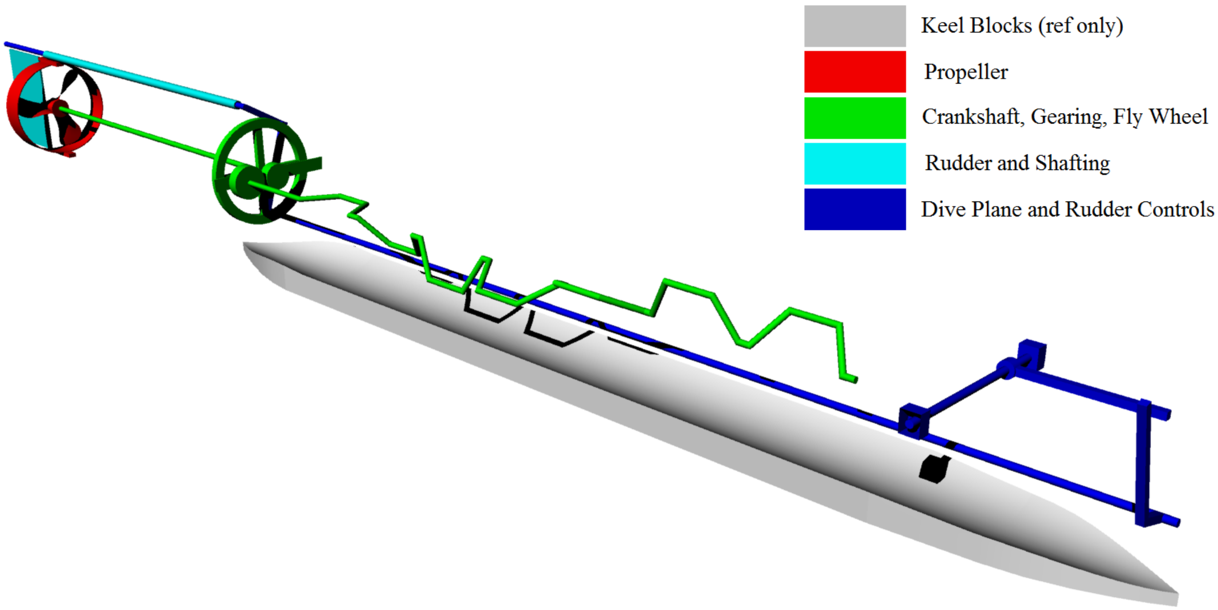


Figure 10: Propulsion plant systems.

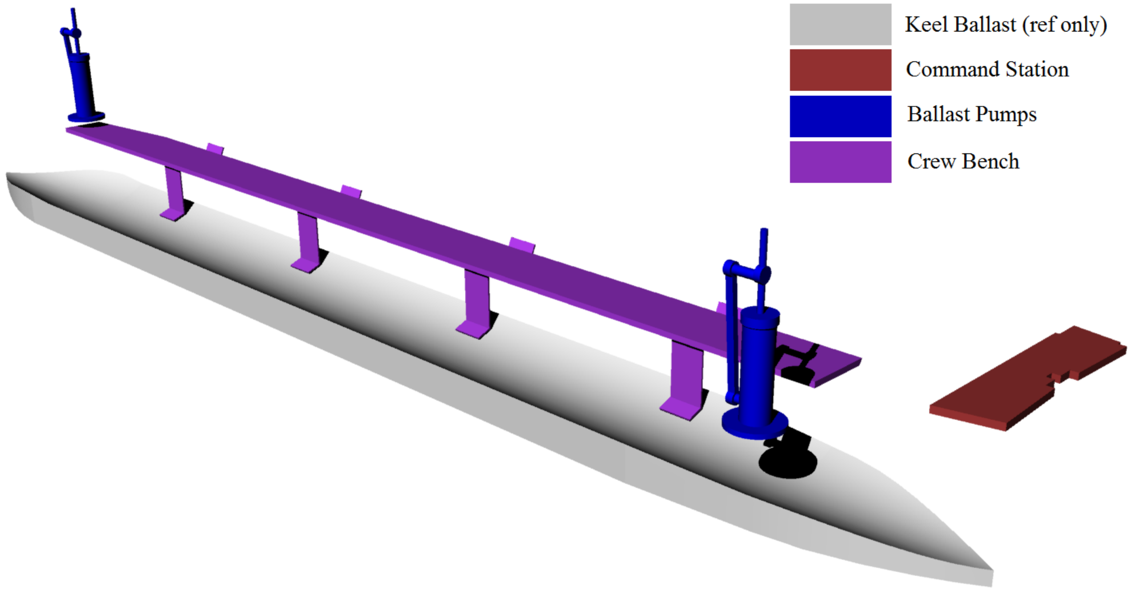


Figure 11: Outfitting systems.

The armament was set using a combination of historical resources and measured dimensions. The spar consists of a three foot length of solid iron bar pipe and 13 foot hollow iron section combined for a 16 foot overall length. The black powder charge geometry was estimated as 132 lbs [5], and sized appropriately. The overall contribution to the weight was 0.09 LT with a variable weight of the black powder charge as 0.06 LT. Figure 6 presents the layout of the armament. Because evidence was only found for a lower spar attachment, the weight estimate does not include an upper spar or torpedo triggering mechanisms.

Finally the crew weight was provided from the volume calculation [17], and spaced according to the location of handles along the crank shaft in Figure 10, with the captain sitting directly below the forward hatch on a removable bench seat. The weights were applied as a single point load, the contributing weight of the crew was 0.57 LT. The individual weight and location of the crew can be found in Table 2, location presented in GHS coordinates found in Figure 7.

Table 2: Distribution of crew weight

Title	Mass (lbs)	X (ft)	Y (ft)	Z (ft)
Dixon	157.50	29.25	-0.13	2.37
Becker	131.00	24.83	0.13	1.79
Lumpkin	157.50	22.83	0.13	1.79
Collins	171.50	20.83	0.13	1.79
Carlsen	159.00	18.83	0.13	1.79
Miller	151.50	16.83	0.13	1.79
Wicks	170.50	14.83	0.13	1.79
Ridgawat	170.00	12.83	0.13	1.79

Variable ballast tank weight was calculated as needed to trim the vessel. The forward and aft ballast tanks were calculated in the GHS geometry file according to the tank configurations in CAD model. The tanks are symmetrical, each with an internal volume of 31.3 cubic feet, or 234 gallons. They are not covered on top, allowing flow between the tanks and the main compartment. The forward and aft ballast tank bulkheads adjoining the main compartment are approximately 3 feet 5 inches high. To be submerged, the calculated volume of water was 0.39 LT in the aft tank and 0.65 LT in the forward tank, which accounted for in the weight estimate's total mass.

Combining all of the ESWBS components gave the vessel a full load departure weight of 9.59 LT. The breakdown of the components can be found in Table 3.

Table 3: ESWBS Weight Estimate - Breakdown as in proceeding sections

Group	Title	Mass (LT)	X (ft)	Y (ft)	Z (ft)
1	Hull Structure	5.06	20.04	0.00	1.48
2	Propulsion Plant	0.45	11.20	0.09	1.88
3	Electrical Plant	0.00	00.00	0.00	0.00
4	Command	0.57	19.93	0.09	1.86
5	Auxiliary Systems	0.00	00.00	0.00	0.00
6	Outfitting Systems	0.11	19.50	0.12	1.77
7	Armament	0.09	52.82	0.00	0.00
M	Margins	0.00	00.00	0.00	0.00
F	Loads, Departure	3.31	21.12	-0.09	0.85
	Total	9.59	20.28	-0.02	1.30

Having completed the weight estimate, some basic naval architecture calculations were applied to determine how the vessel will float under the current loading. Displaced volume was calculated using the Orca3D extension in RhinoCAD. This gave a value of 9.89 LT as the displacement. Comparing the weight from Table 3 to the displacement, there is a 3 percent difference. This could be due to unaccounted smaller structure, poor geometry estimation, or poor water ballast estimation. Under this weight configuration, the draft was determined to be 4.20 feet, with the water level just below the conning towers. This places the broken pipe fitting about 19" underwater. The transverse metacentric height is 0.70 feet, and the longitudinal metacentric height is 9.58 feet. These values are estimated while the vessel would be sitting about the surface, acting similar to a traditional boat. Further stability analysis is completed in Section 5.3. The conclusion of this estimation is that the vessel would be able to float as expected at the predicted water ballast estimate, with enough margin to fill the tanks and sink the vessel below the surface.

5.3 Stability Calculation

Stability analysis was completed for four different loading cases to determine how the vessel responded under normal operation. The conditions considered are: Lightship, Pierside, Personnel loading and mission profile.

5.3.1 Lightship Condition

For the lightship condition, the initial center of gravity was estimated using a weighted average of the mass centers of gravity for each item in the SWBS applicable to the most basic lightship loading condition. The lightship loading condition includes the weight of the hull structure, propulsion and steering systems, and permanently mounted equipment such as the ballast pumps, and keel ballast. It does not include the weight of armament, personnel, nor the solid ballast blocks found inside the ballast tanks and main compartment. The objective in assessing the hydrostatic properties of the *Hunley* in its lightship condition was to verify that the designers and operators could lower the hull into the water prior to loading the vessel without capsizing or foundering. Table 4 presents the hydrostatic properties in the lightship condition, while Figure 12 presents a visual of the vessels orientation.

Table 4: Lightship Hydrostatic Properties

Displacement (LT)	Depth (ft)	Trim (deg+stern)	Heel (deg+stbd)	GML (ft)	GMT (ft)
5.62	2.68	1.10	3.25	40.20	0.23

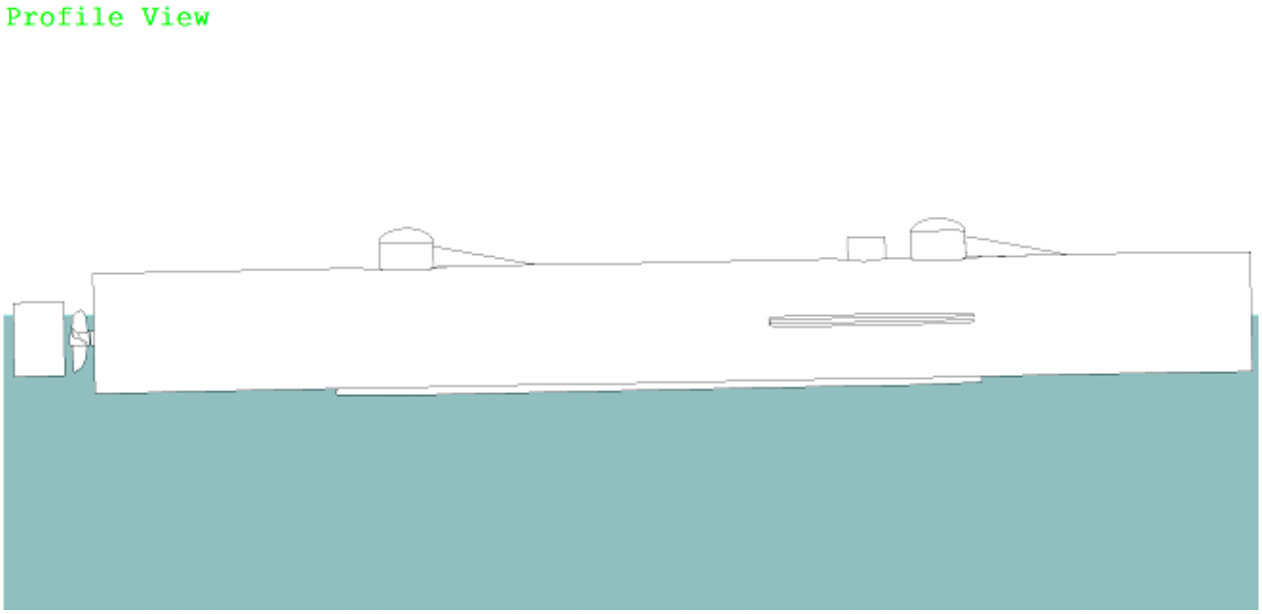


Figure 12: Lightship vessel orientation

5.3.2 Pierside Condition

The pier side loading condition includes all components considered immovable once *Hunley* was in the water at the pier. It includes lightship weights with the addition of the spar assembly, powder keg, and the 23 solid ballast blocks found in the ballast tanks and main compartment individually weighing greater than 70 lbs. Table 5 presents the hydrostatic properties in the pierside condition, Figure 13 presents the vessels orientation.

Table 5: Pierside Hydrostatic Properties

Displacement (LT)	Depth (ft)	Trim (deg+stern)	Heel (deg+stbd)	GML (ft)	GMT (ft)
7.11	3.84	0.61	-2.83	29.20	0.45

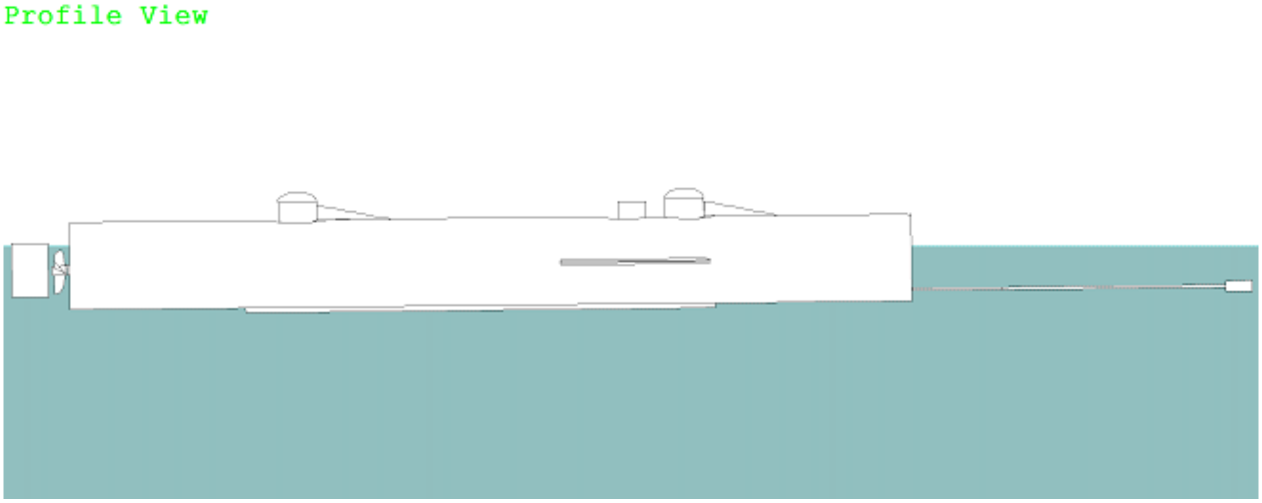


Figure 13: Pierside vessel orientation

5.3.3 Personnel Loading Condition

The personnel loading condition consists of a series of 17 discrete steps simulating one possible process for the crew to safely embark and load the remaining solid ballast blocks. The process simulates the progressive addition of weight to the pier-side loading condition assuming the crew embarked starting from the middle seats and alternating between the forward and aft hatches. The process starts with the pier-side loading condition and simulates the progressive addition of each member of the crew entering from alternating hatches along the centerline of the vessel and shifting amidships and off-centerline to port to simulate each member of the crew taking their final position at their assigned locations on the bench. In Figure 14, odd numbers enter through the forward hatch, even through the aft hatch; Step A is entering the vessel, step B is the final location in the vessel. The remaining solid ballast blocks were the last weights added to complete the personnel loading condition. Note that in operation, it is unlikely that the solid ballast blocks were re-loaded with each mission, once adjusted they could be left in the vessel. Given their low VCG, they would only improve the stability throughout the loading process from what was presented here. Interestingly, the locations of the weights as they were discovered during excavation results in a very reasonable 1.26 degree trim by the stern and effectively negligible 0.3 degree port heel. This suggests that the weights did not likely shift considerably during *Hunley's* attack or sinking. The effect of loading on the hydrostatic properties of the vessel at each step of the loading sequence is graphically shown in Figure 14.

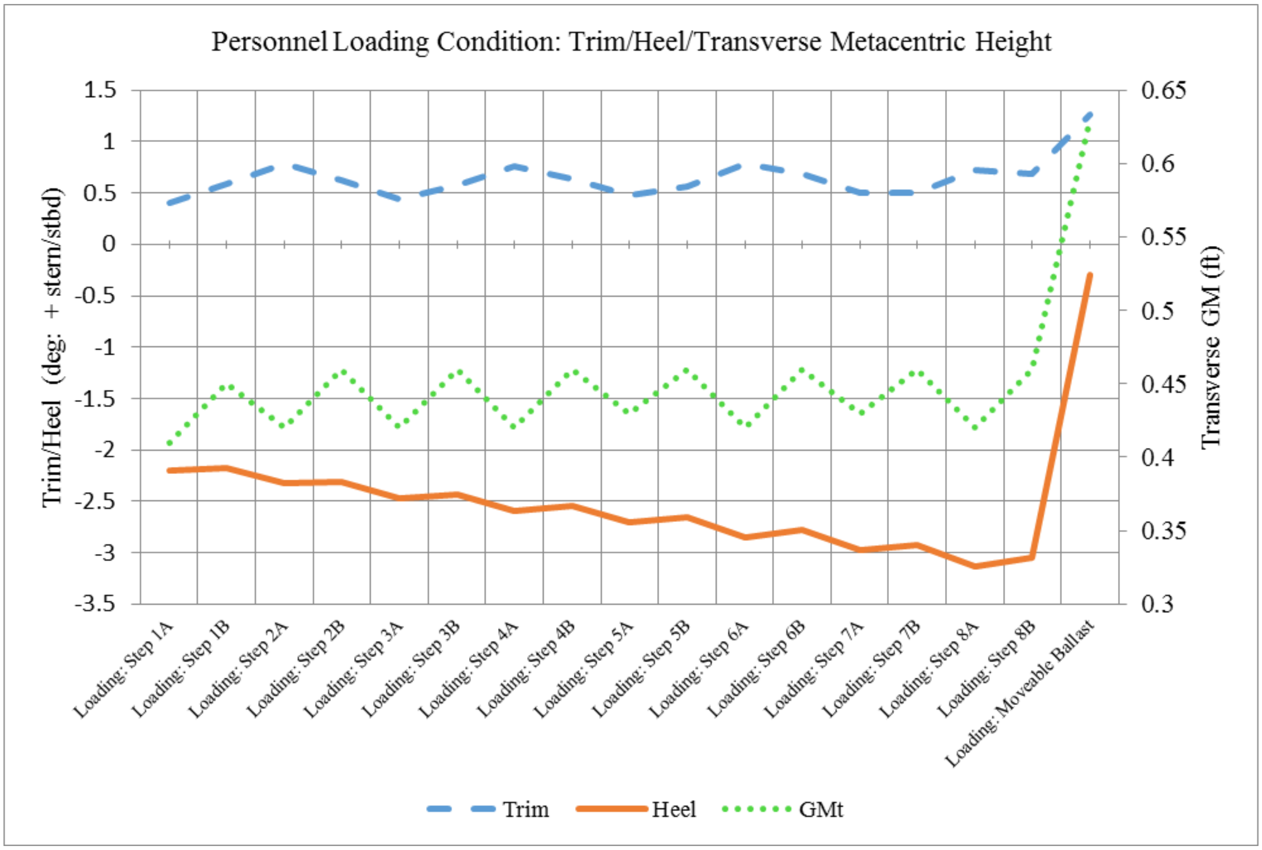


Figure 14: Hydrostatic property progression with personnel loading sequence

The final hydrostatic properties of the personnel loading condition is presented in Table 6. The final vessel orientation after personnel loading is presented Figure 15.

Table 6: Final Personnel Loading Hydrostatic Properties

Displacement (LT)	Depth (ft)	Trim (deg+stern)	Heel (deg+stbd)	GML (ft)	GMT (ft)
8.56	3.86	1.26	-0.30	19.40	0.63

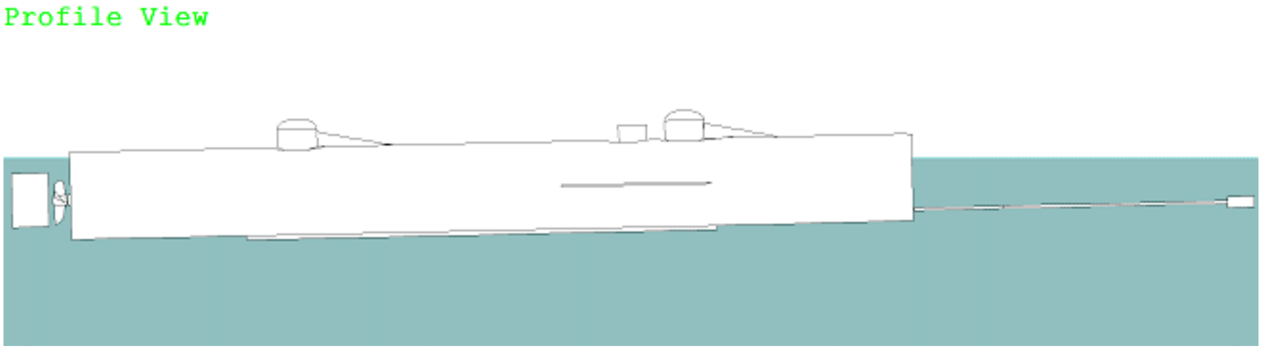


Figure 15: Final Personnel Loading vessel orientation

5.3.4 Pre-Weapon Deployment Condition

The final conditions considered is the attack condition, which adds ballast water in the forward and aft tanks to achieve submergence to the level described by the crew of the *Housatonic* during the attack. Two feasible attack loading conditions that satisfy survivor accounts were considered. The first condition consisted of filling the forward ballast tank to 75 percent of its maximum capacity and the aft tank to 45 percent of its capacity. This ballasting results in a condition where both conning towers and the snorkel box are completely exposed above the waterline and the deck is awash. The pre-weapon deployment condition with the deck being awash hydrostatics are presented in Table 7, Deck Awash pre-weapon deployment hydrostatic properties, the vessel orientation is presented in Figure 16, Deck awash pre-weapon deployment vessel orientation.

Table 7: Deck Awash pre-weapon deployment hydrostatic properties

Displacement (LT)	Depth (ft)	Trim (deg+stern)	Heel (deg+stbd)	GML (ft)	GMT (ft)
9.63	4.06	0.00	-0.24	07.20	0.70

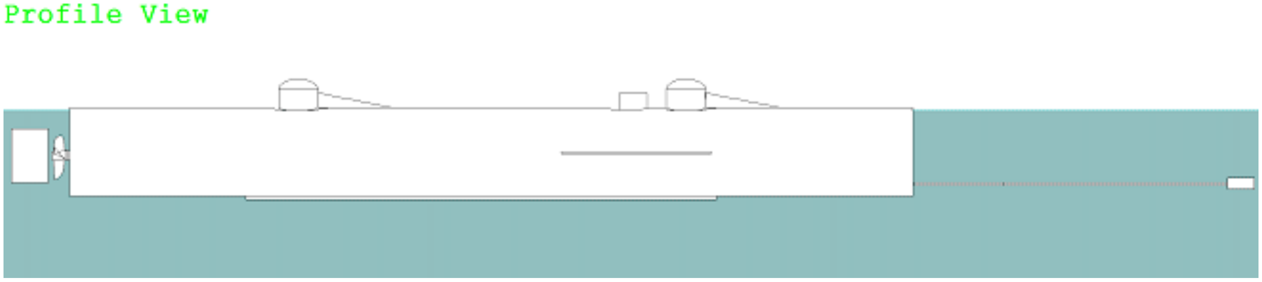


Figure 16: Deck awash pre-weapon deployment vessel orientation

For the second attack condition, the ballasting was adjusted to fill the forward ballast tank to 80 percent of its maximum capacity and the aft tank to 50 percent of its capacity. This ballasting configuration results in the *Hunley* submerging to a point where the deck was fully submerged and only the conning towers and snorkel box pierced the surface. The distinction between these two pre-weapon deployment conditions is characterized by the difference in longitudinal stiffness due to changes in waterplane area. The deck awash pre-weapon deployment condition has the larger waterplane area, giving the vessel greater longitudinal stiffness and consequently making the vessel less sensitive to trimming moments applied by longitudinal weight shifts or fore and aft impulse loading, The deck submerged case is expected to be more sensitive to ships of weight. The pre-weapon deployment with the deck submerged is presented in Table 8, Deck submerged pre-weapon deployment hydrostatic properties. The vessel orientation is presented in Figure 17, Deck submerged pre-weapon deployment vessel orientation.

Table 8: Deck submerged pre-weapon deployment hydrostatic properties

Displacement (LT)	Depth (ft)	Trim (deg+stern)	Heel (deg+stbd)	GML (ft)	GMT (ft)
9.72	4.42	0.23	-0.23	01.60	0.71

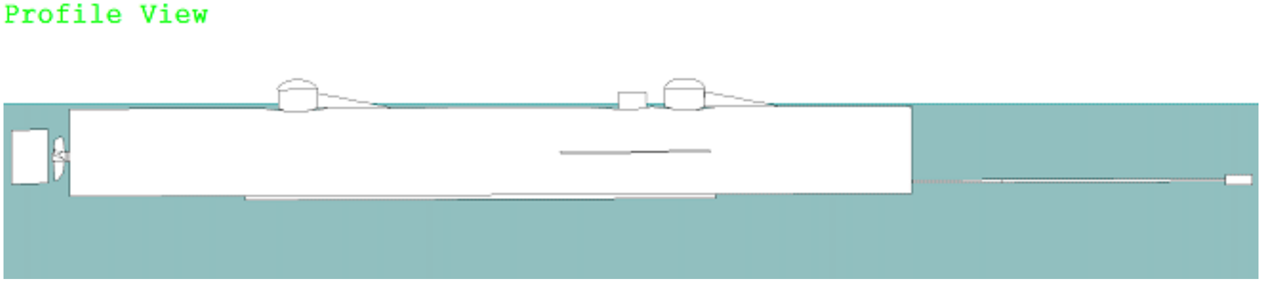


Figure 17: Deck submerged pre-weapon deployment vessel orientation

5.3.5 Post-Weapon Deployment Condition

After completing the analysis for both deck submerged and deck awash, the results reported a drastic change in stability. The model demonstrates that after deploying the weapon, the *Hunley* trims between 2.08 and 3.50 degrees by the stern. This response is due to the significant loss of the forward trimming moment applied by the powder keg and the resultant shift aft of the longitudinal center of buoyancy. The greater trim response of the deck submerged attack condition due to the loss of the powder keg is caused by the smaller longitudinal metacentric height. The results of post-weapon deployment are presented in Table 9.

Table 9: Pre-weapon and post-weapon deployment comparison

	Trim (deg+stern)	GML (ft)
Deck Awash Pre-weapon	0.00	7.20
Deck Awash Post-weapon	2.08	3.60
Deck Submerged Pre-weapon	0.23	1.60
Deck Submerged Post-weapon	3.50	3.00

Analysis of the *Hunleys* general stability shows that overall, the vessels design allows for a stable platform when operated on the surface. Once ballast water is added to submerge the hull to the depths reported by the crew of the *Housatonic*; however, *Hunley* becomes very sensitive to forward and aft weight shifts. This is a result of a loss in longitudinal stiffness due to reduced water plane area. It is also important to note that our model predicts that the *Hunley* could be fully submerged without fully filling its ballast tanks and that overfilling either ballast tank results in unrestricted progressive flooding into the main compartment.

In post-weapons deployment condition, the *Hunley* maintains positive longitudinal and transverse metacentric heights suggesting an ability to recover from heeling and pitching moments.

Considering all operational loading conditions, the least stable condition characterized by the smallest Transverse Metacentric Height is when the *Hunley* is in the deck awash: post-weapons deployment condition. Even in this worst case condition, the *Hunley* maintains positive righting energy through a 90 degree roll as shown in Figure 18.

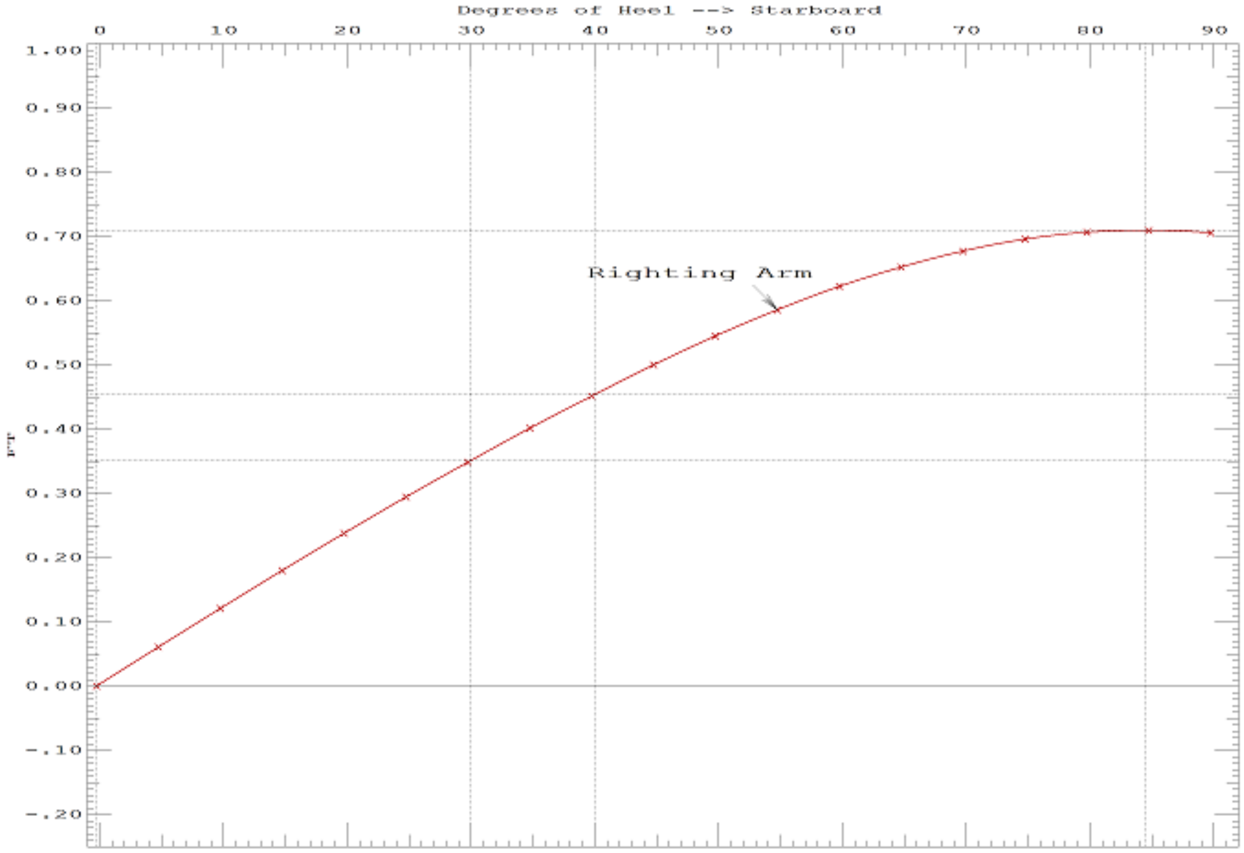


Figure 18: Deck awash post-weapon deployment righting arm curve

5.3.6 Stability Discussion

The *Hunley's* greatest vulnerability in its pre-weapon and post-weapon deployment conditions is the significantly reduced weight-per-inch submergence property. Due to small freeboard and similarly low reserve buoyancy, the *Hunley* is extremely sensitive to added mass specifically added mass due to flooding or additional ballasting. In particular, after deploying the powder keg and taking on a trim by the stern, the model shows that the *Hunley* sinks after taking on approximately 50 gallons of seawater into any compartment in the deck submerged: post-weapons deployment condition. Similarly, in deck awash: post-weapons deployment condition the *Hunley* sinks after the addition of approximately 74 gallons of seawater into any compartment.

The results of our analysis highlight the danger of any uncontrolled rapid flooding due to crew actions or damage inflicted during the attack and its aftermath. It is also important to note that, due to reduced longitudinal stiffness in the Post-Weapons Deployment Conditions, any small amount of flooding also results in rapid and unrecoverable changes in trim. Since weapons deployment results in an immediate trim by the stern, any flooding or added ballast in the main compartment or aft ballast tank immediately exasperates that trim.

This analysis was strictly static to understand stability and required volume of water necessary to cause complete submergence of the vessel. It does not include dynamics from the exploding torpedo, dynamic rotation or flooding of the vessel. However, in terms of scenario 6, it appears that overall the vessel would be reasonably stable in the attack configuration unless new water is introduced to the vessel from the outside.

5.4 Resistance and Powering Calculation

5.4.1 Empirical Model

To better understand if the submarine was underpowered, the resistance of the hull was calculated, then matched to the power output of the propeller. This methodology was taken from Introduction to Naval Architecture [6] on submarines and relies on regression data and approximate relationships for both the submarine drag and propeller efficiency. The values required to complete these calculations can be found in Table 10 below.

Table 10: Submarine resistance characteristics

Symbol	Characteristic	Value
L	submarine length	40 ft
D	submarine diameter	3.75 ft
S	wetted surface area	$612 ft^2$
S_{append}	appendage surface area	$140 ft^2$
g	gravity	$32.174 ft/s^2$
ρ	sea water density	$1.936 slugs/ft^3$
ν	viscosity	$1.217 * 10^{-5} ft^2/s$

These values were found by measuring the components from the geometry model, assuming the vessel was sailing with the deck just barely submerged. This model, designed for modern submarines, assumes a perfectly cylindrical submarine. In this case, an equivalent diameter of the submarine was calculated by averaging the height and width of the submarine. The appendage wetted area was calculated from the geometry model and consists of the rudder, propeller and duct, dive planes, and keel block. The ratio of appendage surface area to the hull surface area is approximately 20 percent.

The coefficient of friction was calculated using the velocity Reynolds number, Equation (1), and the ITTC 1957 approximation found in Equation (2).

$$R_n = \frac{VL}{\nu} \tag{1}$$

$$C_F = \frac{0.075}{(log(R_n) - 2)^2} \tag{2}$$

The viscosity coefficient was calculated using an approximation for a submarine bare hull calculation [6] found in Equation (3). This equation is only an approximation and ignores wave drag. Friction forces were estimated by the ITTC 1957 friction line because the Reynolds numbers were above 10^5, generally following a method similar to larger submarine resistance estimation [6]. The appendage viscosity coefficient was estimated as 1.8 times the hull viscosity coefficient found in Equation (4). Because the surface of the *Hunley* may be rougher than modern submarines, the overall vessel is less slender than larger submarines, and the *Hunley* has higher appendage drag, the *Hunley* is not a perfect fit with the submarines used to develop this model. Thus, the model calculations must be viewed as an initial approximation of resistance.

$$C_V = C_F \left(1 + 0.5\left(\frac{D}{L}\right) + 3\left(\frac{D}{L}\right)^3\right) \tag{3}$$

$$C_{V append} = 1.8 C_V \tag{4}$$

The total resistance calculation uses a combination of the coefficients by the respective wetted area [6], and can be found in Equation (5).

$$R_T = 0.5\rho V^2 \left(\left(C_v + C_a\right) S + C_{V append} S_{append}\right) \tag{5}$$

The value of C_a was approximated as 0.0001, all other values can be found in Table 10. Using this process, the total resistance was found for speeds varying between 0.5 and 4 knots, which is the range of recorded velocities from historical resources. The required power was calculated using Equation (6).

$$EHP = \frac{R_T V}{550} \tag{6}$$

where 550 is the conversion factor to yield power units of Horse Power (HP). Calculating the resistance was the first step to the propeller-hull matching. The next step is to look at the power output of the propeller.

A thrust calculation was completed with open water characteristics to create a power-velocity curve. The geometry was developed from a best fit curve from the laser scan data. The geometry used is presented in Figure 19, with the characteristics presented in Table 11. At the time of this work, the propeller was still covered in concretion, thus this geometry must be viewed as approximate. The propeller has since been cleaned, and an updated calculation with the actually propeller geometry could help significantly.

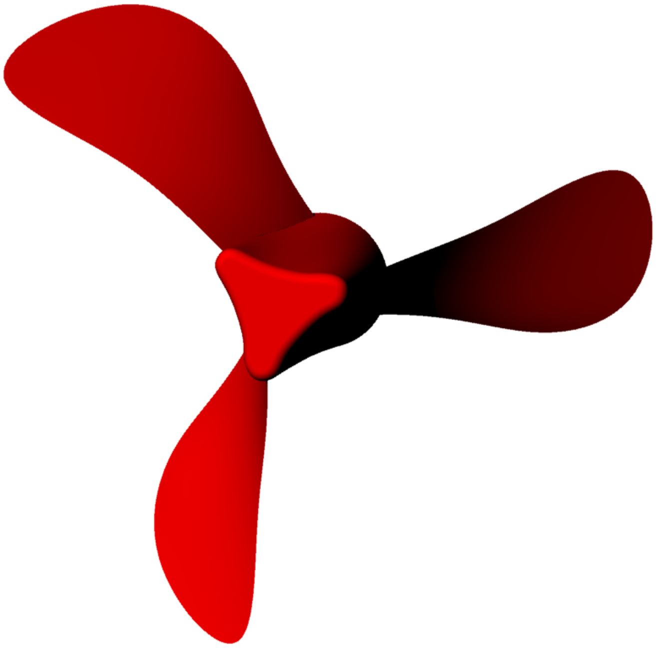


Figure 19: Propeller geometry used for thrust calculations.

Table 11: Propeller characteristics

Symbol	characteristic	Value
D	Diameter	31.63 in
P/D	Pitch to Diameter ratio	0.776
EAR	Expanded Area Ratio	0.2876
w	wake factor	0.1
t	thrust deduction	0.1
	gear ratio	1.285
	depth of shaft	24 in

Using the values above, the propeller was approximated as a Wageningen B Series propeller. The B Series approach represents a more modern propeller and is again an initial rough estimate. However, in the absence of propeller section shape data from a de-concreted propeller, it is a reasonable starting point. A Matlab script was used to develop the thrust and torque coefficients for the propeller. This program used a polynomial fit for the required coefficients based on experimentally tested propellers parameterized by the propeller geometry. The thrust coefficient, torque coefficient, and open water efficiency for various forward speeds are presented in Figure 20.

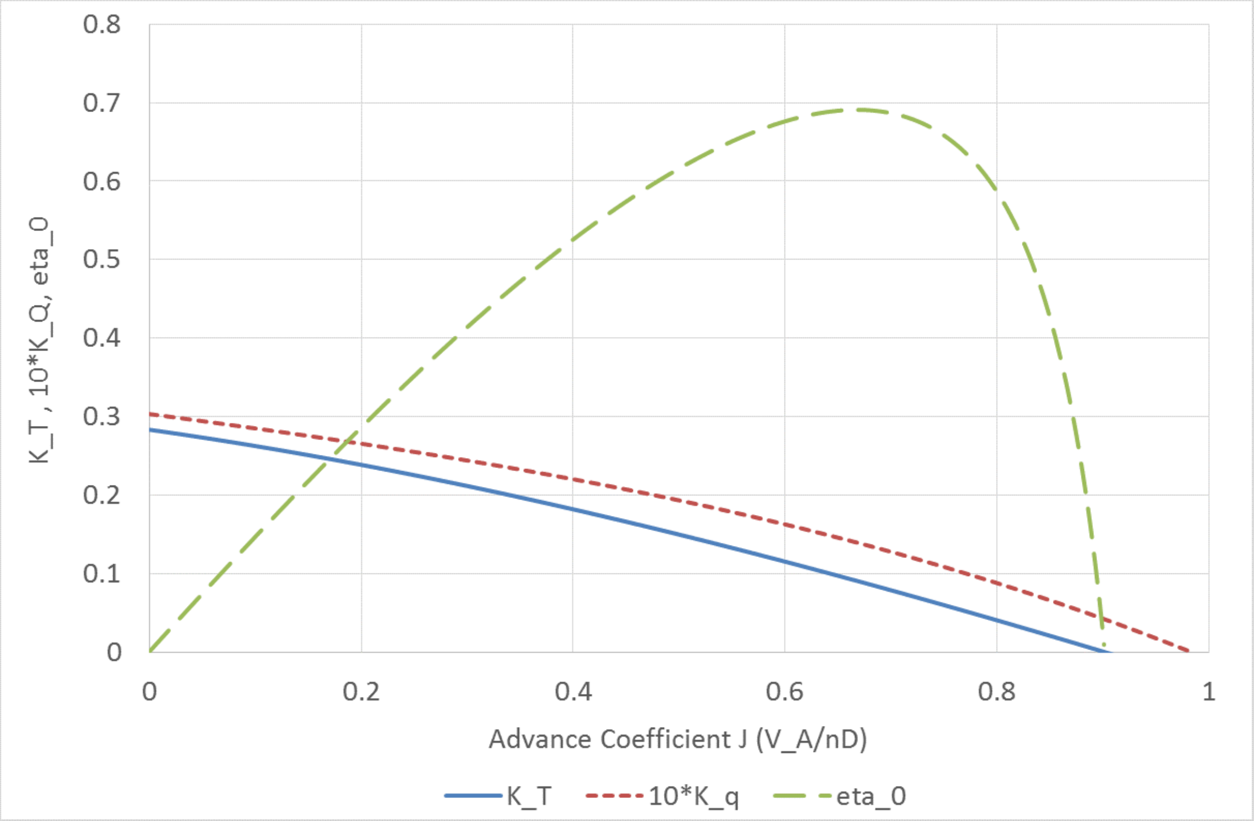


Figure 20: Propeller characteristic curve.

The independent variable was determined to be the rotational speed of the crank. Crankshaft RPM was varied between 5 and 100 RPM, based on the perceived rate at which a human could turn the shaft. This was converted to a propeller RPM using the gear ratio, which was estimated at 1.28 based on the outline of the still-concreted gears. A propeller-hull matching calculation was completed to determine how the vessel would operate under these various rotational speeds. The goal of this analysis was to determine if the limiting factor would be the speed the vessel could travel or sustainable human rotational speed. Because the best case scenario is desired for forward velocity, hull efficiency η_H and rotational efficiency η_R were estimated at values of 1. The steps used are based on the Principles of Naval Architecture (PNA) standard [10]. Usable torque and thrust values were calculated using Equation (7) and Equation (8).

$$Q_0 = K_{Q_0} \rho n^2 D^5 \tag{7}$$

$$T_0 = K_T \rho n^2 D^4 \tag{8}$$

K_{Q_0} is the coefficient of torque, K_T is the coefficient of thrust developed from the Matlab script, n is propeller revolution in rev/s, and ρ is the density value from Table 10.

To find the correct delivered power, the behind hull efficiency was calculated using Equation (9).

$$\eta_B = \eta_R \eta_0 = \frac{Q_0}{Q} \tag{9}$$

η_0 was selected based on the rotation rate of the propeller. The usable thrust was calculated based on Equation (10), then converted to power using Equation (11).

$$T = \frac{\eta_B 2\pi n Q}{V_A} \tag{10}$$

$$P_T = \eta_H T V_A \tag{11}$$

Completing these calculations, the human RPM was varied from 5 to 100 RPM, the forward velocity was calculated based on matching the required power to the power produced by the crew at that RPM. These values were determined to be close enough if the thrust was within five percent over the resistance of the hull. This could be further improved with more refinement in the propeller curve. The results of the propeller matching are presented in Figure 21.

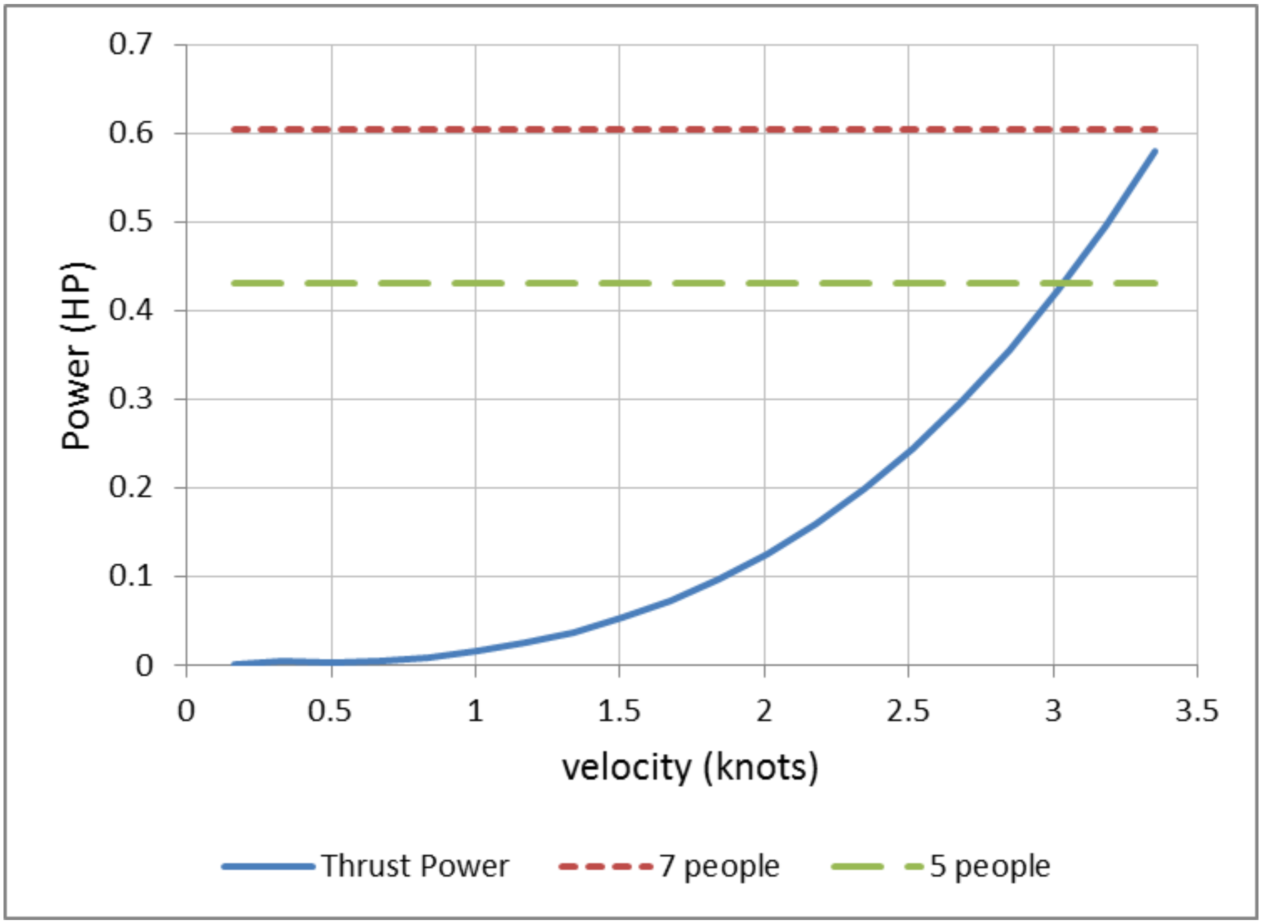


Figure 21: Power required over velocity curve

In the figure, the *Hunley* will move along the thrust power curve until it reaches either the seven person or five person limit. These lines represent the limiting horse power output of each person, assuming 0.067 HP per person. The horse power per person was calculated using the maximum force output per person [1] in a cranking position converted into power output. The five person case represents the potential of vessel damage, and two people would be working the hand pumps to empty the main compartment. The limiting factor is the 5 person case at approximately 3.01 knots. In the seven person case, extrapolation of the curve suggests that the vessel will move only slightly faster at a sprint speed of 3.25 knots.

An RPM to velocity comparison graph was developed to see the maximum speed that would be obtainable under different assumed crankshaft rotation rates. The results are presented in Figure 22.

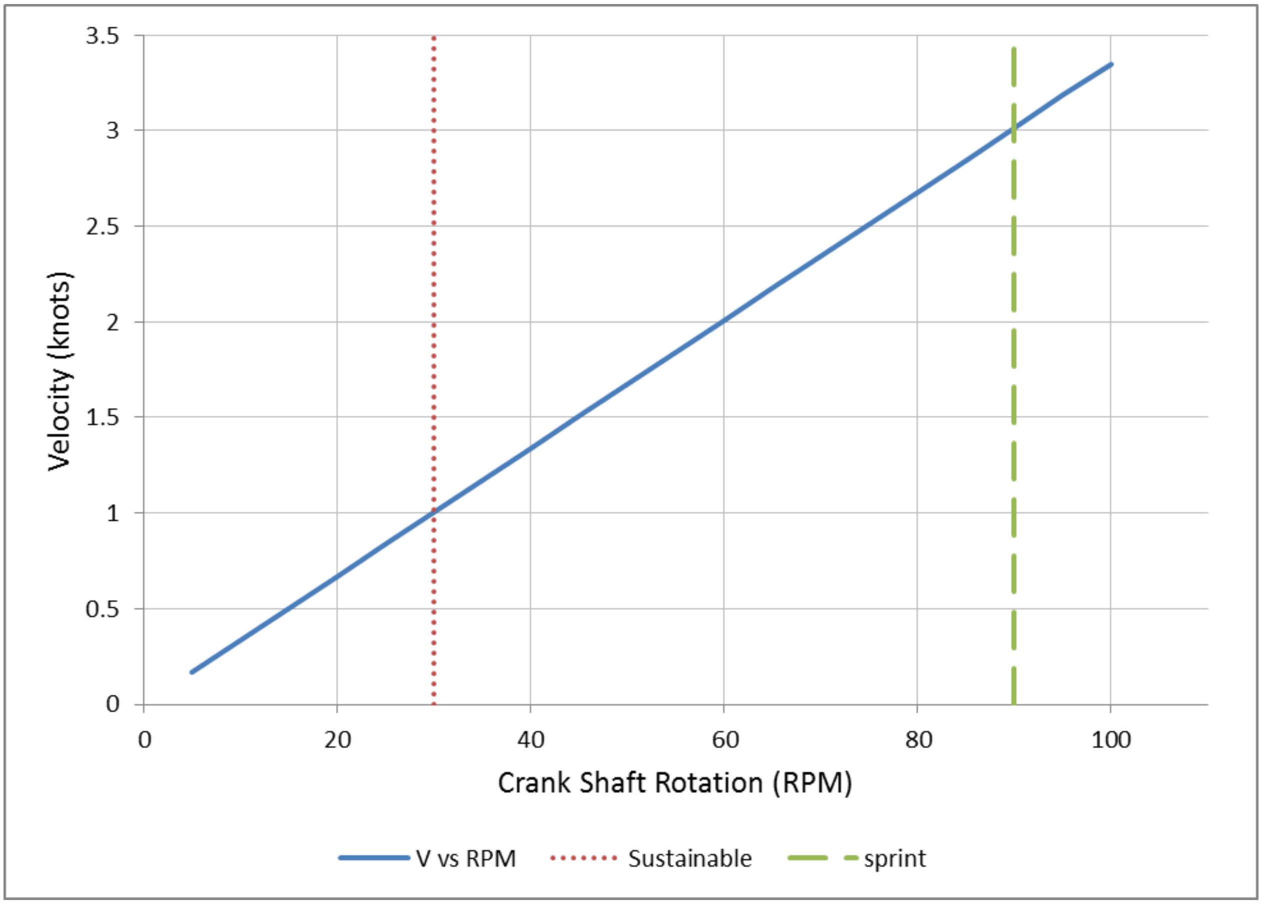


Figure 22: Velocity over RPM graph with RPM bounds

It is observed that to achieve the necessary thrust power for the five person case discussed above, the crew would have to crank at about 90 RPM. To move at 3.25 knots for the seven person case, the rotation rate would be greater than 90 RPM. A more reasonable sustained rate is believed to be around 30 RPM, which would propel the *Hunley* forward at one knot. From this analysis, the long-term sustainable speed of the *Hunley* is probably closer to one knot than three knots. The RPM requirement confirms several aspects of the historical record. It appears that the *Hunley* would be capable of moving roughly three to four knots in a short sprint, but that speed is not sustainable for a long period. A sustained speed closer to one knot would tie in with Alexander's and McClintock's concerns about the vessel not being able to fight the tidal current. The inability to fight the tide indicates that the *Hunley* may not have immediately attempted to return to shore after the attack until the tidal current had begun to switch from ebb to flood.

5.4.2 Experimental Model

Given the relative importance of the powering of the vessel to the vessel's operation, the author's prioritized removing the uncertainty in the approximate powering estimates above. A Master's Thesis undertaken by author Dan Burke [4] built a $\frac{1}{3}$ scale hydrodynamic replica of the vessel. The model was tested in six conditions during the summer of 2016, as listed in Table 12. Given the large area and unclear operating angle of the dive planes (fins) on the hull, the model was developed so that it could be tested with or without fins.

Table 12: Resistance test condition characteristics

Case	**Description**	**Draft - vessel, ft**	**Draft - model, ft^2**
A	Model Lightship, with fins	3.67	1.22
B	Model Lightship, without fins	3.67	1.22
C	Deck awash, with fins	4.17	1.39
D	Deck awash, without fins	4.17	1.39
E	Fully submerged, with fins	5.5	1.83
F	Fully submerged, without fins	5.5	1.83

Each condition was tested between 1.0 and 4.0 knots full-scale speed in increments of 0.5 knots, in calm water. The fins on the model had a total surface area of $31.3ft^2$ full scale and were set at a 0-degree angle of attack. This angle is not expected to be exactly aligned with the flow at all velocities, so both surface friction drag and shape drag from the fins will be present. The model was fixed in both sinkage and trim during the testing. Given the large area of the fins, it is likely that the crew could dynamically impact the trim of the vessel at higher forward speeds by moving the fin position. However, in the current study, this impact was not quantified as neither the fins nor the towing apparatus was configured to measure vertical forces or moments. Additionally, the fully submerged condition was not deep enough to prevent surface waves from being formed in the tank at the higher speeds. At deeper submergences, this drag term would disappear. The geometric parameters of the model are shown in Table 13.

After test data was post-processed, the resistance values were expanded from model scale to full scale using the ITTC 1957 approach. The expanded, full-scale resistance of each configuration is plotted in Figure 23, comparing the resistance of the submarine at each draft with and without fins. The experimentally-measured points are shown with circle markers, and a quadratic best fit regression line is also plotted. Over the speed range of 1 to 4.5 knots full scale, the quadratic regression is a good fit of the resistance for all drafts. Additionally, the relative importance of the fins decreases as the vessel sinks deeper into the water. At lighter drafts, the resistance of the vessel is dramatically reduced — roughly cut in half at three

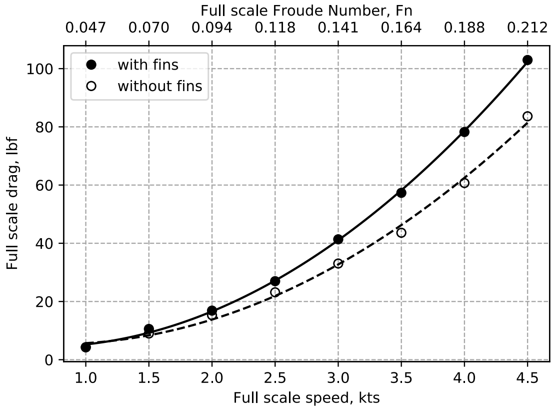
Table 13: Resistance model characteristics

Parameter	**Full scale**	**Model scale**
Overall Length, ft	40.2	13.4
Moulded Depth, ft	4.15	1.38
Depth Overall, ft	5.7	1.90
Beam, ft	3.575	1.19
Surface Area - Cond. A, ft^2	401.9	44.7
Surface Area - Cond. B, ft^2	370.7	41.2
Surface Area - Cond. C, ft^2	483.2	53.7
Surface Area - Cond. D, ft^2	451.9	50.2
Surface Area - Cond. E, ft^2	505.0	56.1
Surface Area - Cond. F, ft^2	473.7	52.6

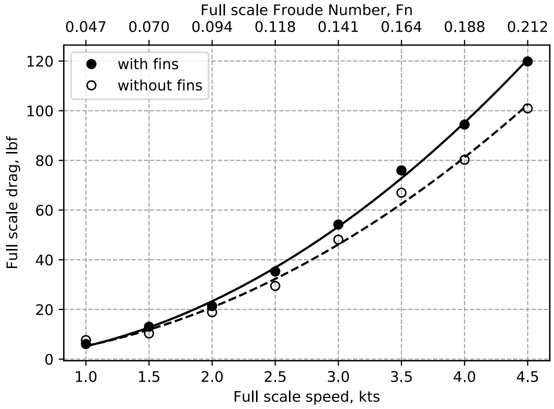
knots between decks awash and fully submerged.

Images of the model being tested at all three drafts are shown in Figure 24. At 3 knots, the model shows a significant but reasonably gentle Kelvin wave pattern in each case. The fins seem to only make a small disturbance to the free-surface flow. However, in the fully submerged case, the round conning tower/hatches have significant separated flow around each of them, adding to drag. The snorkel box, although partially shielded by the forward hatch also adds to the drag. This poorer flow, coupled with the increase in surface area exposed to friction drag, most likely explains the large increase in measured resistance.

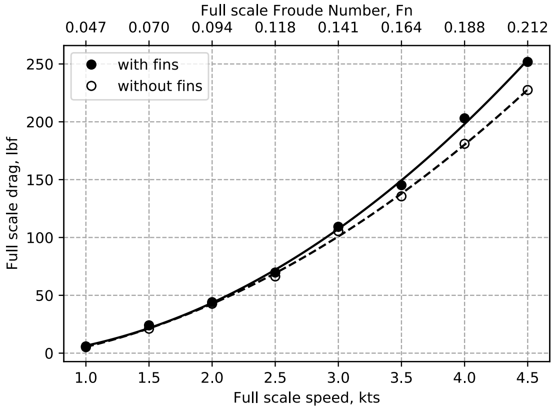
To further understand the resistance characteristics of each model, the total model drag was separated into the components used in the 1957 ITTC resistance scaling procedure: frictional surface drag and residuary resistance. For the submarine in this test, the residuary resistance will include wave making drag as well as flow separation and form drag from the hullform as a 1+k approach similar to the 1978 ITTC was not taken. The percentage of total drag attributable to frictional surface drag is shown in Figure 25. For the slower speeds, the relative contribution of skin friction is higher as expected. The low value of friction for the initial point tested in Case D is believed to be a measurement issue, the total drag at this speed is only on the order of 1 Newton for the model. However, even at three knots, in any of the surfaced conditions, frictional drag contributes more than 50% to the total drag. At lower speeds, the contribution ranges from 60% to 90%.



(a) Resistance Curves for Cases A and B

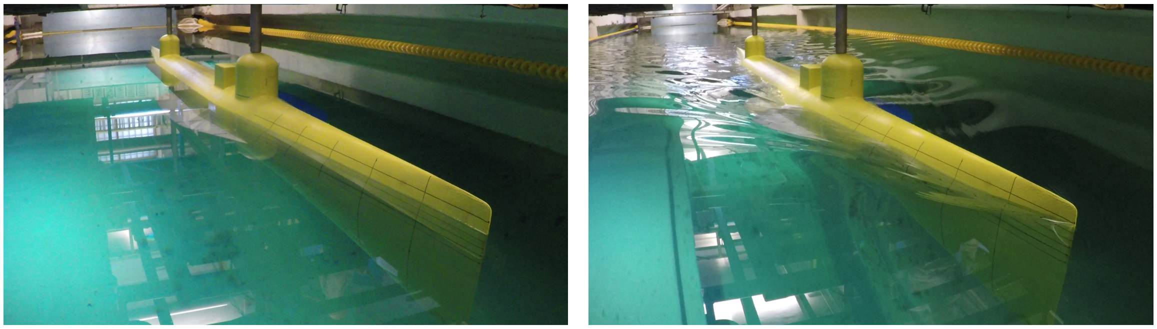


(b) Resistance Curves for Cases C and D



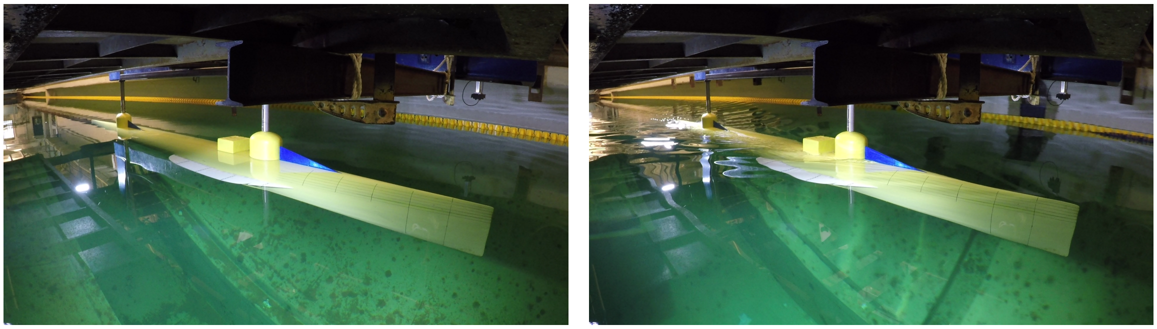
(c) Resistance Curves for Cases E and F

Figure 23: Resistance Curves and Quadratic Fit over Range 1-4 kts



(a) Cases A and B, Model at Rest

(b) Cases A and B, Model at 3.0 kts



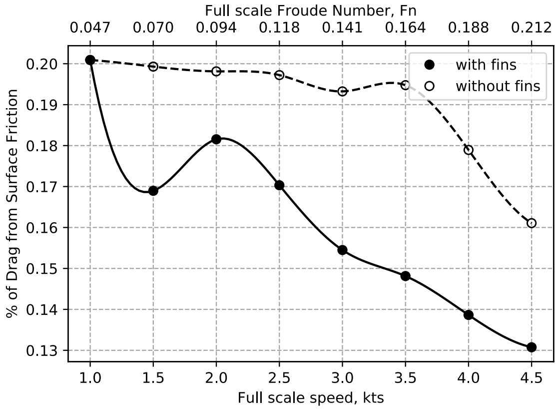
(c) Cases C and D, Model at Rest

(d) Cases C and D, Model at 3.0 kts

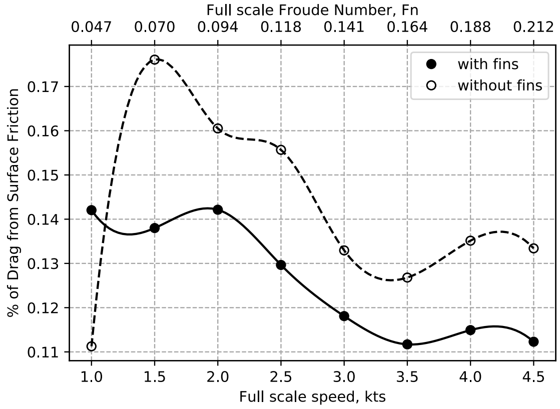
(e) Cases E and F, Model at Rest

(f) Cases E and F, Model at 3.0 kts

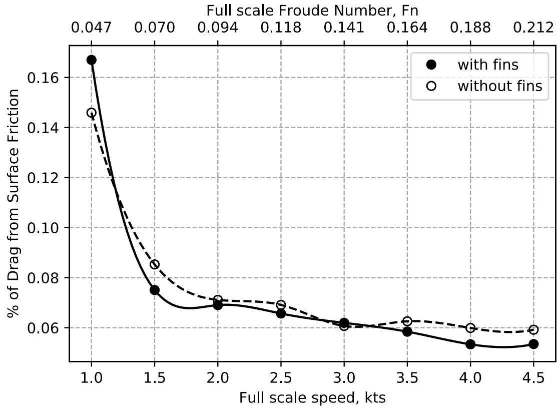
Figure 24: Images of Resistance Tests Configuration in Calm Water and at 3 knots



(a) Resistance Fractions for Cases A and B



(b) Resistance Fractions for Cases C and D



(c) Resistance Fractions for Cases E and F

Figure 25: Resistance Components for Cases A-F

As surface friction is the largest component of drag in these conditions, the accuracy of the friction estimate is critical to the overall accuracy of the resistance prediction in the one to three knot region. Surface friction is primarily influenced by the flow's Reynolds number and the surface roughness. While the Reynold's number can be estimated with good accuracy, the surface roughness of the *H.L. Hunley* is relatively unknown. The surface roughness of the ITTC 1957 friction line corresponds to more modern, and typically larger vessels. If the surface roughness of the *H.L. Hunley* was much rougher, both the friction drag and total drag will increase. The surface roughness of the Hunley would be impacted by both the larger features — rivets, straps etc. — as well as the as-produced finish of the hull plates. Additionally, the *H.L. Hunley* spent most of it career in warm, southern ports. The amount of biofouling present on the vessel is difficult to estimate, but biofouling would also increase the effective hull roughness. The Chapman picture of the vessel on the wharf does not show extensive fouling, though it is possible that any fouling was cleaned off during the repairs made after the second sinking. In interpreting the model test results for the surfaced conditions, especially at the lower speed ranges, the uncertainty in friction drag must be kept in mind. The fully submerged model test results show a lower sensitivity to hull roughness elements, but changes in hull roughness could impact these drag values as well.

The model test data was compared to the empirical drag estimate developed previously. The empirical approach does not match any of the testing conditions exactly - the wetted surface and draft is closest to conditions C and D. However, surface wave drag and separated flow around the conning towers that was observed in the experiment are not included in the empirical formula. Additionally, the empirical formula is based on 100 additional years of naval architectural improvements, and assumes smoother, more hydrodynamic shapes for appendages and the pressure hull. Overall, the best comparison is probably condition C for the empirical formula, however, conditions A and E were also included in the comparison. The results are shown in Figure 26, with quite strong agreement seen between condition C and the empirical equation. Based on these results, the earlier conclusions from the empirical model alone are confirmed. With the vessel low in the water, a sprint speed near 3.0 knots and a sustained speed between 1.0 and 1.5 knots is reasonable.

There are two major sources of uncertainty that still impact this estimate. The first is hull roughness and fouling. As discussed above, the empirical equation also uses more modern surface roughness values, so the good agreement between the experiment and empirical equation gives no additional confidence in the roughness estimate. It is still possible that a heavily-fouled *H.L. Hunley* would be slower than the calculations presented in this report. Secondly, the propeller estimate is also rough - only an approximate outline of the still-concreted propeller was used to estimate the propeller performance. When a more accurate scan of the propeller surface is available, a modern lifting-line approach could be taken to update the propeller efficiency and RPM values.

5.5 Sheared Pipe Analysis

Scenarios three and five from Section 4 consider the role the sheared ballast fill pipe might have played in the loss of the vessel. During conservation of the vessel, archaeologists discov-

Table 14: Resistance Test Results by Case

		Full scale drag, *Lbf*, for each case						
V, *kts*	**V, *Fn***	**A**	**B**	**C**	**D**	**E**	**F**	**Equation (5)**
1	0.047	4.3	4.3	6.1	7.6	5.2	5.8	8.2
1.5	0.07	10.6	9.0	13.0	10.3	24.1	21.1	17.2
2	0.094	16.9	15.3	21.4	18.9	44.1	42.7	29.0
2.5	0.118	27.0	23.2	35.3	29.4	69.7	66.3	43.7
3	0.141	41.4	33.0	54.2	48.1	109.3	105.4	61.1
3.5	0.164	57.3	43.6	76.0	67.0	145.2	135.6	81.1
4	0.188	78.2	60.7	94.4	80.3	203.0	181.0	103.7
4.5	0.212	103.0	83.6	119.8	100.9	251.8	227.5	128.9

ered that the forward ballast tank fill pipe had fractured where it meets the submarine's outer hull (Figure 27). This fracture would allow seawater to directly enter the crew compartment, roughly below the forward conning tower. The stability results show that only 50-75 gallons of flooding water are necessary to sink the vessel when the vessel is floating with the deck awash. Thus, if the ballast pipe sheared off as a result of the weapon firing, it is possible that the vessel foundered owing to the water that would be let in. However, it is not clear how long it would take for such damage to sink the vessel. Thus, understanding the flow rate through the sheared pipe is critical. This work was done in three phases. First, a simple model was built to get a rough estimate of the time to sink through the flooded connection. Then, detailed CFD and a model experiment were used to validate this finding.

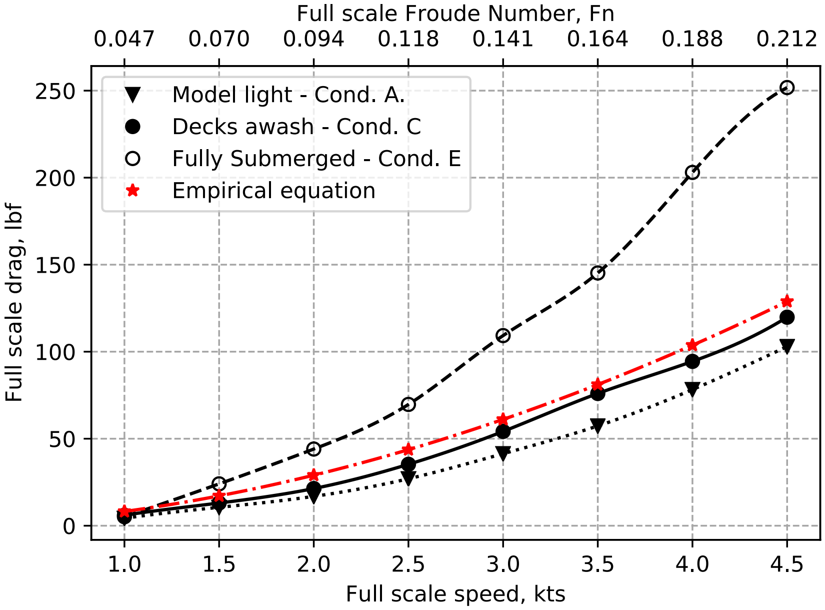


Figure 26: Comparison of Estimated and Measured Drag

5.5.1 Simple Bernoulli Model

The first step was to complete a rapid model using basic Bernoulli equations to obtain a rough estimate of the flooding time. The hole geometry is an irregular shape due to the sheared pipe blocking a portion of the circular opening. The geometry was developed in AutoCAD using the image shown in Figure 27 and known dimensions. The opening of the hole was traced in AutoCAD using two circles which were then scaled to the proper dimensions. The diameter of the hole in the outer hull is 1.54 inches, and the thickness of the pipe is 0.314 inches; It was assumed that the interior diameter of the pipe is the same size as the hole. AutoCAD was used to calculate the area of the hole which came to be 1.016 square inches. This opening area was used in the initial model to calculate the volumetric flow rate.

Figure 27: Geometry of sheared pipe opening

A theoretical model assuming a potential flow within the system was initially used to calculate the flow through the hole. For this initial model, Bernoulli's equation was used along a stream line from the surface to the outlet of the hole and is shown in Equation (12). This model assumes incompressible, laminar, inviscid, and irrotational flow. Since water is the fluid being analyzed the assumption of incompressible is valid; the assumptions of irrotational and laminar cannot be assumed to be particularly applicable to this system and this is noted when assessing the validity of the results. For the system, inviscid effects are significant, requiring additional analysis past this theoretical model. The inviscid results of this model provide an upper bound of the flow rate for comparison and to validate the CFD results and refined model.

$$P_a + 0.5\rho V_a^2 + \rho g h_a = P_b + 0.5\rho V_b^2 + \rho g h_b \tag{12}$$

It is assumed that the velocity at the ocean's surface due to the flow through the hole is zero and the equation can be simplified to solve for the velocity at the outlet assuming the pressure and height difference between points A and B (Δh) is known. This simplified equation is shown in Equation (13).

$$V_b = \sqrt{2\left(\frac{\Delta P}{\rho} + \rho g \Delta h\right)} \tag{13}$$

At the assumed loading condition of the *Hunley*, the hole is located 1.64 feet below the surface and it is assumed that the *Hunley* remains at this depth for the time period being investigated; this makes the height difference term constant making the pressure difference the only changing value to affect the flow rate through the hole for this model.

The pressure at point A was assumed to be constant at atmospheric pressure. The pressure at point B, the outlet, was initially assumed to be at atmospheric pressure, but increase as water flows into the hull. The initial volume of air in the submarine was calculated to be 2518 gallons in [9]. The internal pressure was calculated for each iteration using the following equation using the pressure (P) and volume of air ($\forall$). The volume of air was calculated by subtracting the volume of water in the submarine from the initial volume of air.

$$P_i \forall_i = P_{i+1} \forall_{i+1} \tag{14}$$

This is likely a conservative assumption, as the vessel may not have been airtight at the time of the sinking. It is unclear when the hole in the forward hatch tower occurred, but if this occurred during the attack, the vessel would be open to the atmosphere, and the initial flooding rate would be maintained throughout the sinking process. It is also possible that the vessel was not made completely air-tight by the crew, as they may have had no intention of fully submerging the vessel and would have been more concerned with ease of exchanging the air for breathability.

From the stability analysis, it was found that the *Hunley* will sink after taking on 50-74 gallons of seawater. (Note that the vessel may also be able to dive dynamically by using the dive planes to exert a downward force with sufficient forward speed even if the vessel is net buoyant. The maneuverability of the vessel has not yet been investigated). To explore the entire critical time period and to be conservative, the system was analyzed until 75 gallons had flowed into the submarine through the hole.

A convergence study was conducted for the initial model. For this study, the time step was altered until the solution was no longer dependent on the time step used. The volume of water that flows through the hole during a specified time period, 140 seconds, was used as the solution for comparison. An initial time step of 2.0 seconds was used and it was found that the model converged with a time step of 0.01 seconds; a time step of 0.005 seconds was used to solve the model. The convergence of the model is shown below in Figure 28.

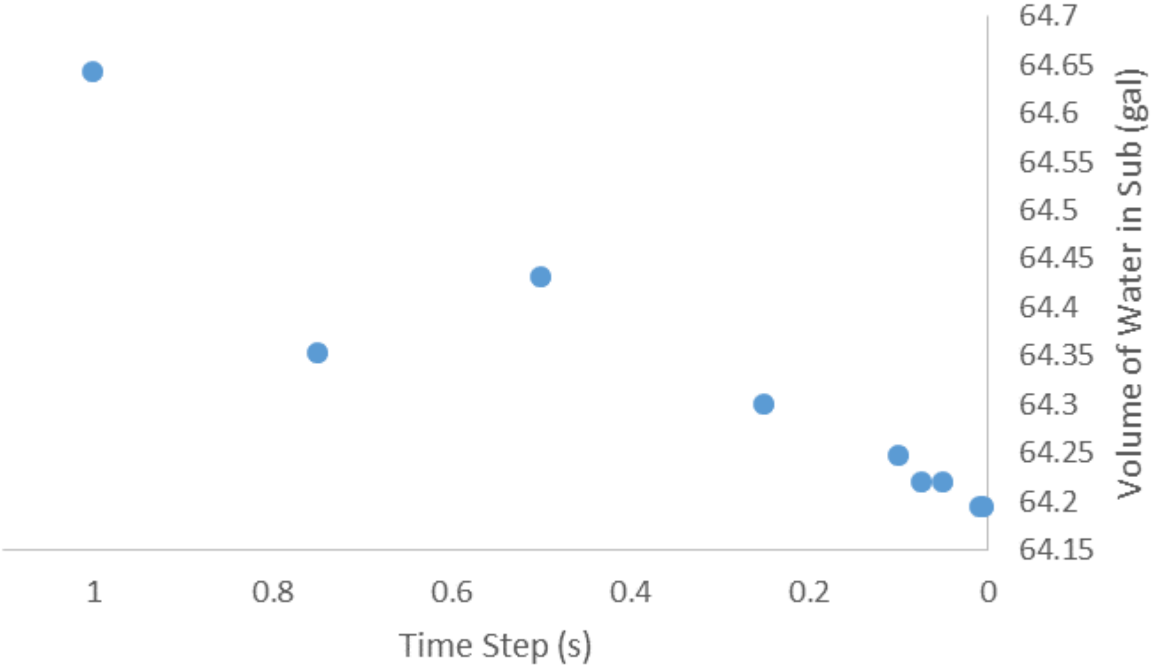


Figure 28: Convergence of Bernoulli Model

In the Bernoulli model, it took 170.5 seconds for 75 gallons to flow into the *Hunley*. The initial pressure difference was 105.00 pounds per square foot and resulted in an initial volumetric flow rate of 0.5425 gallons per second. When 75 gallons had flowed into the *Hunley* the pressure difference reduced to 40.05 pounds per square foot and the volumetric flow rate slowed to 0.3351 gallons per second. The relationship between the flow rate and pressure difference is shown in Figure 29. This flooding time is understood to be a preliminary estimate but is not inconsistent with the battlefield geometry. It is clear that whatever sunk the vessel was not immediately catastrophic as the vessel was able to move about 1,000 feet from the *Housatonic*. It is also possible that the pipe broke later for reasons unrelated to the attack, such as a crew member striking it, especially if the attack damaged, but did not fracture the connection. However, such a scenario is difficult to investigate, at least until more complete examination of the pipe has been made. Thus, further examination of the flow through this break was conducted so that a more accurate time estimate could be made.

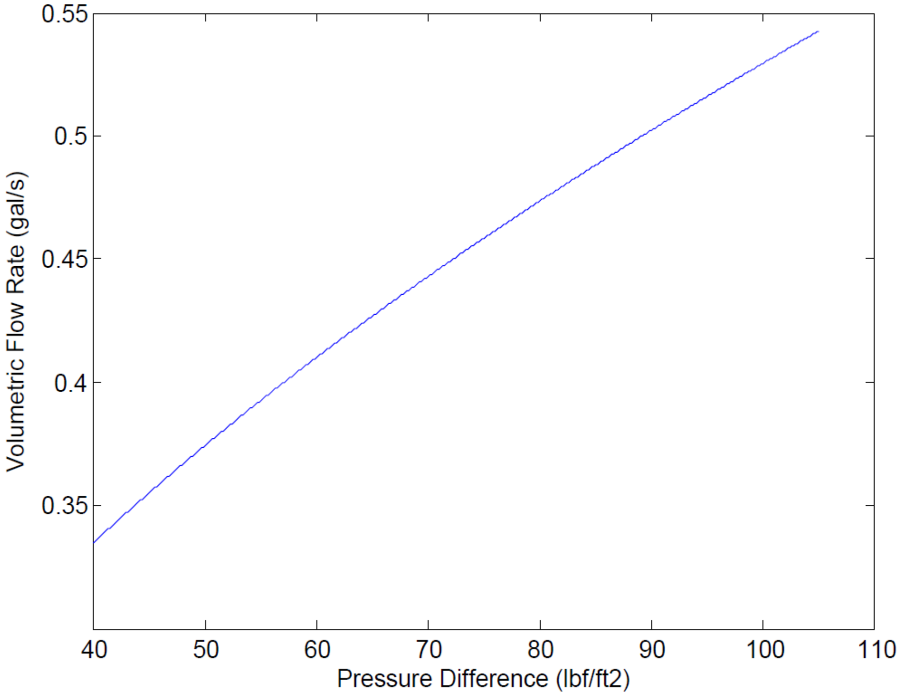


Figure 29: Relationship between Volumetric Flow Rate and Pressure Difference for Bernoulli Model

5.5.2 CFD Model

The irregular shape of the opening means that the simple model used above is unlikely to be accurate. A CFD analysis was conducted to try to determine the flow through the actual dimensions of the break. A static CFD analysis was solved at several pressure differences to determine a relationship between the pressure difference and the flow rate through the hole. Ten different pressure differences, ranging from 11.3 to 105.3 lbf/ft^2, were used in the static model to calculate the resulting flow rate. These results were fitted with a fifth order regression model to describe the relationship between the pressure difference across the hole and the resulting flow rate.

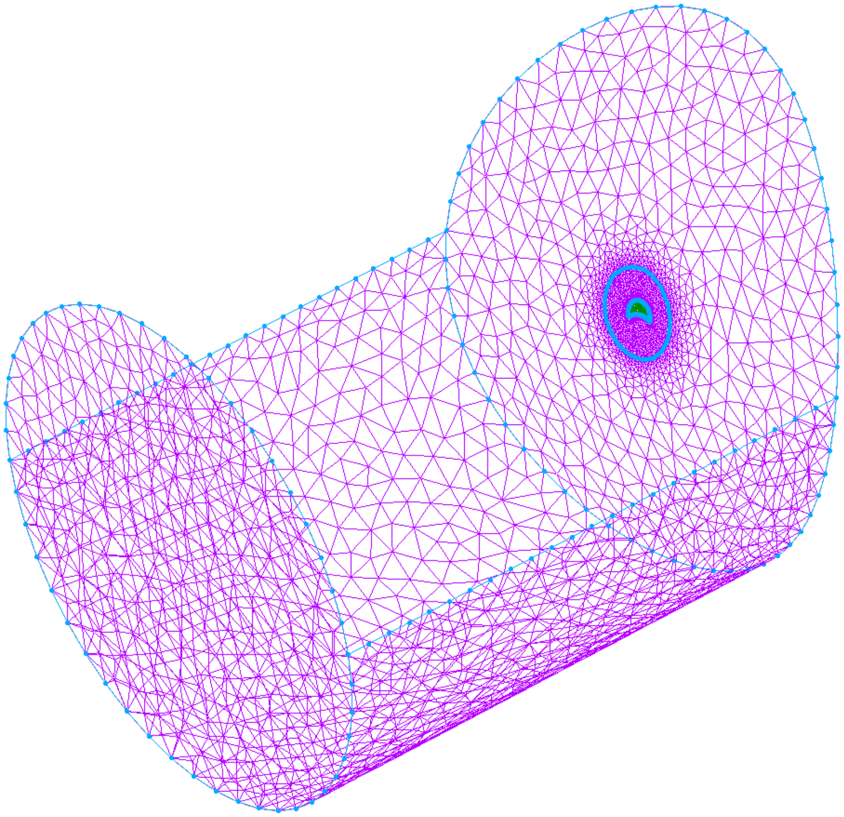


Figure 30: Grid Used for CFD Analysis

The geometry used for the CFD analysis is a horizontal cylinder with one end matching the geometry of the hull around the hole. The mesh geometry is shown in Figure 30; the top half of the cylinder and inner domains are not shown in the figure. The outer hull of the *Hunley* is on the right and the crescent-shaped hole is displayed in green. The mesh size is described in Table 15. The unstructured grid was generated using Pointwise, and T-Rex cells were used around the opening of the hole to capture viscous effects; cells were also concentrated around the opening for a better analysis. The T-Rex cells have an initial height of 0.001 inches, and there are 10 layers with a growth rate of 1.3.

Table 15: CFD Grid Properties

Cells	156,702
Faces	318,524
Nodes	28,682

The cylinder creating the outer boundary has a diameter and length of two feet. This makes the radial distance to the side of the cylinder from the opening approximately eight times the diameter of the hole and the distance to the inlet from the hole to be approximately sixteen times the diameter of the hole; these distances are sufficient to avoid any grid boundary effects on the flow.

The CFD analysis was solved using Ansys Fluent. A pressure based solver with a viscous laminar model was used to solve for the solution. The model was solved as a steady state model with ten different cases. The boundary conditions of the model were chosen to most accurately describe the system. The outer hull of the *Hunley* was set to be a wall boundary. The opening of the hole was set as a pressure outlet. The opposite end of the cylinder and the sides of the cylinder were set as pressure inlets. The pressure inlets were set to the operating pressure, and the pressure outlet pressure was varied to create the required pressure differential. The internal pressures were chosen to cover the entire expected range of the internal pressures for the system. Table 16 shows the exterior and interior pressures and the pressure difference for each case.

Table 16: Pressures used for CFD model

Case	External Pressure (lbf/ft^2)	Internal Pressure (lbf/ft^2)	Pressure Difference (lbf/ft^2)
1	2221	2115.7	105.3
2	2221	2126.1	94.9
3	2221	2136.6	84.4
4	2221	2147.0	74.0
5	2221	2157.5	63.5
6	2221	2167.9	53.1
7	2221	2178.4	42.6
8	2221	2188.8	32.2
9	2221	2199.2	21.8
10	2221	2209.7	11.3

A convergence study was conducted to ensure that the grid for the model was fine enough. The cell size on the face of the outlet and the T-Rex cells were reduced in size until the solution was no longer grid dependent. The flow rate calculated for each case was recorded and through a regression analysis a fifth order model was found to adequately describe the relationship. The volumetric flow rate ($\dot{\forall}_w$) in cubic feet per second is calculated using Equation (15) where dp is the pressure difference.

$$\begin{aligned}\dot{\forall}_w =&((8.66 * 10^{-4}) * dp) - ((1.4 * 10^{-6}) * dp^2)\\ &+ ((1.83 * 10^{-7}) * dp^3) - ((1.3 * 10^{-9}) * dp^4)\\ &+ ((3.59 * 10^{-12}) * dp^5) + 0.006128\end{aligned} \tag{15}$$

A comparison of the calculated values from the CFD model and the regression model is shown below in Figure 31. The R^2 value for the correlation is 0.999997. Over the expected range of pressure differences this model accurately represents the results of the CFD analysis.

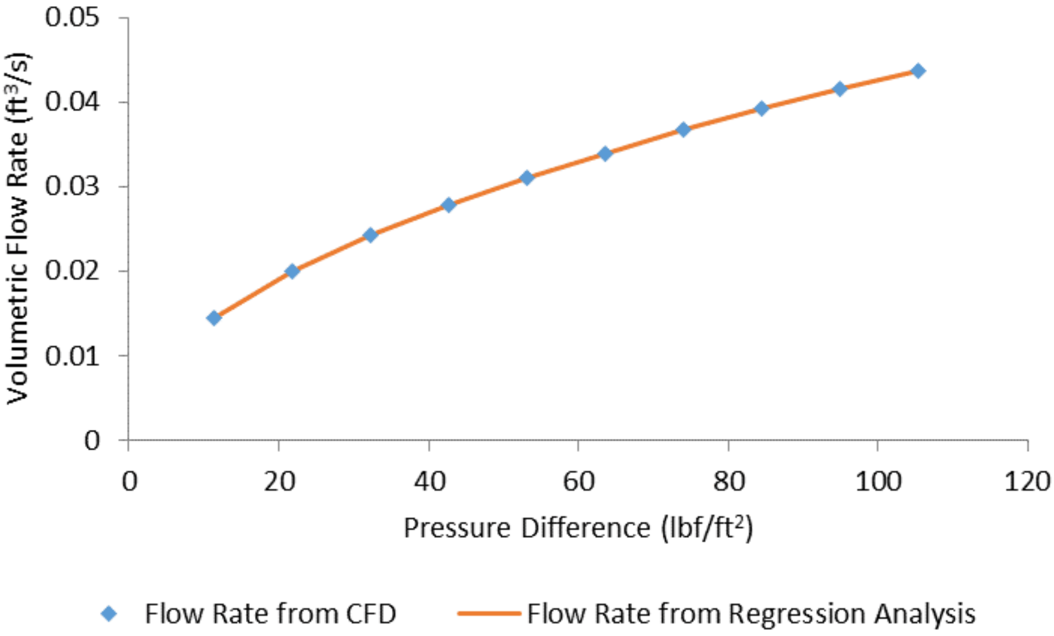


Figure 31: Volumetric Flow Rate from Equation and CFD Analysis

The flooding simulation was re-run, with the flow rate calculated via Equation (15) instead of Bernoulli's equation. This model considers the viscous effects and no longer assumes irrotational flow. This simulation continues with the assumption that the *Hunley* remains at a constant depth with the hole located 1.64 feet below the surface. This simulation also uses the same algorithm to calculate the interior pressure. Similar to the Bernoulli-based simulation, this simulation was used to calculate the flow through the hole until 75 gallons has flowed into the *Hunley*.

The CFD-base simulation calculated that it took 283.9 second for 75 gallons to flow into the *Hunley*. The initial pressure difference was 105.00 pounds per square foot and resulted in an initial volumetric flow rate of 0.317 gallons per second. When 75 gallons had flowed into the *Hunley* the pressure difference reduced to 40.05 pounds per square foot and the volumetric flow rate slowed to 0.203 gallons per second. The relationship between the flow rate and pressure difference is shown in Figure 32. As the submarine sinks below the free surface, the pressure will rise quickly, roughly 64 pound per square foot per foot of additional submergence. At the seafloor, the flowrate would be much higher than with the vessel running in the decks awash position, even at the relatively shallow depths where the attack took place.

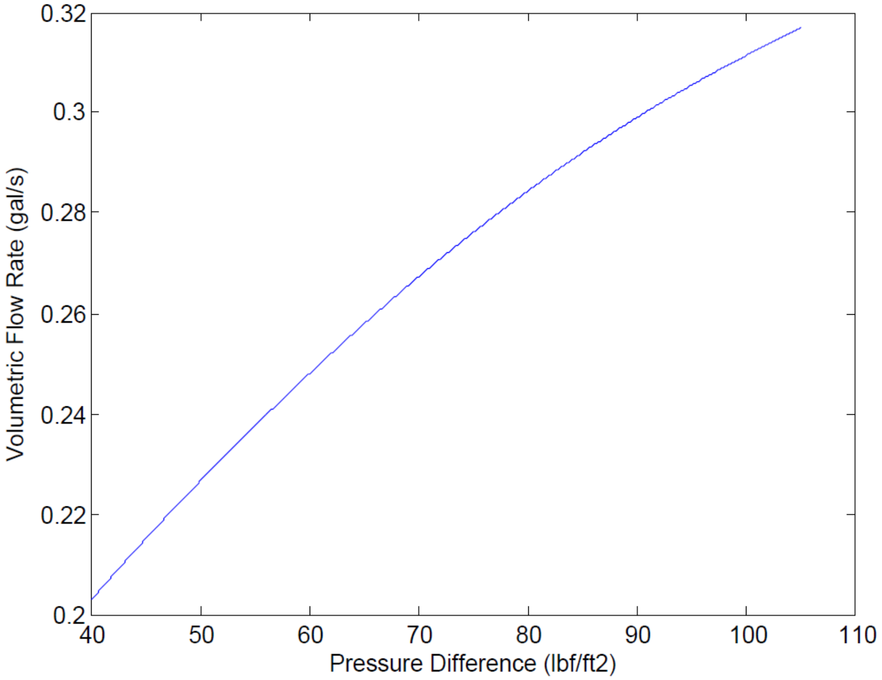


Figure 32: Relationship between Volumetric Flow Rate and Pressure Difference for Refined Model

Thus, the CFD model predicts a much slower flow rate than the simple Bernoulli model, taking over four and half minutes for the vessel to sink. However, the time frame remains consistent with the battlefield geometry - even if the vessel suffered the sheared ballast pipe during the attack, the vessel would remain on the surface for several minutes, giving it time to get away from the *U.S.S. Housatonic*. However, the CFD model also contains approximations compared to the real-world pipe geometry. Most significantly, the opening is considered a simple orifice, with no flow restrictions from the pipe inside the hole, and no interaction between the open pipe ending and the flow. Including these details in the CFD model would have required extensive development and validation. Given the small size of the failure, experimental confirmation was judged a more effective approach.

5.6 Experimental Results

To validate the CFD model and time to sink estimates, a full-scale mock up of the broken ballast pipe, hull surface, and hull opening were created and experimentally tested. The geometry of the fracture was modeled and then created via additive manufacturing in ABS plastic. An image of the geometry is shown below in Figure 33. A section of the hull geometry, capturing the curvature of the hull near the through-hull termination of the ballast fill line was modeled. Based on measurements and photographs of the broken pipe, the through-hull opening and offset, and inner fill pipe were included in the model. Additionally, the ballast fill line that had broken off was modeled back the location of the seacock valve in the fill line. This valve was in the closed position when the vessel was recovered, the closed valve was simulated by printing a solid end to the pipe. The pipe was printed hollow, with the same wall thickness observed on the vessel, to capture and flow patterns involving the open end of the pipe. The model was also surrounded by a simple square box for mounting in a pressure chamber.

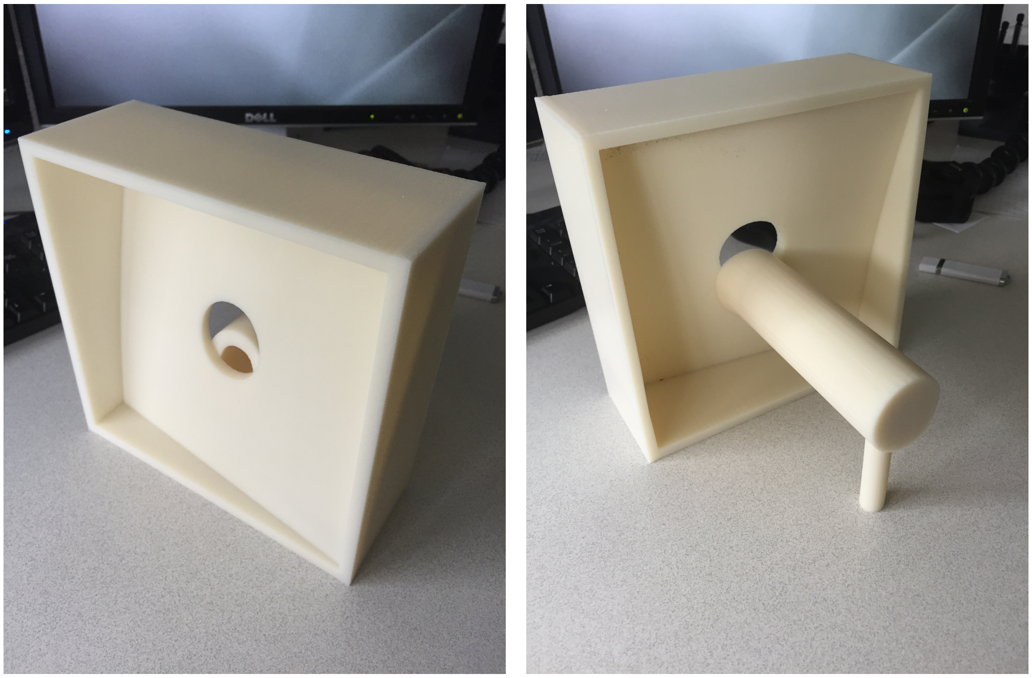


Figure 33: 3-D Printed Pipe Geometry and Failed Connection

A variable-pressure water chamber was built to test the pipe break. The chamber consisted of a large pressure vessel that could be partially filled with water. The pressure in the air above the water could be modified via a control system to simulate different external pressures. With this configuration, the flowrate at different external pressures could be determined. A schematic of the arrangement and pipe specimen mounted in the chamber is shown in Figure 34.

The results from the experimental analysis are shown in comparison with the other two methods in Figure 35. The experimental results fall between the other two methods, but generally closer to the CFD results. There is a slight discontinuity in the experimental results at the point when the air pressurization systems was initially engaged at $100\frac{lbf}{ft^2}$, otherwise the plots all follow the same shape. The results indicate that the timings calculated by the CFD results are an upper bound for the estimated time to sink as:

- The CFD results have the lowest flowrate
- The CFD results assume an air-tight hull, with pressure build up. Battle damage (the grapefruit-size hole discussed in Scenario 2 in Table 1), or lack of attention to making the vessel airtight would result in no pressure build up and a faster flooding rate.

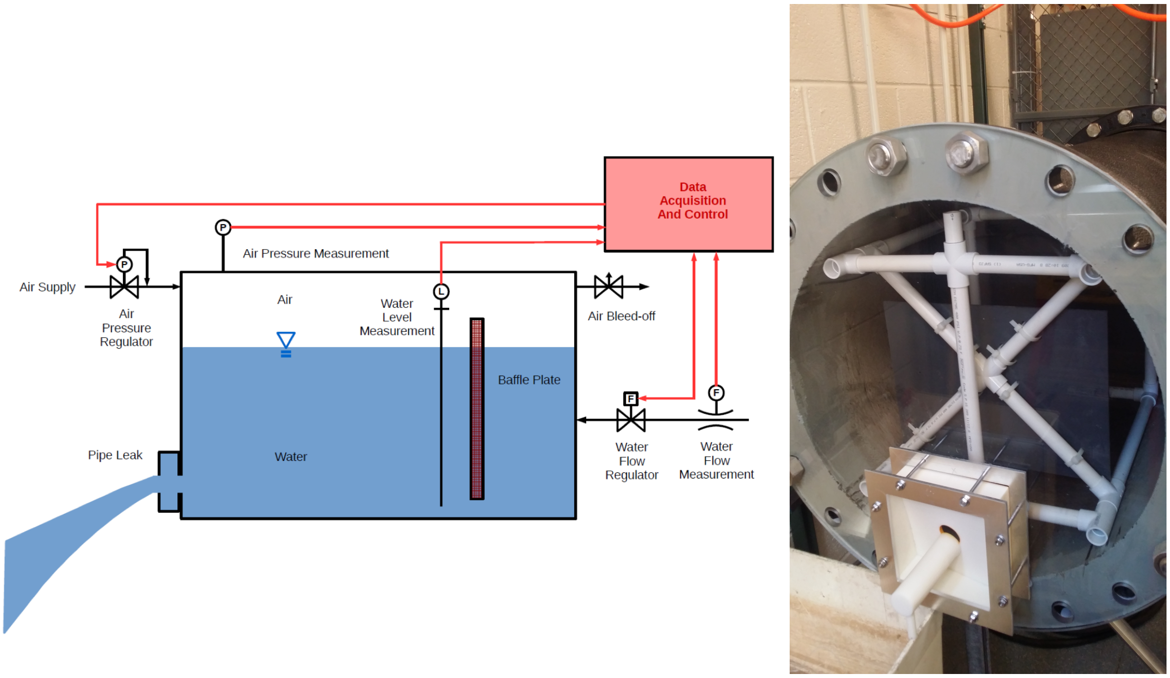


Figure 34: Pipe Model Test Schematic and Setup

- If the forward conning tower damage occurred during the attack, when this part of the vessel submerged, the flooding rate would further increase.

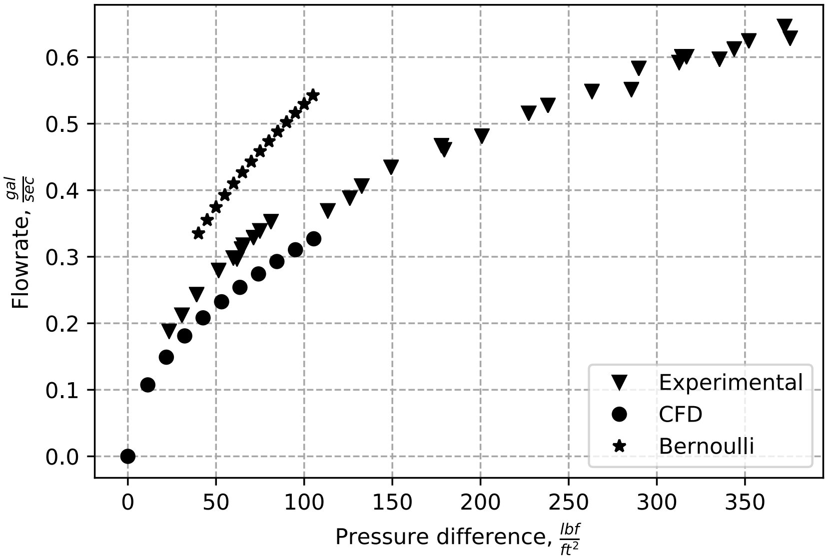


Figure 35: Experimental Flow Results Compared to Simple Model and CFD Model

Knowing the maximum time to sink of 4 minutes and 44 seconds is valuable. Combining this distance with the battlefield geometry allows a required speed to be calculated. To cover the 1000 feet that the vessel moved from the *Housatonic* in 4 minutes 44 seconds requires an average speed of 2.07 knots. While the vessel would have to fall through the water column to reach the seabed, the shallow depth in this area of the coast means that the vertical distance to fall is only on the order of 20 feet. Given that the vessel's fore and aft balance would already be upset by the loss of the charge, it is unlikely the vessel maintained an even keel line while sinking, further reducing the distance necessary to sink before the vessel hits the seafloor. An uneven keel at impact is further supported by the broken rudder observed at the wreck site, suggesting the vessel may have hit stern first. Thus, the time falling the vertical distance to the seafloor is not thought to add significantly to the overall time.

5.7 Drift Forces

Knowing the time it takes for the submarine to sink, the question turns to how the *Hunley* covered this distance. To analyze options for the vessel's movement, information was found about the sea state to determine if the current would be able to move the *Hunley* a significant distance without the crew contributing. Such an unpowered drift would be necessary if the crew members were disabled by their vessel's weapon.

From the NPS report, some background is provided about the metocean data along the South Carolina shoreline. The tidal forces and currents are the predominant acting forces along the South Carolina shore line in this time frame [12]. The tidal range is five and a half feet with a maximum of eight feet. At the lower tidal ranges, we would expect to see predominately wave forces. The currents are alongshore currents, varying in velocity and direction heading southward, developed from the waves hitting the shore. The annual wave data suggests a significant wave height of 4 feet with a period of five seconds. The wind acting along the coast is seasonal. South and southwest winds can be found during the summer with an annual average of 12.5 knots found offshore. It is expected that the waves would follow the same approximate seasonal trends [12].

A significant wave height of 4 feet would be dangerous to the submarine and perhaps prove that flooding through the forward hatch would be an option. However, because all personal accounts state that the particular night of the attack was calm, and the records are from an averaged set of values, it is safe to eliminate flooding through the forward hatch as an option for the sake of discussion in this paper.

To learn more about the potential for current-powered drift, National Oceanic and Atmospheric Administration (NOAA) was contacted to obtain tidal variation and current data from the Fort Sumter region to be able and verify accounts that the *Hunley* left around high tide. Some difference in tide timings is likely between the *Hunley* site and the Fort, owing to the harbor location of the latter, however, tide data was not available at the attack location. The results are presented in Figure 36.

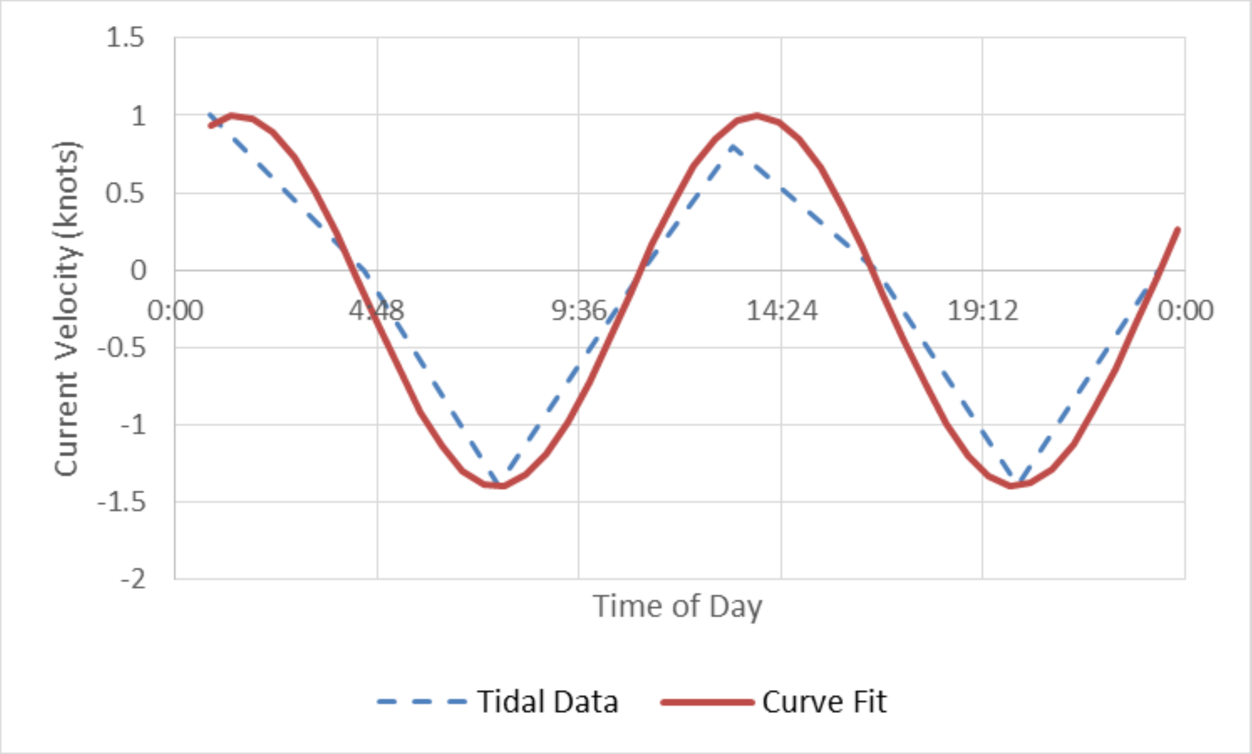


Figure 36: Current Velocity over February 17, 1864

The current data was only available at a few discrete points. A smooth curve fit to the current data was created to simulate the vessel's drift. The fit uses the crossing between 4:40 pm and 11:21 pm as anchors. The curve's offset and amplitude were selected to fit a maximum current of 1.4 knots away from Fort Sumter. This fitting strategy is sufficient because the time of interest is between 7:00 pm and 11:00 pm, so the fit is not as critical for the first half of the data. The fit equation is found in Equation (16), where the equation is in seconds from midnight on February 17th, and velocity is in knots.

$$v_{Current} = 1.2 * sin\left(\frac{2\pi}{44400} * t + 240\right) - 0.2 \tag{16}$$

Using this data, the first thing to verify is the assertion that the *Hunley* was able to leave around 7:00 pm and ride the tide to the attack site. Ebb tide at Fort Sumter is 4:11 pm, reaching full speed at 8:01 pm. This timing verifies that the current would have been at the crews back on the way to the attack site, and would continue until around 11:21 pm. After the attack however, the crew would have to wait for 2 hours 30 minutes before flood tide to ride the current back to shore; otherwise, they would have to fight the ebb tide traveling between zero and one knots. The propulsion study presented previously indicates that the vessel's maximum sustained speed is probably on the order of one knot. Thus it is quite likely that the vessel would plan to wait until almost slack water before starting the journey to shore.

The next area of interest is to determine how far the vessel is able to drift under the forcing of the current alone. If all the crew members were disabled by the blast of their own weapon and the ballast pipe sheared, the vessel would need to travel the 1000 feet to the vessel's final resting location in less than 5 minutes by current alone. Assuming the *Hunley* has instantaneous acceleration after the attack into the current, two simulations were run to see how far the vessel would drift. The first calculation used a linear fit between the NOAA data points, and the second used the sinusoidal curve fit from Equation (16). The results are presented in Figure 37. The drift distance is measured from the point of attack at the Housatonic, while the time is measured in seconds from the attack, assumed to be at 8:58 pm. There is a small difference between the tidal current models which increases as time increases, about 70 seconds of difference at 1000 feet.

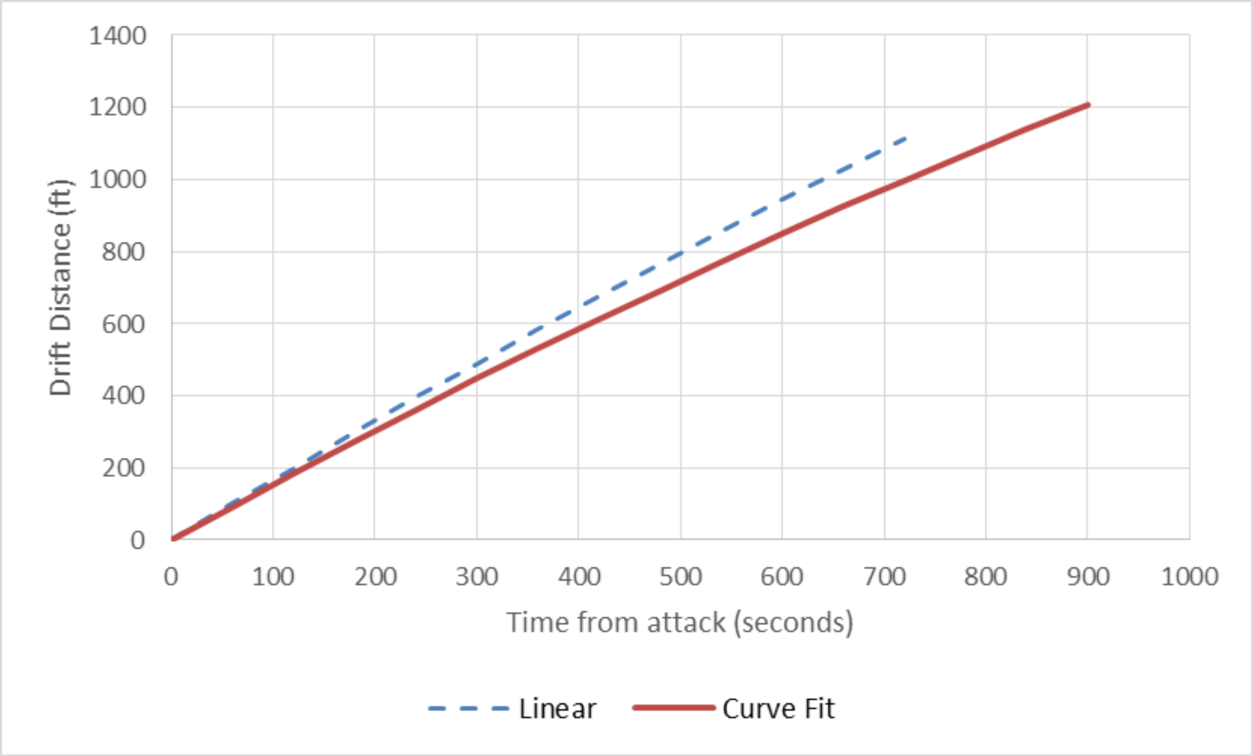


Figure 37: Drift distance calculated with the current velocity over time

Section 3.4 suggests that the required travel distance is 1000 feet based on relative location of the *Housatonic* and the *Hunley* wrecks. Figure 37 shows that it would take about 13 minutes of drifting to cover this distance, which is beyond the 4 minutes 44 seconds that were found in Section 5.5. This timing makes it unlikely the pipe failure at the time of the attack and a completely disabled crew would lead to the battlefield geometry that was observed. Several other explanations could fit some of these facts, but at the moment none of them are fully consistent with what was observed:

- It is possible the crew had the *Hunley* much higher in the water than assumed here. The extra reserve buoyancy would allow for additional time for the vessel to drift before sinking. However, this would contradict the memories of William Alexander who otherwise correctly recalled many details of the vessel. Additionally, it is not clear why they would reduce the vessel's stealth by doing so. Eyewitness testimony from the court of inquiry indicates that some of the deck seemed to be visible, but also that the protrusions, probably the hatches or snorkel box, were making waves. Thus, it is hard to say conclusively where the vessel was in the water.

- It is possible the crew was not incapacitated, and either helped propel the vessel to the final sinking location or tried to slow the water flow in from the broken pipe. However, if this was the case why were the keel weights not released, or more effort made to escape the slowly sinking vessel?
- It is possible the pipe break did not occur during the attack run but was a result of damage during the many attempts to find the wreck with grapples after the attack. However, this requires a second, independent, reason for the vessel's loss to be postulated.

6 Conclusions

A detailed naval architecture study of the *H.L. Hunley* reconciled the historical and archaeological record of the vessel with numerical simulation and engineering analysis. Detailed geometry studies, weight estimation, stability estimation, resistance and propulsion estimates and model tests, and flowrate estimates from the damaged ballast fill pipe were carried out. Overall, the historical record and archaeological interpretation are remarkably consistent with the results of the simulations carried out. Specifically:

1. The vessel's stability, based on the measured lines plan and detailed weight estimate, appears to support the historical concept of operations. The vessel is stable throughout the fit-out, loading, and submergence process. While not planned to operate as a submarine on the final voyage, the vessel could submerge if needed based on its stability.
2. The vessel's powering calculation estimates agree with the historical record, which contained statements that the vessel could sprint between three and four knots, but that missions were planned around the tide as the vessel would struggle to fight the tide. The resistance and propulsion estimates and model test seem to confirm that the vessel would be limited to speeds near one knot for prolonged operation, but could sprint up to three or three and a half knots for short periods.
3. The broken ballast fill pipe would likely prove fatal to the submarine within a short period of time. Without efforts to stem the flow of water, the vessel would leave the surface within five minutes of the break occurring from a decks-awash draft.
4. The limited tidal data available for the night of the attack suggests that it would take roughly 13 minutes to drift from the attack site to the final resting place of the *Hunley.* The time to drift is more than twice the time estimated to sink from the fractured ballast fill line. Thus, both all the crew being incapacitated and the pipe breaking during the attack does not appear compatible with the final battlefield geometry.

Based on this analysis, it is possible to comment further on several of the initially proposed scenarios:

1. **The *Hunley* was underpowered and unable to fight the tide to shore:** From the analysis, it is clear that the *Hunley* was unlikely to make much progress towards the shore immediately after the attack. Given that the crew was experienced with the vessel, and left with the tide, they most likely were not planning to immediately return. This increases the likelihood that they might have been planning to hide until the tide turned.

2. **A grapefruit sized hole in the forward hatch caused significant flooding:** No further information on this scenario was generated.

3. **The sheared ballast pipe caused enough flooding to cause instability and ultimately sinking:** The sheared ballast line continues to appear to be central to the loss of the vessel, but its exact role and timing of the breach remains unclear. Based on the results of this study, if the line sheared and no corrective action was taken, the *Hunley* should have been found closer to the *Housatonic*. However, there is no other evidence of corrective action taken on board the vessel - no effort to release the keel ballast weights can be seen from the condition of the wreck.

4. **The broken rudder caused sufficient loss in control that the *Hunley* drifted till it sank:** No further information on this scenario was generated in this work, the current theory is that the final separation of the rudder occured after the vessel was on the bottom.

5. **The crew was knocked unconscious from the blast, and drifted until natural leaks or other flooding caused them to sink:** As investigated by NSWCCD, the explosion alone did not seem to be severe enough to fully disable crew. Additionally, the fast flooding rate from the sheared ballast pipe indicates that a straightforward combination of scenarios three and five do not match the battlefield geometry.

6. **Significant instability caused by water flooding over the bulkheads from the ballast tanks caused the *Hunley* to sink:** Based on the initial stability results, it seems unlikely that the vessel lost stability immediately after the attack. The vessel has a fair amount of reserve stability as long as additional water is not added to the hull, and such an event would most likely have resulted in the *Hunley* being found closer to the attack site.

7. **Upon signaling a successful attack, a wave came over the forward hatch causing the vessel to rapidly downflood:** No further information on this scenario was generated.

8. **The *Hunley* crew retreated a safe distance and waited on the bottom, dying from asphyxiation:** Given the vessel's powering characteristics, this scenario now appears to be more likely. It appears that the vessel could not rapidly return to shore against the tide, so the crew may have decided to wait until slack water. More work on the air consumption of the crew would help further evaluate this scenario.

9. **The *Hunley* crew intentionally grounded the vessel to hide the secrets of it construction from the Union Navy:** No further information on this scenario was generated.
10. **The *Hunley* was unable to back away from the *Housatonic* after the attack, and was trapped underneath the hull of the *Housatonic*:** Not investigated as does not fit with the battlefield archaeology; additionally the vessel appears to have a strong sprint ability in the three to four knot range.

The review of the scenarios confirms a somewhat disappointing aspect of this work. While the *Hunley* is much better understood technically after this work, a simple, coherent story for explaining the vessel's loss remains elusive. The sheared ballast pipe points to a rapid sequence of events, but both the battlefield geometry and vessel's powering indicate that the *Hunley* may have intentionally been kept near the attack site by the vessel's crew for a prolonged period of time. One of the key challenges of working with the *Hunley* is that the need to wait for the tide to change raises the probability that the crew may have simply run out of breathable air while either actively attempting to escape or waiting for the change of tide. This scenario is very difficult to disprove at this point, as the only evidence from this sequence of events would have been in the soft tissue of the crew which has long since disappeared.

There are also a number of limitations to the work presented here, as well as open questions that could use further analysis:

1. **The vessel's resistance is highly influenced by skin friction:** Especially at lower speeds, the majority of the vessel's drag was a result of skin friction. In the work presented, modern friction line approaches were used to estimate this drag component. However, if the actual vessel had a very rough outer surface, or had extensive biofouling during the attack, the vessel's resistance would be higher than that presented here. The exact state of the vessel's outer surface is not presently known.
2. **A more accurate propeller model is still needed:** When this work was completed, the propeller was not yet de-concreted. Thus, only an approximate model of the propeller could be made. A more refined model, based on the actual propeller geometry, would be helpful.
3. **A better understanding of the air consumption onboard would further help understand the vessel's final movements:** With a better propeller model, a more detailed calculation of the crew's aerobic activity to move the vessel through the attack sequence could be made. With the known internal volume of the vessel, the crew's ability to continue to receive the oxygen necessary to function after this sequence could be evaluated, shedding more light on scenario eight.
4. **The vessel's position in the water is important to the final event sequence:** The analysis here was based on the assumption that the vessel operated low in the water, with the hull's top surface just awash. This matches the historical sketches of the vessel with a waterline somewhat up on the conning towers. However, if the vessel was higher in the water on the final night, a combination of scenarios three and five

may again become practical. As the final depth of the vessel was most likely set by the crew during the mission, the exact attack position may never be known. It is not clear that there would be any advantage in operating the vessel at a lighter draft - stability would increase, as would visibility but the stealth characteristics would be reduced.

5. **The longitudinal stability of the vessel with crew moving should be investigated** The inside of the submarine is very tight, making it difficult for the crew to move fore and aft once in place. However, it is possible if the commander of the vessel became disabled, the crew near the front may try to move forward to help operated the ballast system or vessel controls. Also, if the ballast pipe burst, efforts to stop the leak may have involved more than one person to help. The impact of such shifts on the vessel's longitudinal stability should be investigated.

Thus, more work exploration of the *Hunley* and its naval architecture characteristics is highly recommended.

Acknowledgments

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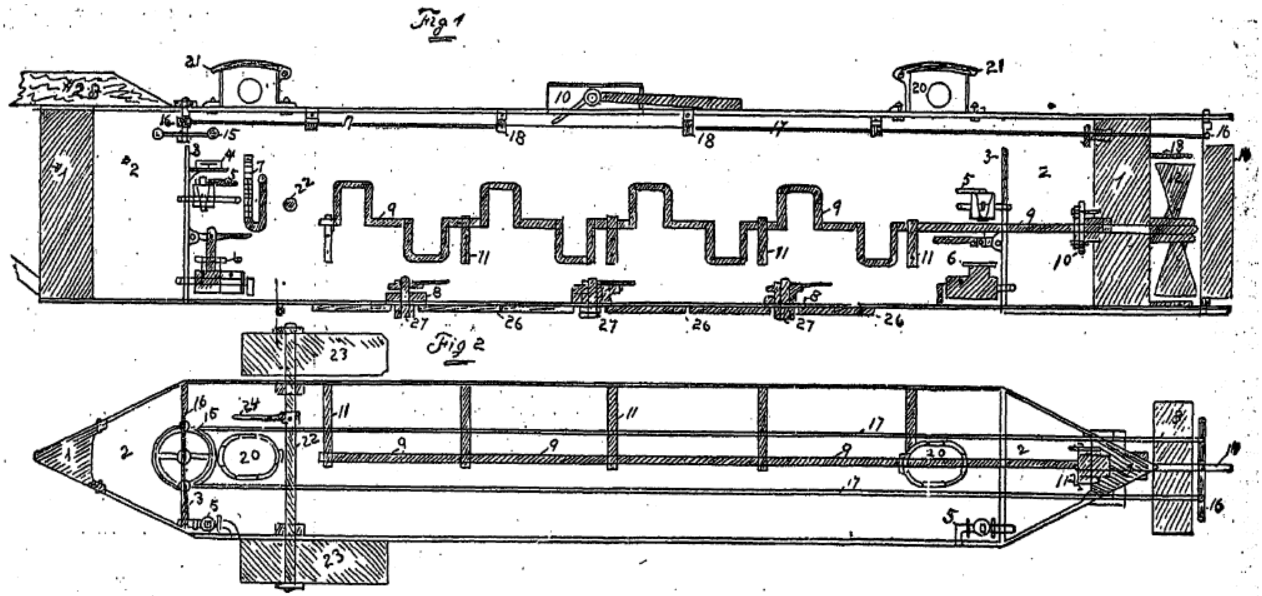
Appendices

A Historical — and often inaccurate — descriptions of the *Hunley*

Many resources over the years have presented a variety of information about the features of the *Hunley* with no certain accuracy. At the current time, it is best to directly consult the Warren Lasch Conservation Center to receive the latest archaeological findings on the vessel, as they work with the preservation of the wreck. However, this appendix presents the historical sources in context, so that future researchers will have an understanding of the various sources that have discussed the *Hunley* in the intervening decades. **Note that the data in this section are what the sources reported, work with the actual submarine has not backed up many of these findings.** Not every error is explicitly called out in this section. There are three major resources that are continually cited as being the best resource on the *Hunley*, and are referenced throughout this paper: the 1902 *New Orleans Picayune* article written by William Alexander, the Official Records of the Union and Confederate Navies series: dated from 1863 to 1864; and finally the National Park Service (NPS) Site Assessment completed in 1998.

An article published in the *New Orleans Picayune* [1] was written by the surviving *Hunley* crew member, William Alexander, who did not sail on the final mission. He admits that it had been 40 years and details are strictly from memory. Alexander describes the *Hunley* as being created from a cylinder boiler, cut longitudinally in two pieces, then riveted together with a 12 inch strip of plate. This would give the *Hunley* an overall dimension of 30 feet long, by 4 feet wide, and 5 feet deep. Alexander describes the vessel being ballasted by flat iron castings, fitted to the outside of the hull which could be detached by a square bolt. The dive planes consisted of two 5 foot by 8 inch sections that had been cast, they were operated by a lever amidships at the captain station. The rudder was operated by a wheel (not yet located on the vessel) and levers connected to rods (only one rod appears on the actual vessel) passing through the aft casting, controlled by the captain. The propeller was an ordinary boat propeller attached to a crank shaft with eight stations, where the crew would sit. The crank shaft was offset to the starboard side, and the men sat on the port side of the crank. Alexander also mentions the propeller duct to prevent fouling. Three openings were cut in the top of the hull, two for a fore and aft hatch, and one for a snorkel box with two 4 foot tube attachments. He describes the open top bulkheads, and operating with a two pump ballast system. The torpedo is described as a copper shell holding 90 pounds of black powder, with a friction primer and set off by a trigger. This was intended to float behind the vessel on 200 feet of line, but the final design attached it to a 22 foot pine boom off the front of the bow. This description does not match the archaeology, which found a boom of a different design. The sketch accompanying the description is presented in Figure 38 below.



LONGITUDINAL ELEVATION IN SECTION AND PLAN VIEW OF THE CONFEDERATE SUBMARINE BOAT HUNLEY.

From Sketches by W. A. Alexander.

No. 1. The Bow and Stern Castings. No. 2. Water ballast tanks. No. 3. Tank bulkheads. No. 4. Compass. No. 5. Sea cocks. No. 6. Pumps. No. 7. Mercury gauge. No. 8. Keel ballast stuffing boxes. No. 0. Propeller shaft and cranks. No. 10. Stern bearing and gland. No. 11. Shaft braces. No. 12. Propeller. No. 13. Wrought ring around propeller. No. 14. Rudder. No. 15. Steering wheel. No. 16. Steering lever. No. 17. Steering rods. No. 18. Rod braces. No. 19. Air box. No. 20. Hatchways. No. 21. Hatch covers. No. 22. Shaft of side fins. No. 26. Cast-iron keel ballast. No. 27. Bolts. No. 28. Butt end of torpedo boom. No. 28. Side fins. No. 24. Shaft lever. No. 25. One of the crew turning propeller shaft. No. 81. Keel ballast.

Figure 38: Drawing completed by William Alexander in 1902 accompanying the *Picyune* article

Testing showed the vessel could make 4 miles per hour (3.47 knots) in relatively smooth water [1]. Alexander also noted that it was very difficult to fight the tide back to shore, if they missed the timing. The practiced operation of the submarine was to open the forward and aft ballast tank valves, let the vessel sink to about halfway up the forward porthole, then dive to about 6 feet below the surface. The submarine would come to the surface occasionally to open the hatches and let fresh air into the main compartment. Finally, Alexander stated that during operation, should the vessel ever be unable to surface, there was an agreement between the crew members that they would open the seacocks and flood the compartment to prevent dying from asphyxiation.

A report presented by two deserters of the Confederate Navy, stating that they had worked closely with the *Hunley* during the first and second testing, shows details of the vessel to the Union that warned them of the Torpedo boat [4]. They noted the vessel was about 35 feet long with a height of 5 feet 5 inches, two man holes were spaced 12 or 14 feet apart. The vessel was hand cranked and could make about 5 knots. They also noted that the vessel would make it about a half mile on a dive before surfacing.

Lieutenant George Washington Gift, who was working on CSS *Gaines* had described the submarine as ”a curious machine for destroying vessels” [3]. He described it as a high pressure steam boiler about 4 foot diameter one way and 3 feet 6 inches the other way, drawn closed at either end. He stated that the keel ballast was 4,000 pounds, making the vessel steady to dive. On top there were two man hole plates with glass on top, just large enough for a man to fit through. The propeller was described as having a 3 feet 6 inch diameter (close but not matching the actual propeller which is just over 31" in diameter), hand powered by men turning a crankshaft. Lieutenant Gift noted that when the vessel was fully loaded, she floated about half way out of the water, to sink the *Hunley* used two compartments which filled with water. The air was supplied by pipes that turned up from a depth of 10 feet, but with the air in the compartment the *Hunley* could last three hours, approximated as 15 miles. The torpedo is described as being 100 lbs of black powder attached to a plank of wood floating 200 feet behind the vessel [3].

The design of the *Hunley's* spar is discussed by Ragan's work [4]. Unfortunately, the original description has not been supported by recent work on the spar and charge. It is believed that Ragan's work primarily drew on an article in the October 1937 issue of *U.S. Naval Institute Proceedings* [2]. However, the description is outlined below as it was commonly referenced before actual data from the vessel was available. This states a torpedo was a copper container, designed such that could be mounted on a pole, and the detonated with a triggering mechanism. The torpedo had a steel head that fit over a 10 foot spar attached to the bow. The head of the torpedo also had a saw toothed projection that when rammed into an enemy vessel would stick. The trigger is described as a coiled lanyard of 150 yards of rope that would tighten then trip a trigger. Speculation suggests that the spar was introduced when the *Hunley* was being moved to Sullivan's Island, based on additional news articles from 1864 to 1870 [4]. Speculation also suggests that based on previous expense reports filed by Dixon, that the trigger coil was probably 150 feet instead of 150 yards.

James McClintock describes the vessel in a letter to the British Navy as having an elliptical shape with modeled ends. He states the vessel was built of 5/8 inch thick iron, the vessel was 40 feet long top to bottom, 42 inches wide in the middle, and 48 inches high. The *Hunley* was fit with a geared crank and propeller that was turned by eight people. The sketch completed by James McClintock can be found in Figure 39 below.

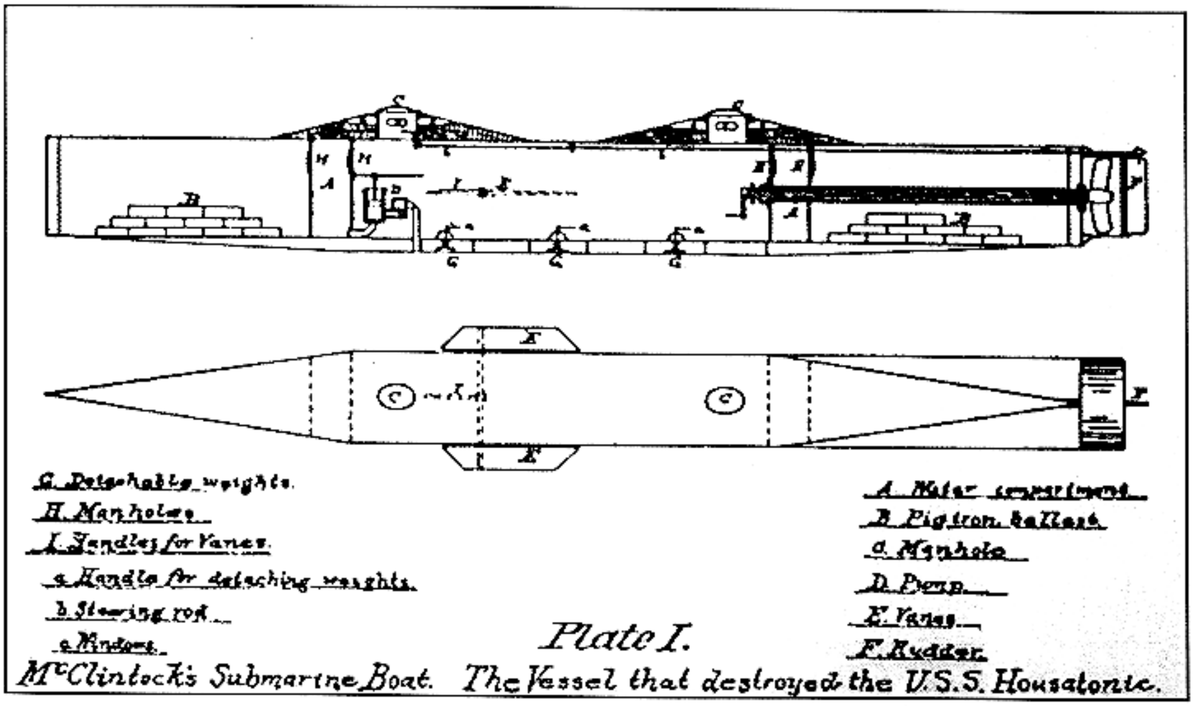


Figure 39: Sketch completed by James McClintock in 1872 accompanying his description of the *Hunley*

The most accurate portrayal of the submarine is Conrad Chapman's sketch made while the vessel was on a pier or wharf after the seconding sinking [3] found in Figure 40. The location of the main features are generally in the correct placement. The important difference between this painting and the Alexander sketch in Figure 38 is the fairness of the hull. Differences recorded after surveying the submarine include location of the spar torpedo and the aft cutwater forward of the hatch [3]. However it is possible those were changed since the *Hunley* was undergoing major modifications at this time.

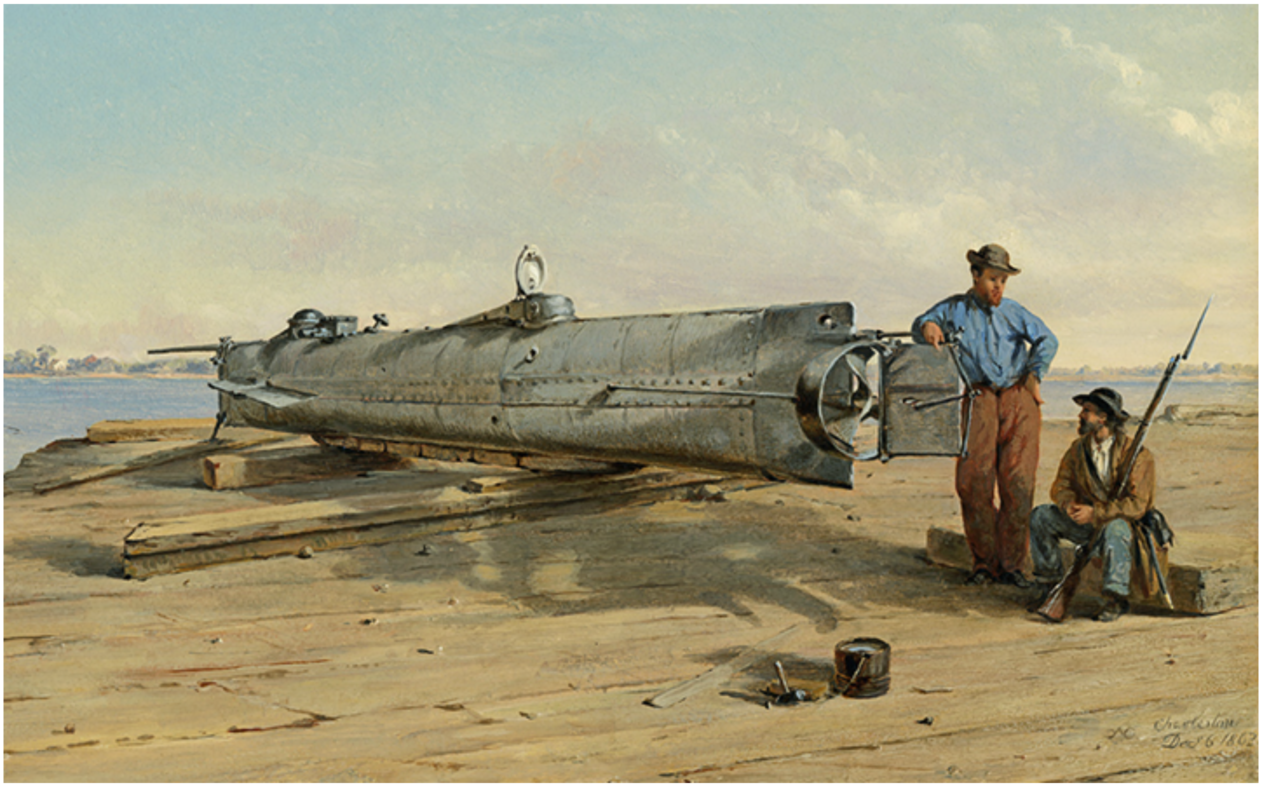


Figure 40: The painting completed in 1863 by Conrad Chapman depicting the submarine after the second sinking

The pre-disturbance survey completed before recovering the *Hunley* presents more important dimensions of the vessel. *In-situ* overall measured length was 39 feet 5 inches from the tip of the upper bow to the aft most part of the upper hull. Profile measurements show 3 feet 10 inches wide and 4 feet 3 inches from the hull top to the bottom of the keel ballast. These are quite close to the final dimensions of 40 feet long, 3' 6" wide and 4' 0" tall found after recovery during conservation. The keel ballast is four and a half inches thick, with a concave shape fitting the hull. The iron strip running longitudinally along the side was measured to be about 9 inches tall.

To properly verify the *Hunley*, the NPS located the forward hatch and cutwater, snorkel box, aft hatch, port dive plane, keel ballast, and deadlights along the length of the hull [3]. The hatches were observed at 16 feet 3 inches apart, with the hatches opening toward each other. They are two feet long at the base, 1 foot 2 inches at the centerline or 1 foot 4 inches on the outside edge. The snorkel box is located 4 inches after of the forward hatch, and consists of a rectangular box about 1 foot 2 inches wide, 1 foot 3 inches long and 8 inches high. Each side had a stuffing box that was 11 inches long and 5 inches wide. The cutwater is identified as a 3 foot 4 inch long section that is 9 inches tall at the forward hatch. A second cutwater, believed for the aft hatch, was found near the submarine during later excavations. The deadlights were spaced evenly along the hull starting 2 feet 6 inches aft of the snorkel box. The port dive plane was measured as 6 feet 10 inches, with a 3 inch diameter pivot point. The width is about 8 inches with a thickness between 1 and 1/4 inch and 1 and 1/2 inches. The drawing accompanying this description can be found in Figure 41.

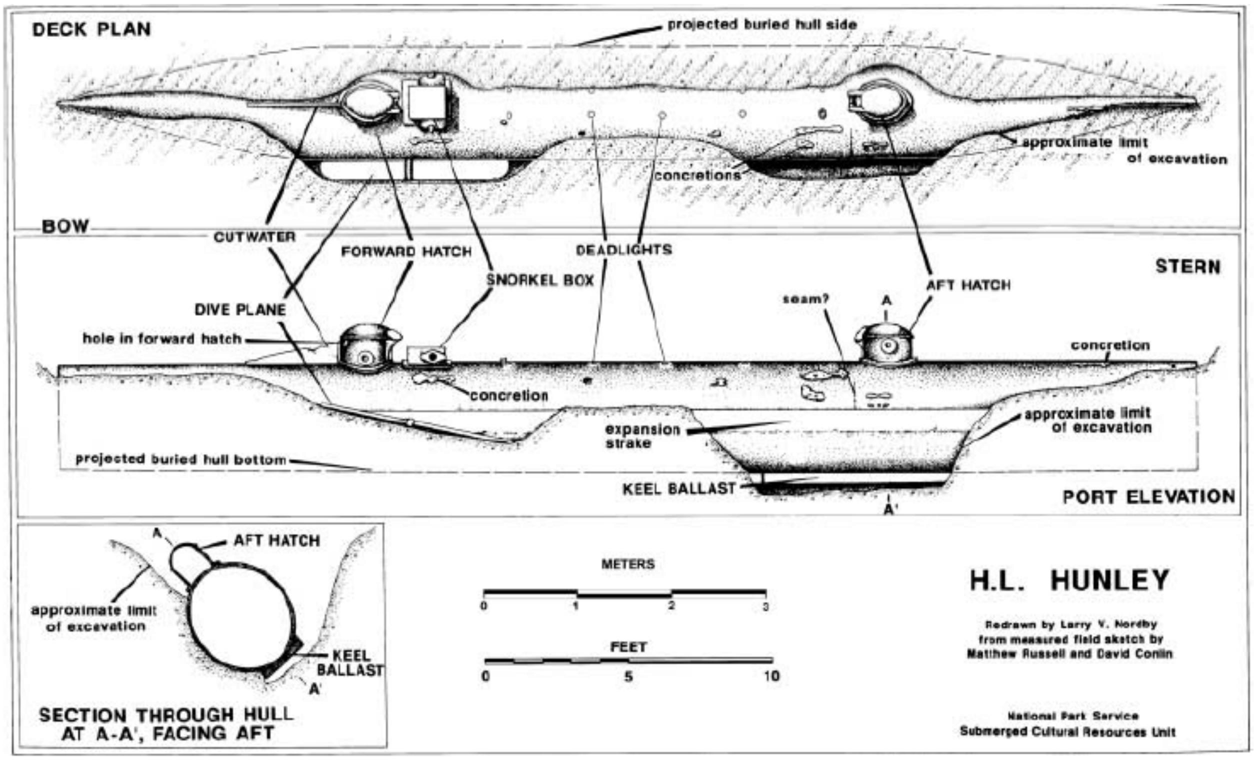


Figure 41: Drawing of the main features of the *Hunley* as discovered during the pre-disturbance survey in 1998

Important hull damage that was found during the survey shows that there was a grapefruit sized hole that is in the forward part of the forward hatch. This is believed to have been involved with the sinking, as initial corrosion analysis shows similar results to the rest of the hull [3].

References

[1] W. A. Alexander. “The True Stories of the Confederate Submarine Boats”. In: *The Daily Picayune* (1902), pp. 6–7.

[2] Harry von Kolnitz. “The Confederate Submarine”. In: *USNI Proceedings Magazine* 63.October (1937), p. 1453.

[3] Larry E. Murphy. *H.L. Hunley Site Assessment*. Tech. rep. National Park Service, Naval Historical Center, South Carolina Institute of Archaeology and Antrhopology, 1998.

[4] Mark K. Ragan. *The Hunley: submarines, sacrifice & success in the Civil War*. 1st ed. Miami: Narwhal Press, 1995. ISBN: 978-1-886391-04-8 978-1-886391-05-5.

B Resistance Model Test Report

Hunley Submarine Model Hydrodynamic Testing

January 17th, 2017
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Dept. of Naval Architecture and Marine Engineering

Introduction

The CSS H. L. Hunley was a submarine-type naval vessel operated by the Confederate States of America during the American Civil War. The recent finding and restoration of its remains has prompted interest in its hydrodynamic characteristics in order to potentially better understand its operation, and ultimately its demise.

A physical hydrodynamic testing program of the CSS Hunley was commissioned at the University of Michigan Marine Hydrodynamics Laboratory (UM MHL). This report presents the findings of the hydrodynamic model testing and the resulting full-scale hull performance prediction.

Test Program

A one-third (1/3) scale model was designed and constructed based upon the current understanding of the CSS Hunley's design, which is assumed to be 39.5 feet long, 3.83 feet in width, displace approximately 7.5 short tons and operate at a top speed of 4.0 knots utilizing a hand-cranked propeller.

A rendering of the side view is shown in Figure 1. In this view, the bow is to the right. Cylindrical conning towers and a ventilation box are located on the top and a weighted steel keel is located on the hull bottom. A dark horizontal line near the top indicates one of the estimated running conditions. The grid shown is drawn full-scale with major grid lines indicating feet.

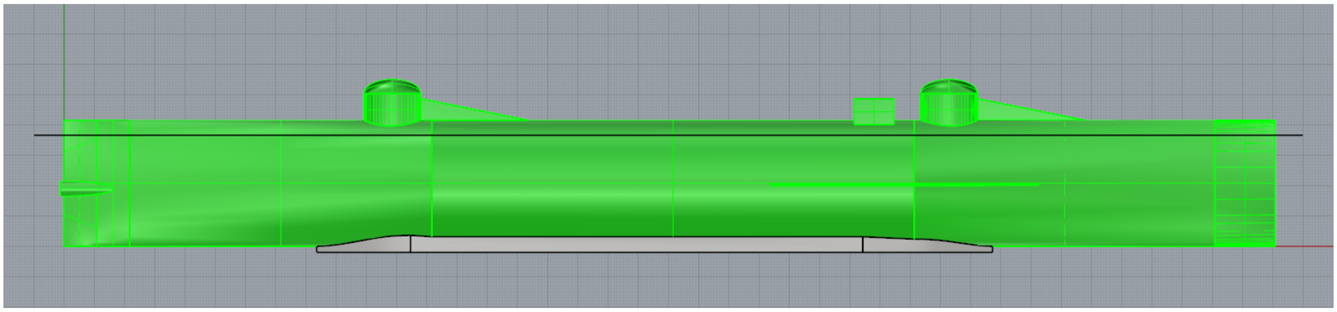
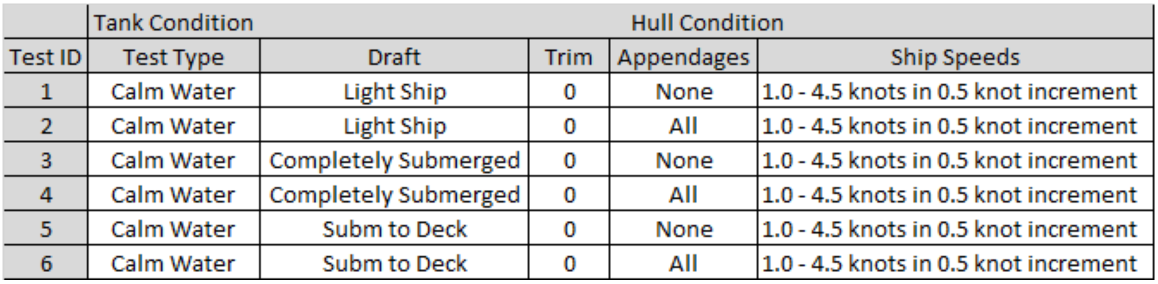


Figure 1: Rendering of CSS Hunley model hull design side view

The model was constructed of wood with an interior filled with steel and lead ballast to achieve the appropriate trim conditions. The model was sealed with an epoxy coating and painted. It is believed that the boat had rivet heads and metal plate joining seams exposed on the exterior of the hull; no attempt was made to recreate the exterior surface to that level of detail. However, the model exterior paint surface was not finished to the typical 'hydrodynamically smooth' condition, in order to provide some level of roughness exposed to the passing fluid.

The model was secured to the UM MHL Physical Model Basin powered carriage utilizing a force dynamometer. The model was towed through the water at a variety of speeds and draft conditions and the resulting hydrodynamic drag on the hull was measured by the force dynamometer.

In addition to changing the hull ballast condition and speed, tests were conducted both with and without the hull control surfaces in order to quantify their hydrodynamic impact on the hull. The model test matrix is shown in Table 1.



	Tank Condition	Hull Condition			
Test ID	Test Type	Draft	Trim	Appendages	Ship Speeds
1	Calm Water	Light Ship	0	None	1.0 - 4.5 knots in 0.5 knot increment
2	Calm Water	Light Ship	0	All	1.0 - 4.5 knots in 0.5 knot increment
3	Calm Water	Completely Submerged	0	None	1.0 - 4.5 knots in 0.5 knot increment
4	Calm Water	Completely Submerged	0	All	1.0 - 4.5 knots in 0.5 knot increment
5	Calm Water	Subm to Deck	0	None	1.0 - 4.5 knots in 0.5 knot increment
6	Calm Water	Subm to Deck	0	All	1.0 - 4.5 knots in 0.5 knot increment

Table 1: CSS Hunley model hull test matrix

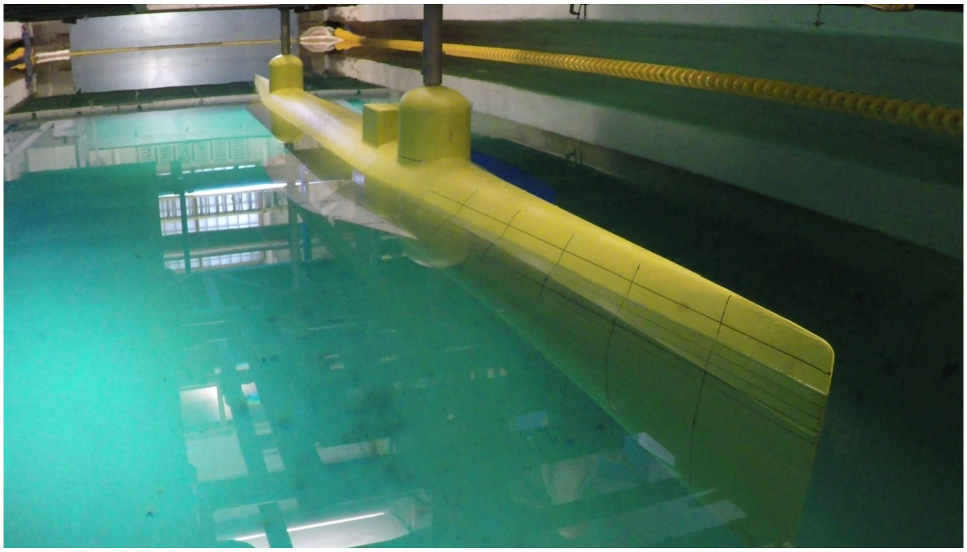


Figure 2: CSS Hunley model at static lightship condition (test cases 1 and 2)

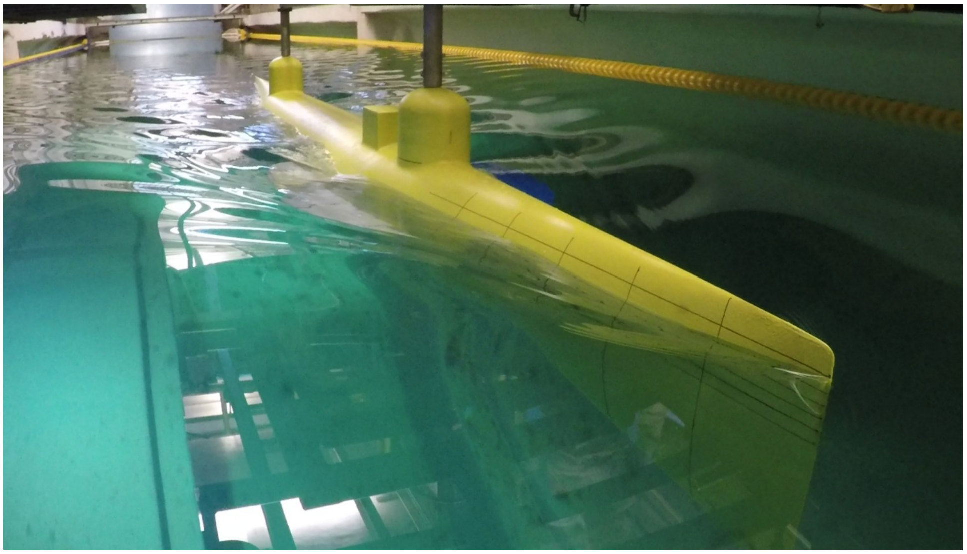


Figure 3: CSS Hunley model at 3.0 knots scaled speed for lightship condition (test cases 1 and 2)

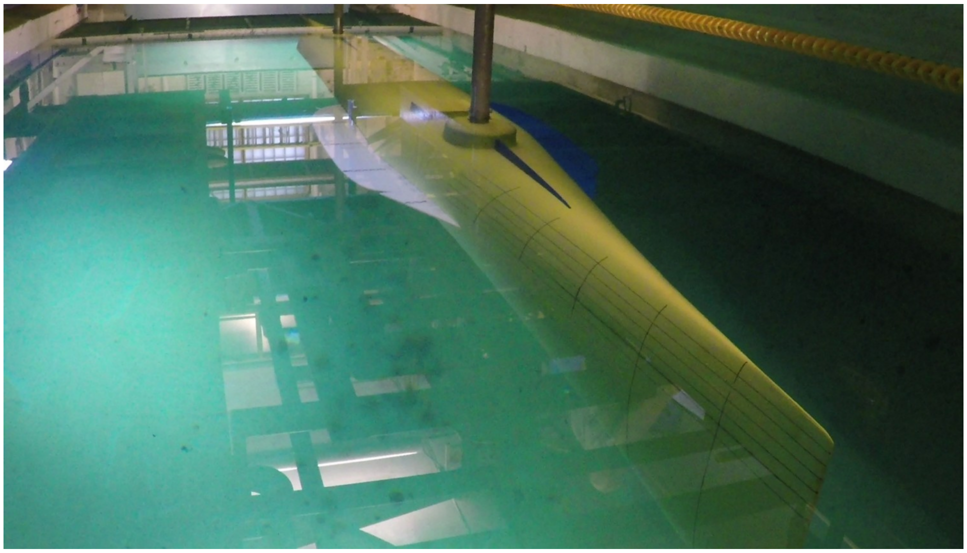


Figure 4: CSS Hunley model at static completely submerged condition (test cases 3 and 4)

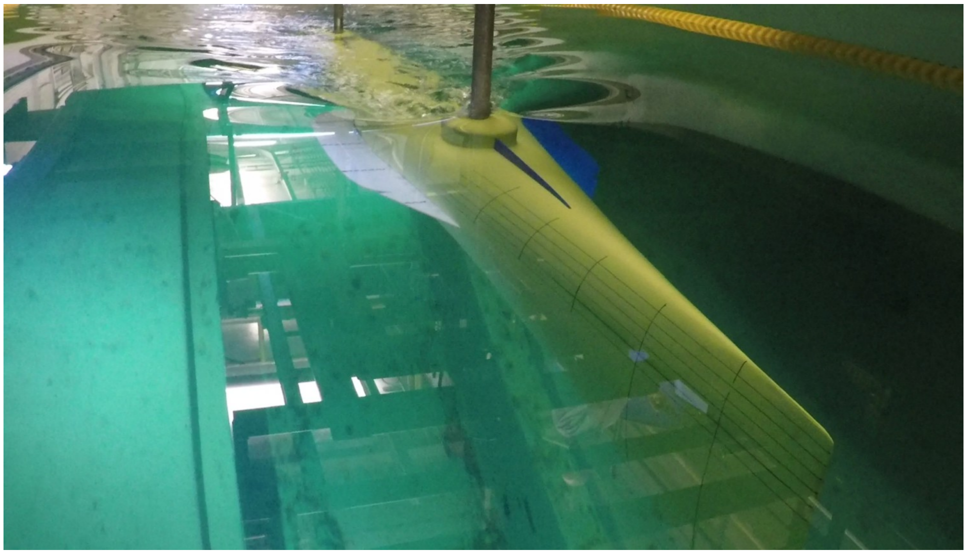


Figure 5: CSS Hunley model at 3.0 knots scaled speed for completely submerged condition (test cases 3 and 4)

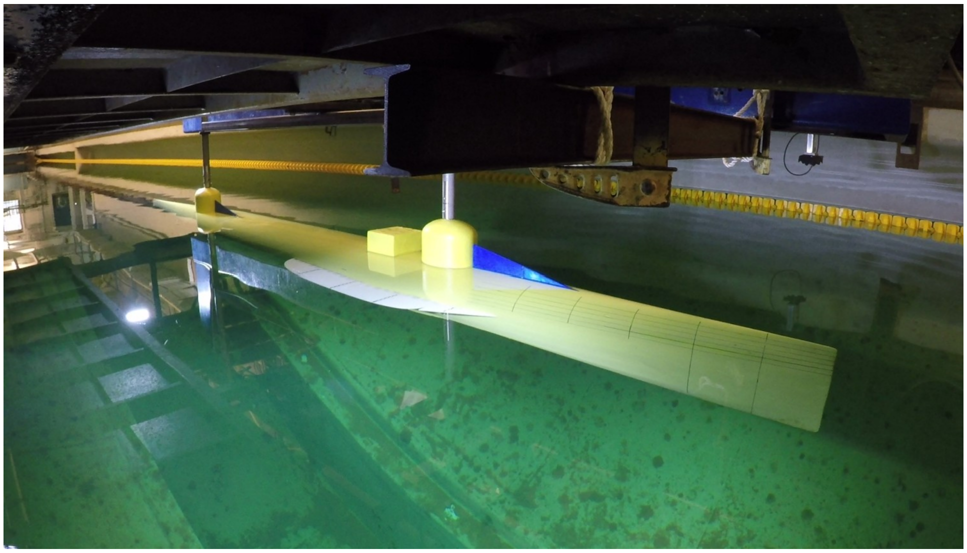


Figure 6: CSS Hunley model at static deck submerged condition (test cases 5 and 6)

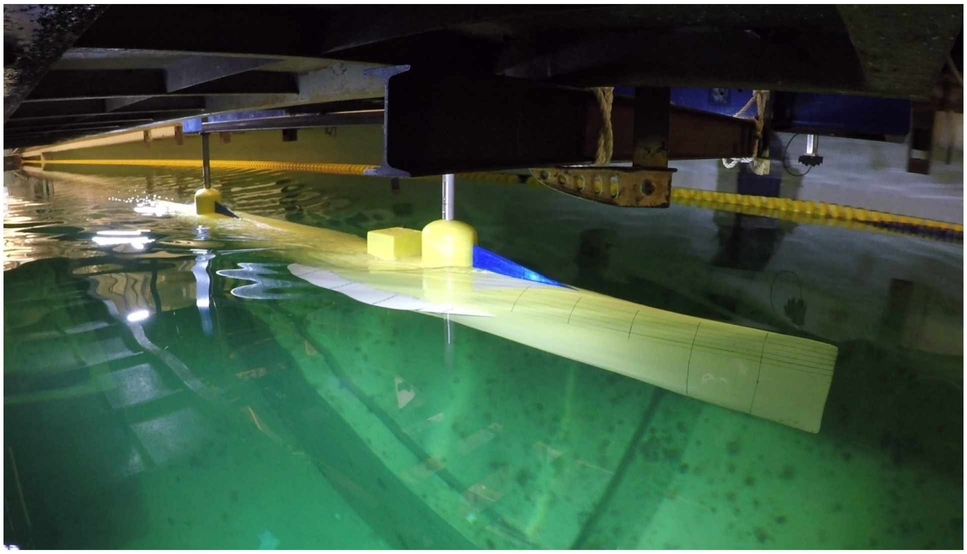
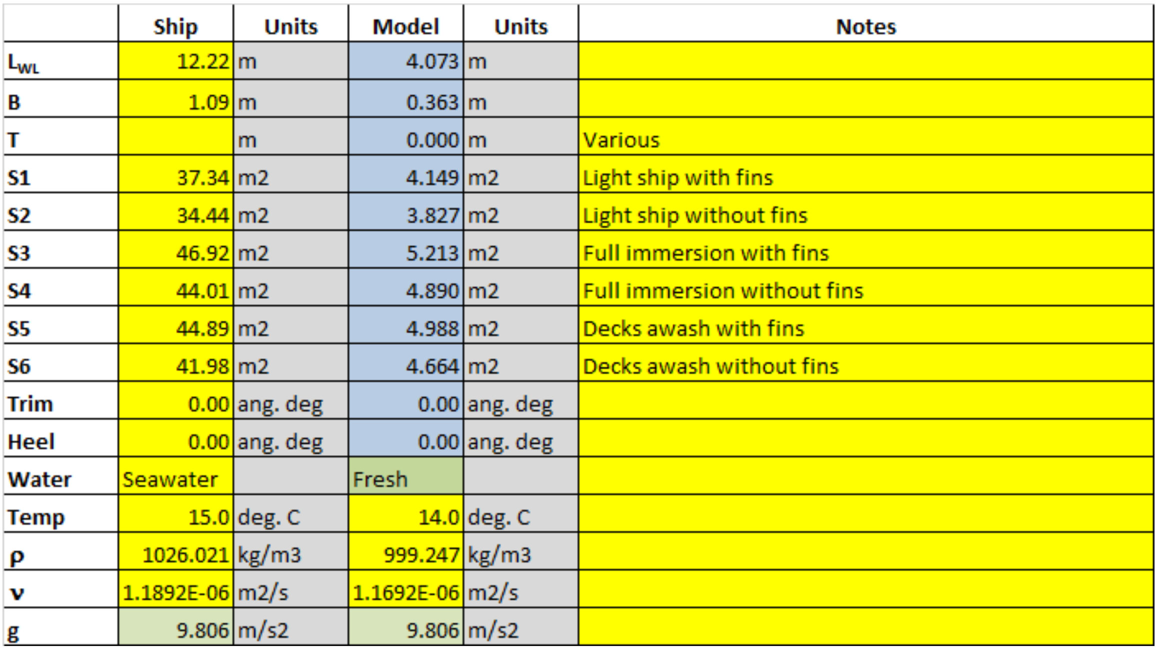


Figure 7: CSS Hunley model at 3.0 knots scaled speed for deck submerged condition (test cases 5 and 6)

Test Results

For each test condition, based on the independent variables of immersion depth, control surface implementation and forward speed, the hull resistance (drag) was recorded utilizing a National Instruments data acquisition system. For the following analyses, forward speed and drag was averaged while the hull was moving at a steady state forward speed.

The following hull and test conditions apply to the analysis, as shown in Table 2:



	Ship	Units	Model	Units	Notes
L_{WL}	12.22	m	4.073	m	
B	1.09	m	0.363	m	
T		m	0.000	m	Various
S1	37.34	m2	4.149	m2	Light ship with fins
S2	34.44	m2	3.827	m2	Light ship without fins
S3	46.92	m2	5.213	m2	Full immersion with fins
S4	44.01	m2	4.890	m2	Full immersion without fins
S5	44.89	m2	4.988	m2	Decks awash with fins
S6	41.98	m2	4.664	m2	Decks awash without fins
Trim	0.00	ang. deg	0.00	ang. deg	
Heel	0.00	ang. deg	0.00	ang. deg	
Water	Seawater		Fresh		
Temp	15.0	deg. C	14.0	deg. C	
ρ	1026.021	kg/m3	999.247	kg/m3	
ν	1.1892E-06	m2/s	1.1692E-06	m2/s	
g	9.806	m/s2	9.806	m/s2	

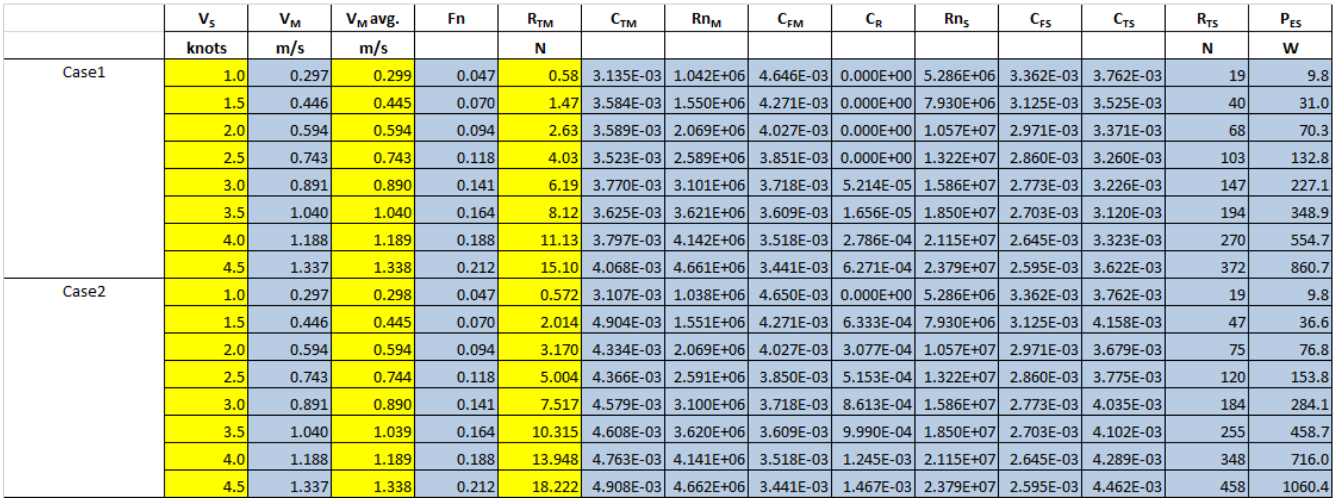
Table 2: Values used for the drag prediction analysis

The average model steady state forward speed, V_M, and total resistance, R_{TM}, are shown in the second and third columns of Tables 3, 4 and 5. The columns further to the right in blue are calculated values using Froude's Method to calculate the predicted full scale ship resistance, R_{TS}, and effective power, P_{ES}. As expected, the total drag on the hull increases with speed, immersion and total surface area (by including the control surfaces).

The following abbreviations are used in Tables 2, 3 and 4:

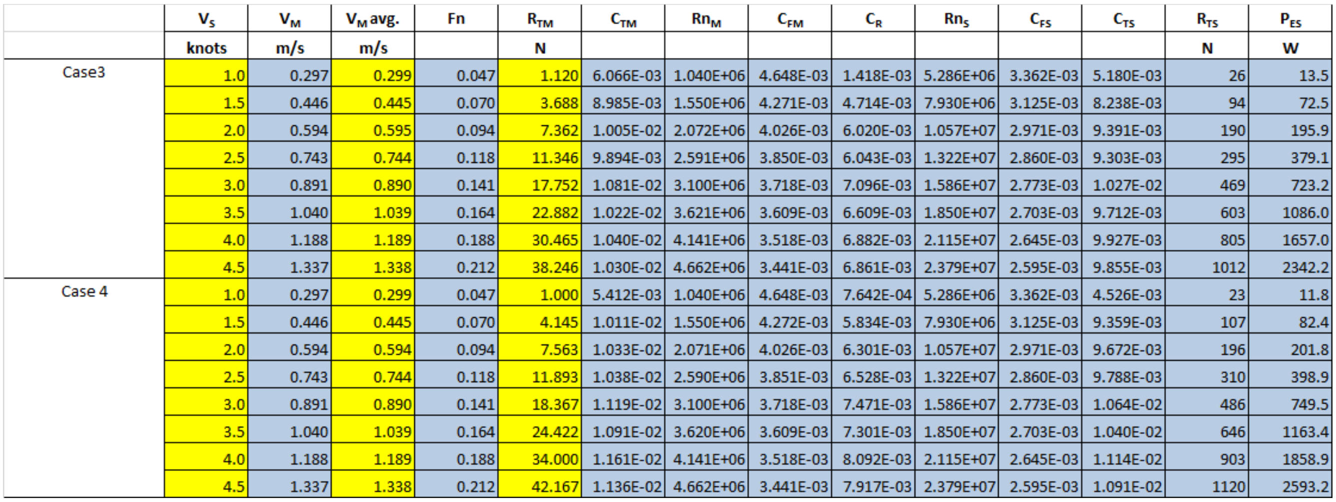
V_S	Velosity of the full scale ship
V_M	Velocity of the model
Fn	Froude number of the model: $V_M/(L_M g)^{0.5}$
R_{TM}	Total resistance of the model
C_{TM}	Coefficient of total resistance of the model: $R_{TM}/(0.5\rho V_M^2 S_M)$
Rn_M	Reynolds number of the model: $V_M L_M/\nu_M$
C_{FM}	Coefficient of friction of the model (ITTC-78): $0.075/(\text{Log}_{10}(Rn_M)-2.0)^2$
C_R	Coefficient of residual resistance (same for ship and model): $C_{TM}-C_{FM}$
Rn_S	Reynolds number of the full scale ship: $V_S L_S/\nu_S$

C_{FS}	Coefficient of friction of the full scale ship: $0.075/(\text{Log}_{10}(Rn_S)-2.0)^2$
C_{TS}	Coefficient of total resistance of the full scale ship: $C_{FS}+C_R$
R_{TS}	Total resistance of the model: $C_{TS}(0.5\rho V_S^2 S_S)$
P_{ES}	Total effective power required to propel the full scale ship: $R_{TS}V_S$
ν	Water kinematic viscosity (m^2/s) – temperature and salinity dependent
ρ	Water density (kg/m^3) – temperature and salinity dependent
g	Acceleration due to gravity ($9.806\ m/s^2$)
S_M	Wetted surface area of the model hull (m^2) for the given test condition
S_S	Wetted surface area of the full scale ship hull (m^2) for the given test condition
L_M	Length of the model hull
L_S	Length of the full scale ship



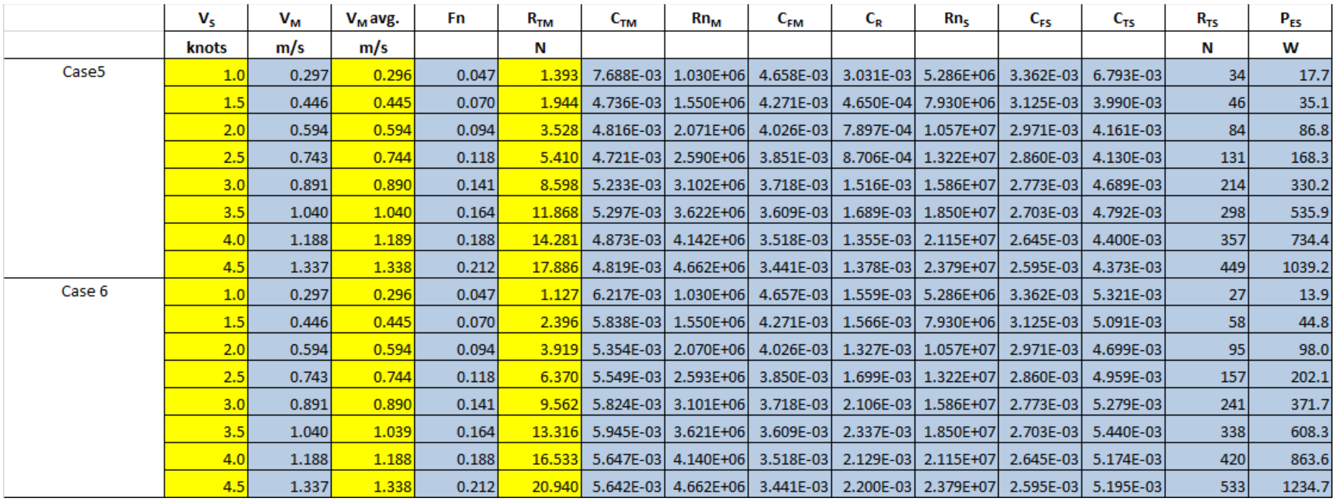
	V_S	V_M	V_M avg.	Fn	R_{TM}	C_{TM}	Rn_M	C_{FM}	C_R	Rn_S	C_{FS}	C_{TS}	R_{TS}	P_{ES}
	knots	m/s	m/s		N								N	W
Case1	1.0	0.297	0.299	0.047	0.58	3.135E-03	1.042E+06	4.646E-03	0.000E+00	5.286E+06	3.362E-03	3.762E-03	19	9.8
	1.5	0.446	0.445	0.070	1.47	3.584E-03	1.550E+06	4.271E-03	0.000E+00	7.930E+06	3.125E-03	3.525E-03	40	31.0
	2.0	0.594	0.594	0.094	2.63	3.589E-03	2.069E+06	4.027E-03	0.000E+00	1.057E+07	2.971E-03	3.371E-03	68	70.3
	2.5	0.743	0.743	0.118	4.03	3.523E-03	2.589E+06	3.851E-03	0.000E+00	1.322E+07	2.860E-03	3.260E-03	103	132.8
	3.0	0.891	0.890	0.141	6.19	3.770E-03	3.101E+06	3.718E-03	5.214E-05	1.586E+07	2.773E-03	3.226E-03	147	227.1
	3.5	1.040	1.040	0.164	8.12	3.625E-03	3.621E+06	3.609E-03	1.656E-05	1.850E+07	2.703E-03	3.120E-03	194	348.9
	4.0	1.188	1.189	0.188	11.13	3.797E-03	4.142E+06	3.518E-03	2.786E-04	2.115E+07	2.645E-03	3.323E-03	270	554.7
	4.5	1.337	1.338	0.212	15.10	4.068E-03	4.661E+06	3.441E-03	6.271E-04	2.379E+07	2.595E-03	3.622E-03	372	860.7
Case2	1.0	0.297	0.298	0.047	0.572	3.107E-03	1.038E+06	4.650E-03	0.000E+00	5.286E+06	3.362E-03	3.762E-03	19	9.8
	1.5	0.446	0.445	0.070	2.014	4.904E-03	1.551E+06	4.271E-03	6.333E-04	7.930E+06	3.125E-03	4.158E-03	47	36.6
	2.0	0.594	0.594	0.094	3.170	4.334E-03	2.069E+06	4.027E-03	3.077E-04	1.057E+07	2.971E-03	3.679E-03	75	76.8
	2.5	0.743	0.744	0.118	5.004	4.366E-03	2.591E+06	3.850E-03	5.153E-04	1.322E+07	2.860E-03	3.775E-03	120	153.8
	3.0	0.891	0.890	0.141	7.517	4.579E-03	3.100E+06	3.718E-03	8.613E-04	1.586E+07	2.773E-03	4.035E-03	184	284.1
	3.5	1.040	1.039	0.164	10.315	4.608E-03	3.620E+06	3.609E-03	9.990E-04	1.850E+07	2.703E-03	4.102E-03	255	458.7
	4.0	1.188	1.189	0.188	13.948	4.763E-03	4.141E+06	3.518E-03	1.245E-03	2.115E+07	2.645E-03	4.289E-03	348	716.0
	4.5	1.337	1.338	0.212	18.222	4.908E-03	4.662E+06	3.441E-03	1.467E-03	2.379E+07	2.595E-03	4.462E-03	458	1060.4

Table 3: Test results for model at lightship condition (cases 1 and 2)



	V_S	V_M	V_M avg.	Fn	R_{TM}	C_{TM}	Rn_M	C_{FM}	C_R	Rn_S	C_{FS}	C_{TS}	R_{TS}	P_{ES}
	knots	m/s	m/s		N								N	W
Case3	1.0	0.297	0.299	0.047	1.120	6.066E-03	1.040E+06	4.648E-03	1.418E-03	5.286E+06	3.362E-03	5.180E-03	26	13.5
	1.5	0.446	0.445	0.070	3.688	8.985E-03	1.550E+06	4.271E-03	4.714E-03	7.930E+06	3.125E-03	8.238E-03	94	72.5
	2.0	0.594	0.595	0.094	7.362	1.005E-02	2.072E+06	4.026E-03	6.020E-03	1.057E+07	2.971E-03	9.391E-03	190	195.9
	2.5	0.743	0.744	0.118	11.346	9.894E-03	2.591E+06	3.850E-03	6.043E-03	1.322E+07	2.860E-03	9.303E-03	295	379.1
	3.0	0.891	0.890	0.141	17.752	1.081E-02	3.100E+06	3.718E-03	7.096E-03	1.586E+07	2.773E-03	1.027E-02	469	723.2
	3.5	1.040	1.039	0.164	22.882	1.022E-02	3.621E+06	3.609E-03	6.609E-03	1.850E+07	2.703E-03	9.712E-03	603	1086.0
	4.0	1.188	1.189	0.188	30.465	1.040E-02	4.141E+06	3.518E-03	6.882E-03	2.115E+07	2.645E-03	9.927E-03	805	1657.0
	4.5	1.337	1.338	0.212	38.246	1.030E-02	4.662E+06	3.441E-03	6.861E-03	2.379E+07	2.595E-03	9.855E-03	1012	2342.2
Case 4	1.0	0.297	0.299	0.047	1.000	5.412E-03	1.040E+06	4.648E-03	7.642E-04	5.286E+06	3.362E-03	4.526E-03	23	11.8
	1.5	0.446	0.445	0.070	4.145	1.011E-02	1.550E+06	4.272E-03	5.834E-03	7.930E+06	3.125E-03	9.359E-03	107	82.4
	2.0	0.594	0.594	0.094	7.563	1.033E-02	2.071E+06	4.026E-03	6.301E-03	1.057E+07	2.971E-03	9.672E-03	196	201.8
	2.5	0.743	0.744	0.118	11.893	1.038E-02	2.590E+06	3.851E-03	6.528E-03	1.322E+07	2.860E-03	9.788E-03	310	398.9
	3.0	0.891	0.890	0.141	18.367	1.119E-02	3.100E+06	3.718E-03	7.471E-03	1.586E+07	2.773E-03	1.064E-02	486	749.5
	3.5	1.040	1.039	0.164	24.422	1.091E-02	3.620E+06	3.609E-03	7.301E-03	1.850E+07	2.703E-03	1.040E-02	646	1163.4
	4.0	1.188	1.189	0.188	34.000	1.161E-02	4.141E+06	3.518E-03	8.092E-03	2.115E+07	2.645E-03	1.114E-02	903	1858.9
	4.5	1.337	1.338	0.212	42.167	1.136E-02	4.662E+06	3.441E-03	7.917E-03	2.379E+07	2.595E-03	1.091E-02	1120	2593.2

Table 4: Test results for model at completely submerged condition (cases 3 and 4)



	V_S	V_M	V_M avg.	Fn	R_{TM}	C_{TM}	Rn_M	C_{FM}	C_R	Rn_S	C_{FS}	C_{TS}	R_{TS}	P_{ES}
	knots	m/s	m/s		N								N	W
Case5	1.0	0.297	0.296	0.047	1.393	7.688E-03	1.030E+06	4.658E-03	3.031E-03	5.286E+06	3.362E-03	6.793E-03	34	17.7
	1.5	0.446	0.445	0.070	1.944	4.736E-03	1.550E+06	4.271E-03	4.650E-04	7.930E+06	3.125E-03	3.990E-03	46	35.1
	2.0	0.594	0.594	0.094	3.528	4.816E-03	2.071E+06	4.026E-03	7.897E-04	1.057E+07	2.971E-03	4.161E-03	84	86.8
	2.5	0.743	0.744	0.118	5.410	4.721E-03	2.590E+06	3.851E-03	8.706E-04	1.322E+07	2.860E-03	4.130E-03	131	168.3
	3.0	0.891	0.890	0.141	8.598	5.233E-03	3.102E+06	3.718E-03	1.516E-03	1.586E+07	2.773E-03	4.689E-03	214	330.2
	3.5	1.040	1.040	0.164	11.868	5.297E-03	3.622E+06	3.609E-03	1.689E-03	1.850E+07	2.703E-03	4.792E-03	298	535.9
	4.0	1.188	1.189	0.188	14.281	4.873E-03	4.142E+06	3.518E-03	1.355E-03	2.115E+07	2.645E-03	4.400E-03	357	734.4
	4.5	1.337	1.338	0.212	17.886	4.819E-03	4.662E+06	3.441E-03	1.378E-03	2.379E+07	2.595E-03	4.373E-03	449	1039.2
Case 6	1.0	0.297	0.296	0.047	1.127	6.217E-03	1.030E+06	4.657E-03	1.559E-03	5.286E+06	3.362E-03	5.321E-03	27	13.9
	1.5	0.446	0.445	0.070	2.396	5.838E-03	1.550E+06	4.271E-03	1.566E-03	7.930E+06	3.125E-03	5.091E-03	58	44.8
	2.0	0.594	0.594	0.094	3.919	5.354E-03	2.070E+06	4.026E-03	1.327E-03	1.057E+07	2.971E-03	4.699E-03	95	98.0
	2.5	0.743	0.744	0.118	6.370	5.549E-03	2.593E+06	3.850E-03	1.699E-03	1.322E+07	2.860E-03	4.959E-03	157	202.1
	3.0	0.891	0.890	0.141	9.562	5.824E-03	3.101E+06	3.718E-03	2.106E-03	1.586E+07	2.773E-03	5.279E-03	241	371.7
	3.5	1.040	1.039	0.164	13.316	5.945E-03	3.621E+06	3.609E-03	2.337E-03	1.850E+07	2.703E-03	5.440E-03	338	608.3
	4.0	1.188	1.188	0.188	16.533	5.647E-03	4.140E+06	3.518E-03	2.129E-03	2.115E+07	2.645E-03	5.174E-03	420	863.6
	4.5	1.337	1.338	0.212	20.940	5.642E-03	4.662E+06	3.441E-03	2.200E-03	2.379E+07	2.595E-03	5.195E-03	533	1234.7

Table 5: Test results for the model at deck submerged condition (cases 5 and 6)

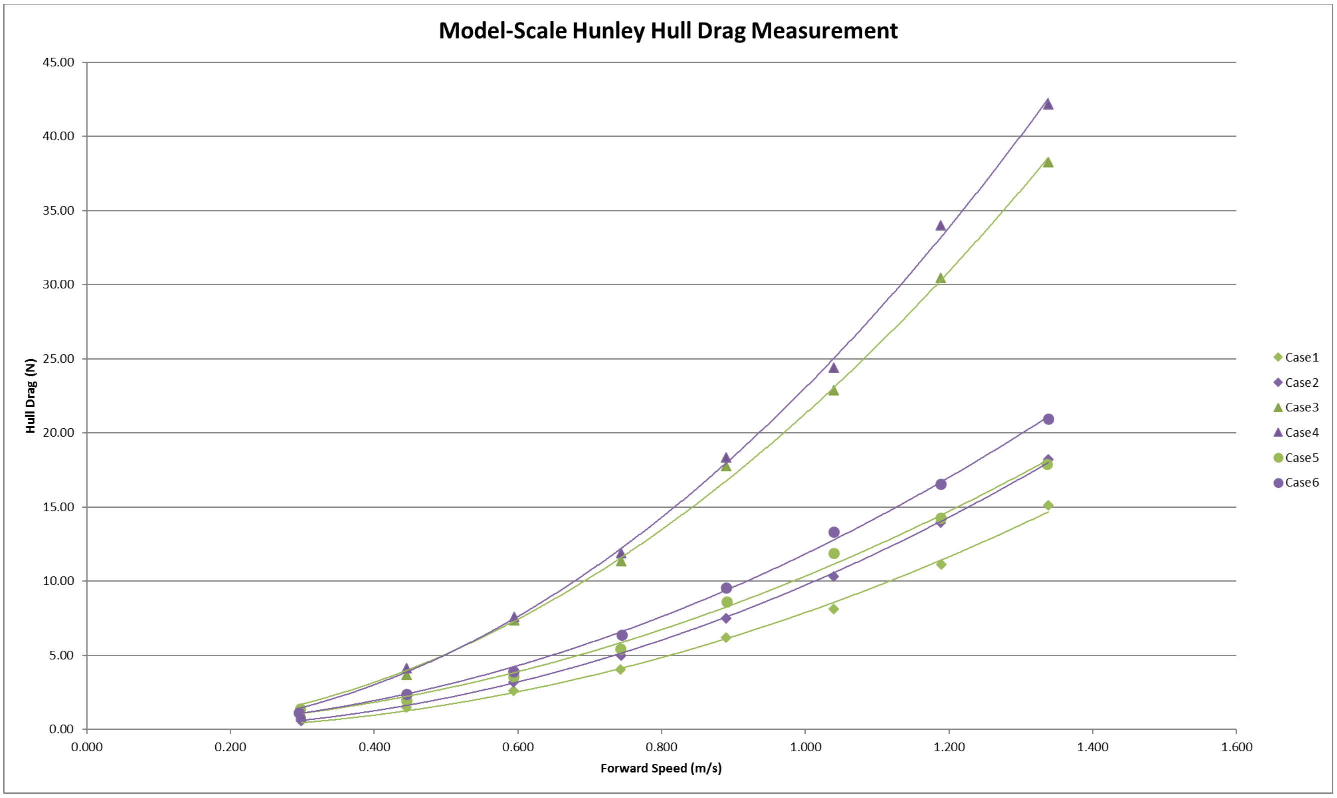


Figure 8: Plot of the model test results for each of the conditions

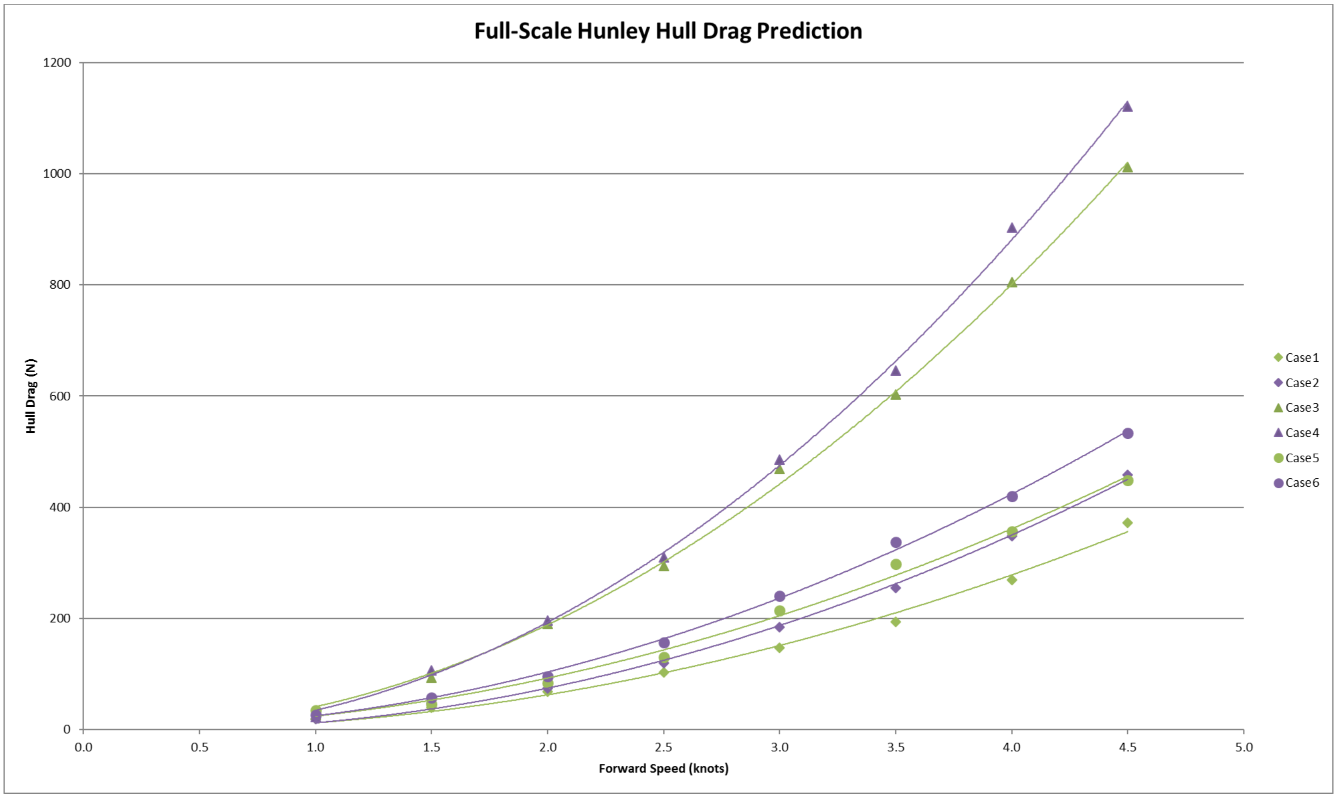


Figure 9: Plot of the predicted full scale hull drag characteristics for each of the conditions