MAKING WAVES IN THE CLASSROOM

January, 2019

Engaging Students in STEM through Hands-on Coastal Oceanography and Engineering

The Making Wave in the Classroom STEM outreach program is sponsored by the Office of Naval Research. The emphasis is to inspire, engage, and educate high school students on the concepts of coastal oceanography and engineering and provide context on naval applications. Multiple learning modules are designed around the wave flume apparatus and provide students the opportunity for inquiry-based learning of coastal processes.

MAKING WAVES IN THE CLASSROOM

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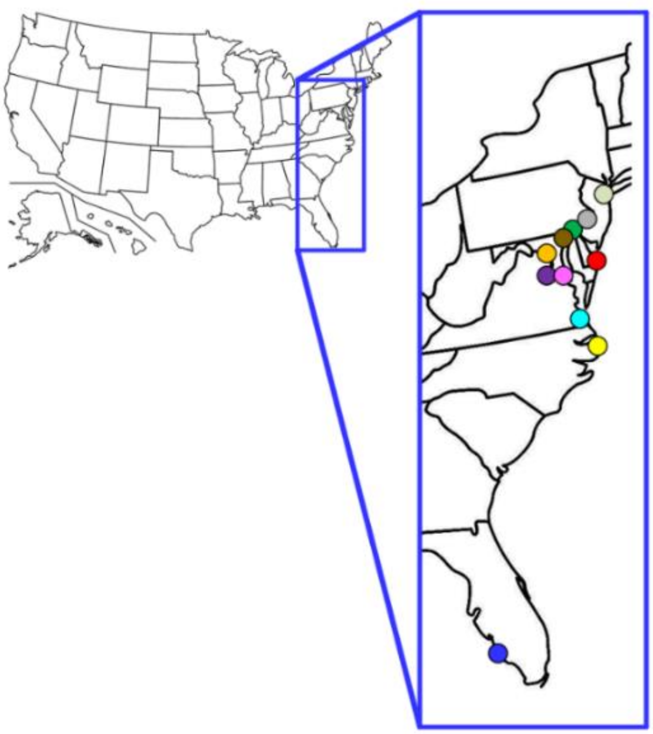
Making waves in the classroom

ENGAGING STUDENTS IN STEM THROUGH HANDS-ON COASTAL OCEANOGRAPHY AND ENGINEERING

OVERVIEW

The Making Waves in the Classroom STEM outreach program is sponsored by the Office of Naval Research. The principal investigator, Dr. Jack A. Puleo, began using portable wave flumes in 2005 for education outreach (at the time sponsored by NOAA Sea Grant and the National Science Foundation). The success of those initial efforts lead to the present project where 12 wave flumes will be delivered to high schools along the east coast of the United States (Figure 1).



	High School
	Marine Academy of Science and Technology Sandy Hook, NJ
	Science Leadership Academy Philadelphia, PA
	Central High School Philadelphia, PA
	Newark Charter, Newark, DE
	Elkton High School Elkton, MD
	Cape Henlopen High School, Lewes DE
	Landon School, Bethesda, MD
	Thomas Jefferson High School for Science and Technology, Alexandria, VA
	Waldorf High School Waldorf, MD
	Lake Taylor High School Norfolk, VA (Chris with U.S. Fleet Forces)
	First Flight High School Kill Devil Hills, NC
	Barron Collier High School Naples, FL

Figure 1. Map and legend showing locations of high schools that are part of the Making Waves in the Classroom program.

The emphasis of the project is to inspire, engage, and educate high school students on the concepts of coastal oceanography and engineering and provide context on naval applications. These processes are taught and explained using the 16' wave flume. The flume contains a voltage-controlled wave paddle at one end. Acetal beads are used as a sediment surrogate at the other end to create a "natural" beach that evolves quickly. Acetal is chosen for two reasons: 1) Acetal is non-abrasive and will not scratch the acrylic; 2) the specific gravity of Acetal is 1.42, roughly half that of sand making it easily mobile under these scaled laboratory conditions. The pedagogical benefit of enhanced mobility is that beach changes are observed in just a few minutes, allowing students to immediately comprehend the resulting effect of changing the paddle speed, water level, or initial morphology conditions.

Multiple learning modules (Table 1) are designed around the wave flume apparatus and provide students the opportunity for inquiry-based learning of coastal processes.

Table 1. STEM modules for the Making Waves in the Classroom program.

Module 1: What is a wave?	**Module 8**: Beach profiles and basic theory
Module 2: Wave parameters	**Module 9**: Application: Beach slope and slope predictions
Module 3: Deep vs. shallow water	**Module 10**: Beach erosion
Module 4: Wave speed	**Module 11**: Application: Beach nourishment
Module 5: Particle trajectories	**Module 12**: Sea level rise – Effect on beaches
Module 6: Wave energy	**Module 13**: Application: Protecting the beach
Module 7: Tsunami	

Module 1- What is a wave?

Background material

What is a wave? Most people think of ocean waves when the word "wave" is mentioned. But, waves exist in many different forms in nature. In general, a wave is a disturbance in some medium that transports energy from one location to another without transporting matter. Some examples of waves are shown in Figure 2:

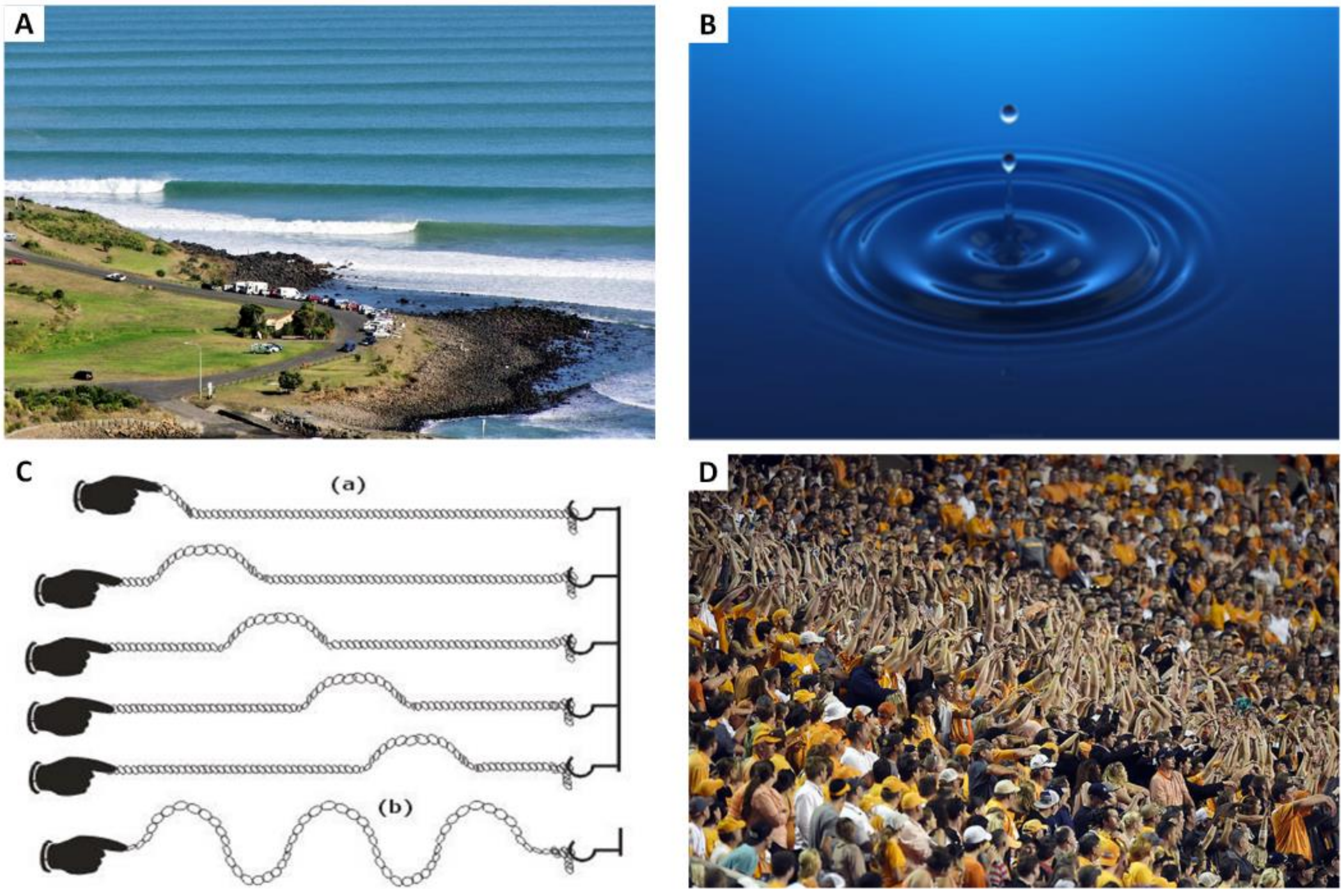


Figure 2. Examples of different types of waves. A) Ocean surface wave approaching a coast (surfertoday.com). B) Ripples on a pond surface (gapcommunity.com). C) Waves traveling along a fixed rope (letsbehumanbeings.com). D) People creating a wave in stadium (imasportsphile.com).

We will work only with surface gravity waves (Figure 2A) with the wave flume. In a simple world, these waves travel on the surface where an individual fluid particle has a circular trajectory. Thus, the particle has no net displacement and returns to its original start point for each wave cycle (see module 5).

What causes ocean surface waves? Many people incorrectly assume that tides cause waves (aside: Tides themselves, are waves, but not the kind we associate with waves breaking on beaches).

Ocean waves are caused by wind. Waves in the open ocean are generated when wind speeds exceed roughly 1 m/s. But, wind must blow for an extended period of time before waves are generated and propagate. In fact, wave growth in the open ocean is governed by three parameters: wind speed; wind duration; and fetch. Fetch is the area that the wind blows over. A massive storm area with sustained winds can generate larger waves than a local storm lasting a short duration.

Pre-Module 1 Questionnaire

1) What is a wave?

2) (T or F). Waves transport matter.

3) Provide some examples of a wave.

Module 1 Experiment and Worksheet

1) What is a wave?

2) (T or F). Waves transport matter.

3) Provide some examples of a wave.

4) Blow across the water surface and describe what you see and what happens.

5) Describe what might happen if you used a fan or leaf blower instead of your breath.

6) Describe the three parameters that govern wave growth in the open ocean.

7) How do the parameters from question 6 relate to what you observed in the wave flume?

Module 2 – Wave Parameters

It is most straightforward to examine an idealized small amplitude deep water wave that has a sinusoidal shape (Figure 3).

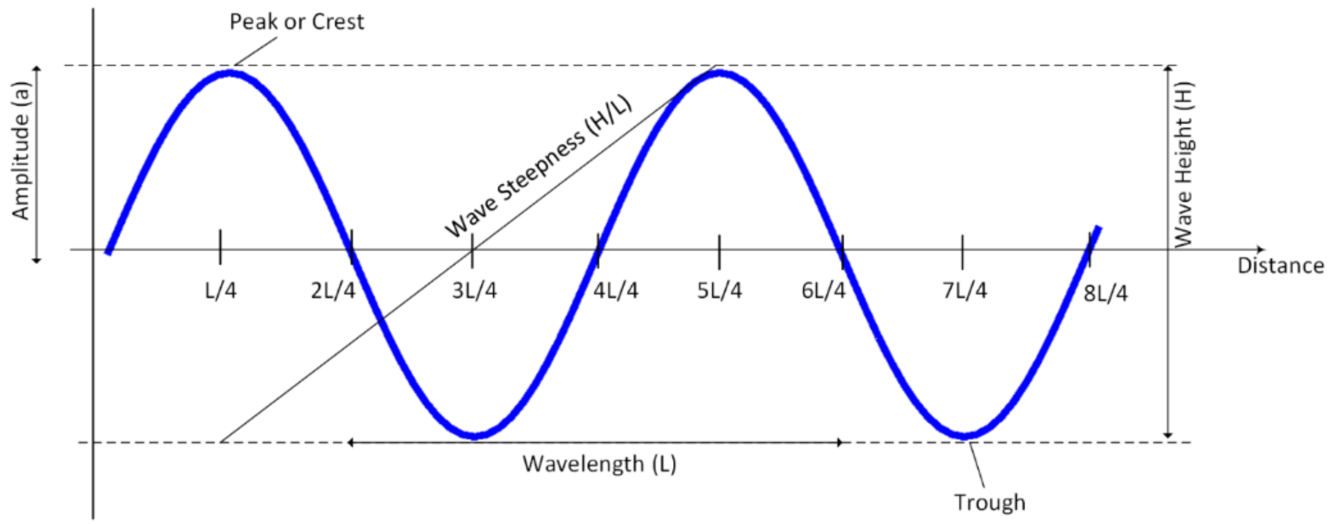


Figure 3. Image showing the parts and parameters of a wave train.

The top of a wave shape is referred to as the wave peak or crest. The bottom is referred to as the trough. The distance between these locations is known as the wave height (H). The wave amplitude (a) is half the wave height and is the distance from the mean water level to either the crest or trough. The wavelength (L) is the distance between two successive peaks or troughs. The wave steepness (H/L) is the ratio of the wave height to wavelength.

If the horizontal axis in Figure 3 is changed from distance to time additional parameters can be identified. The wave period (T) is the time it takes for a wave to complete a single cycle. The wave frequency (f) refers to how often a wave peak or trough occurs. Frequency is usually given in units of Hertz (Hz) described as cycles per second. Period and frequency are inverses of each other:

$$T = \frac{1}{f} \;\; and \;\; f = \frac{1}{T}\,. \qquad (1)$$

The wave shape in the open ocean can be thought of as sinusoidal. Thus, it can be described as

$$\eta = asin(kx - \sigma t), \qquad (2)$$

where η is the free surface, *x* is the distance, *t* is the time, *k* is a parameter called the radial wave number (or just wave number) and defined as ${}^{2\pi}/_{L}$, and σ is a parameter call the angular frequency, similar to before, but defined as ${}^{2\pi}/_{T}$ instead of ${}^{1}/_{T}$. Equation (2) is helpful because it allows us to identify the elevation of the free surface at any space-time location. But, the easiest way to use equation (2) is to fix either time or space. That is, set *t* = 0 or *x* =0. Example: Setting *t* = 0 means one is observing a single snapshot of the wave shape (analogous to taking a photo of the side of the flume with your cell phone). Example: Setting *x* = 0 means the person (or sensor) is making an observation of the water level over time at a particular fixed location in space. Examples follow:

Example: Determine the free surface elevation of a wave with amplitude (*a*) = 1.3 m and a wavelength (*L*) of 100 m at a distance 452 m from the origin.

$$\eta = 1.3 * \ sin\left(\frac{2\pi}{100} * 452\right) = -0.16\, m$$

Example: Determine the free surface elevation of a wave with amplitude (*a*) = 0.4 m and a wave period (*T*) of 10 s at a time of 56 s from wave initiation.

$$\eta = 0.4 * \ sin\left(-\frac{2\pi}{10} * 56\right) = 0.22\, m$$

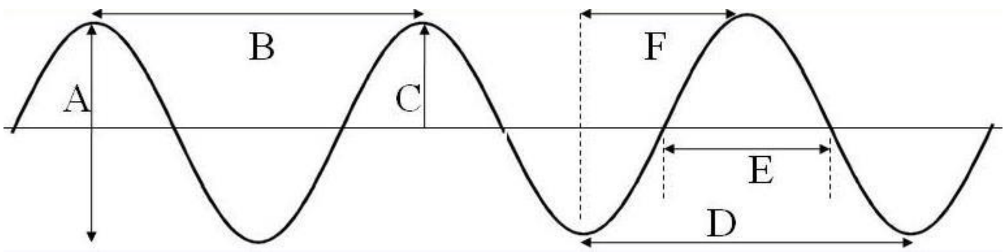
Example: Determine the free surface elevation of a wave with amplitude (*a*) = 0.4 m, a wave period (*T*) of 10 s, and a wavelength of 156 m at a time of 52.3 s from wave initiation and *x* = 23 m an initial position.

$$\eta = 0.4 * \ sin\left(\frac{2\pi}{156} * 23 - \frac{2\pi}{10} * 52.3\right) = -0.20\, m$$

Pre-Module 2 Questionnaire

1) From the picture below, which letter represents the wave amplitude?

2) From the picture below, which letter(s) represents the wavelength?



3) What is a wave period?

4) What is wave frequency?

5) How are wave period and frequency related?

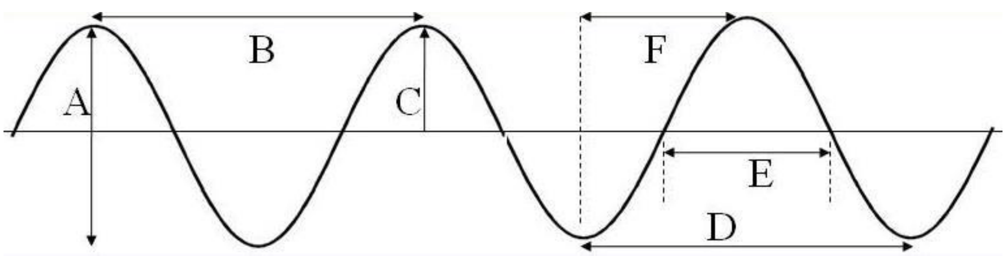
6) Bobby sneezes frequently when around cats. One time he sneezed with a frequency of 0.2 Hz. How many times did he sneeze in 10 seconds?

7) Storm waves have a period of 6 seconds. How many waves will pass by a fixed boat in a minute?

Module 2 Experiment and Worksheet

1) From the picture below, which letter represents the wave height?

2) From the picture below, which letter(s) represents the wavelength?



3) What is a wave period?

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6) Bobby sneezes frequently when around cats. One time he sneezed with a frequency of 0.2 Hz. How many times did he sneeze in 10 seconds?

7) Storm waves have a period of 6 seconds. How many waves will pass by a fixed location in a minute?

8) Summer waves have a frequency of 0.1 Hz. How long will a surfer have to wait in between wave crests?

9) At the wave flume, devise a way to measure the wave period with the wave paddle speed dial at two different speeds (recommended with the dial somewhere between setting 6 and 7). Do not use the sensor yet.

10) Postulate why there is a difference in wave periods from question 9.

11) Transfer the estimated wave periods into frequency and angular frequency.

12) Using values from question 9, estimate the period and frequency for a wave with the dial set between the two speed values used. Check your answer using the wave flume.

13) A free surface (η) of 0.17 m was measured at a distance x = 100 m from the origin. If the wavelength (L) is 15 m, determine the wave height (H).

14) At the wave flume, record the free surface elevation using the acoustic sensor a meter or more from the wave paddle. That location can be identified as your horizontal origin (x = 0). Copy and paste

the data into the spreadsheet MakingWaves.xlsx (tab: Wave Parameters) to estimate the wave height, amplitude, period, and angular frequency.

15) From the graph, estimate the time when the data first cross the x-axis and paste into the marked cell (I9). The plot will update with the theoretical sine curve. Modify the time when the data first crosses the x-axis until the shifted data crosses an elevation of 0 at time 0. How similar are the measured and theoretical curves? Postulate about any differences.

Module 3 – Deep vs. Shallow Water

The wavelength was already described as the distance between successive peaks or troughs. The wavelength can be described mathematically as a function of the wave period as:

$$L = \frac{gT^2}{2\pi} tanh\left(\frac{2\pi h}{L}\right), \tag{3}$$

where *h* is the water depth, *g* is acceleration due to gravity (= 9.81 m/s^2), and *tanh* is called the hyperbolic tangent function. Equation (3) has to be solved iteratively because the wavelength exists on both sides of the equation. Also, the wavelength depends on wave period **and** water depth. Thus, knowing the wave period alone is not enough to determine wavelength. Knowledge of the water depth is also required. The depth is required because as waves enter different water depths their amplitude and shapes can change.

The ocean can be divided into three regions with respect to wave propagation: shallow; intermediate, and deep water. Shallow water refers to shallow water relative to the wavelength (generally $h < L/20$). Similarly, deep water refers to deep water relative to the wavelength (generally $h > L/2$). In between these depth regions is intermediate water depth. The major benefit of using these shallow and deep relationships is:

For shallow water

$$tanh\left(\frac{2\pi h}{L}\right) \approx \frac{2\pi h}{L}, \tag{4}$$

Leaving

$$L = T\sqrt{gh}\,. \tag{5}$$

For deep water

$$tanh\left(\frac{2\pi h}{L}\right) \approx 1, \tag{6}$$

Leaving

$$L = \frac{gT^2}{2\pi}. \tag{7}$$

Figure 4 shows an example of the wavelength of a 10 s wave as it propagates from deep to shallow water (black curve; true value). The deep (gray curve) and shallow (blue curve) water approximations are also plotted. The region of mismatch between the two end member estimates is the intermediate region.

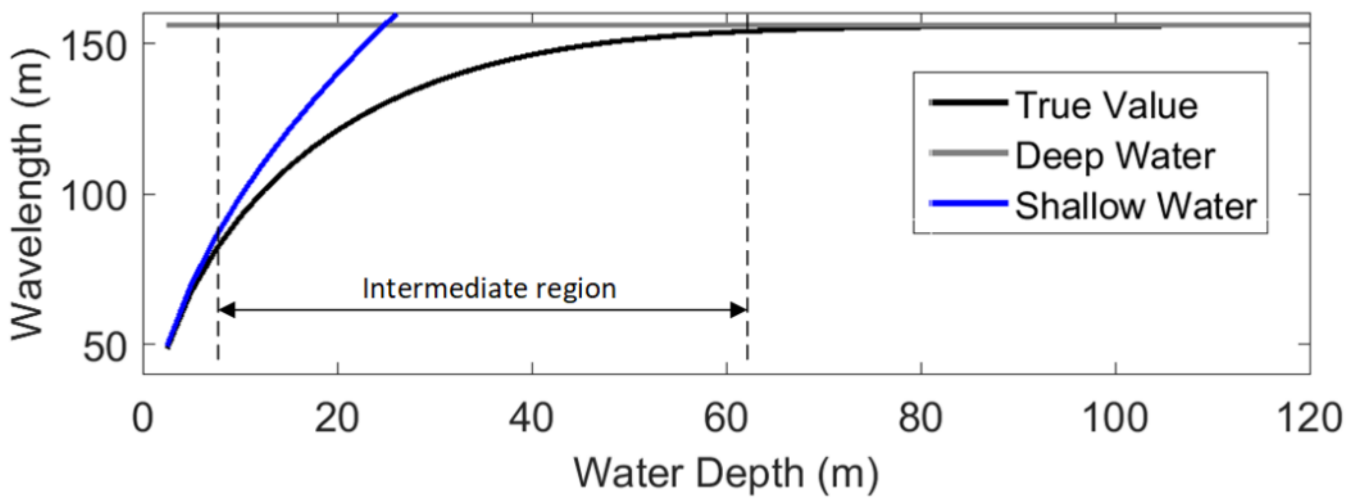


Figure 4. Wavelength as a function of water depth with deep and shallow water estimates shown in relation to the true wavelength.

Table 2 provides a summary of which equations to use when estimating wavelength. Recall that the intermediate water wavelength equation requires iteration. In general, one will not know initially if the wave of interest is in deep or shallow water and the intermediate depth equation should be used. A spreadsheet is provided to facilitate this calculation (see spreadsheet MakingWaves.xlsx; tab: Wavelength).

Table 2. Wavelength equations for different water depth regions.

Water Depth	Nomenclature	Equation to use
$h \leq L/20$	Shallow water	$L = T\sqrt{gh}$
$h > \frac{L}{20} and\ h < L/2$	Intermediate water	$L = \frac{gT^2}{2\pi} tanh\left(\frac{2\pi h}{L}\right)$
$h \geq L/2$	Deep water	$L = \frac{gT^2}{2\pi}$

Figure 4. showed how the wavelength changes with water depth across the different regions of the nearshore. Waves also change shape as they enter shallower water (Figure 5) by transitioning from a nearly sinusoidal shape, to what is called a skewed wave to finally what is termed a sawtooth wave after the wave has broken.

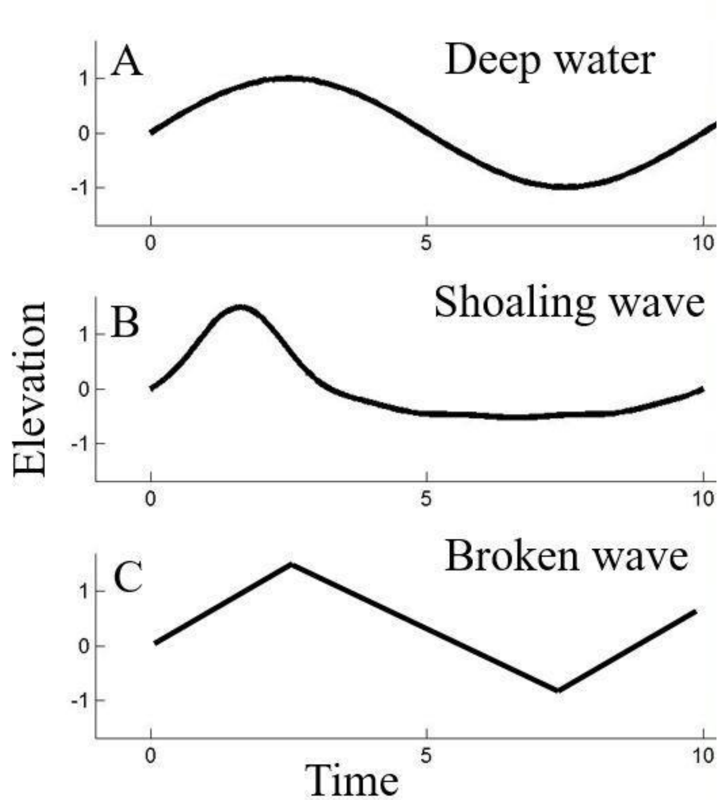


Figure 5. Wave shape variation across the nearshore.

Module 3 Experiment and Worksheet

1) A wave has a period (T) of 10 s and is propagating in water depth (h) of 100 m. Is it in deep, intermediate, or shallow water. Students can use the included excel spreadsheet (MakingWaves.xlsx, tab: Wavelength).

2) A wave has a period (T) of 10 s and is propagating in water depth (h) of 5 m. Is it in deep, intermediate, or shallow water. Students can use the included excel spreadsheet (MakingWaves.xlsx, tab: Wavelength).

3) What is the maximum wave period for a wave to be considered a deep water wave if the depth is 40 m?

4) At the wave flume, devise a way to measure the wavelength?

5) Measure the wavelength with the wave paddle set at two different speeds. Use the methods devised earlier to also determine the wave period. Are these shallow water, intermediate, or deep water waves?

6) Use the equations in Table 2 and the MakingWaves.xlsx spreadsheet (tab: Wavelength) as needed to quantify the theoretical wavelength for the correct type of wave (shallow, deep, intermediate).

7) Compare the corresponding wavelength values from question 5 and 6. Do they differ? If so by how much? Postulate some reasons why there may be differences in the measured and theoretical values.

8) Set the wave paddle to an intermediate speed.

9) Set up the LabQuest Mini logger and acoustic sensor.

10) Record with the acoustic sensor the water level time series just seaward of mid-flume. Copy and paste the acoustic sensor time and elevation data (2 columns) from the LoggerPro software into the spreadsheet MakingWaves.xlsx (tab: Deep vs. Shallow Water) in the appropriate columns.

11) Record with the acoustic sensor the water level time series near the shore but before wave breaking. Copy and paste the acoustic sensor time and elevation data (2 columns) from the LoggerPro software into the spreadsheet MakingWaves.xlsx (tab: Deep vs. Shallow Water) in the appropriate columns.

12) Record with the acoustic sensor the water level time series near the shore after wave breaking. Copy and paste the acoustic sensor time and elevation data (2 columns) from the LoggerPro software into the spreadsheet MakingWaves.xlsx (tab: Deep vs. Shallow Water) in the appropriate columns.

13) The spreadsheet MakingWaves.xlsx (tab: Deep vs. Shallow Water GRAPH) will plot all three time series on the same graph. Investigate the overlain time series. Describe what you see as the differences/similarities with respect to maximum and minimum elevations.

Module 4 – Wave Speed

Wave crests can be observed to propagate across the ocean. The time it takes for the crest to propagate from one point to another (Figure 6) is the velocity, often termed celerity (C). The velocity is merely the wavelength divided by the wave period:

$$C = \frac{L}{T} \tag{8}$$

Or

$$C = Lf, \tag{9}$$

using the relation provided in equation (1).

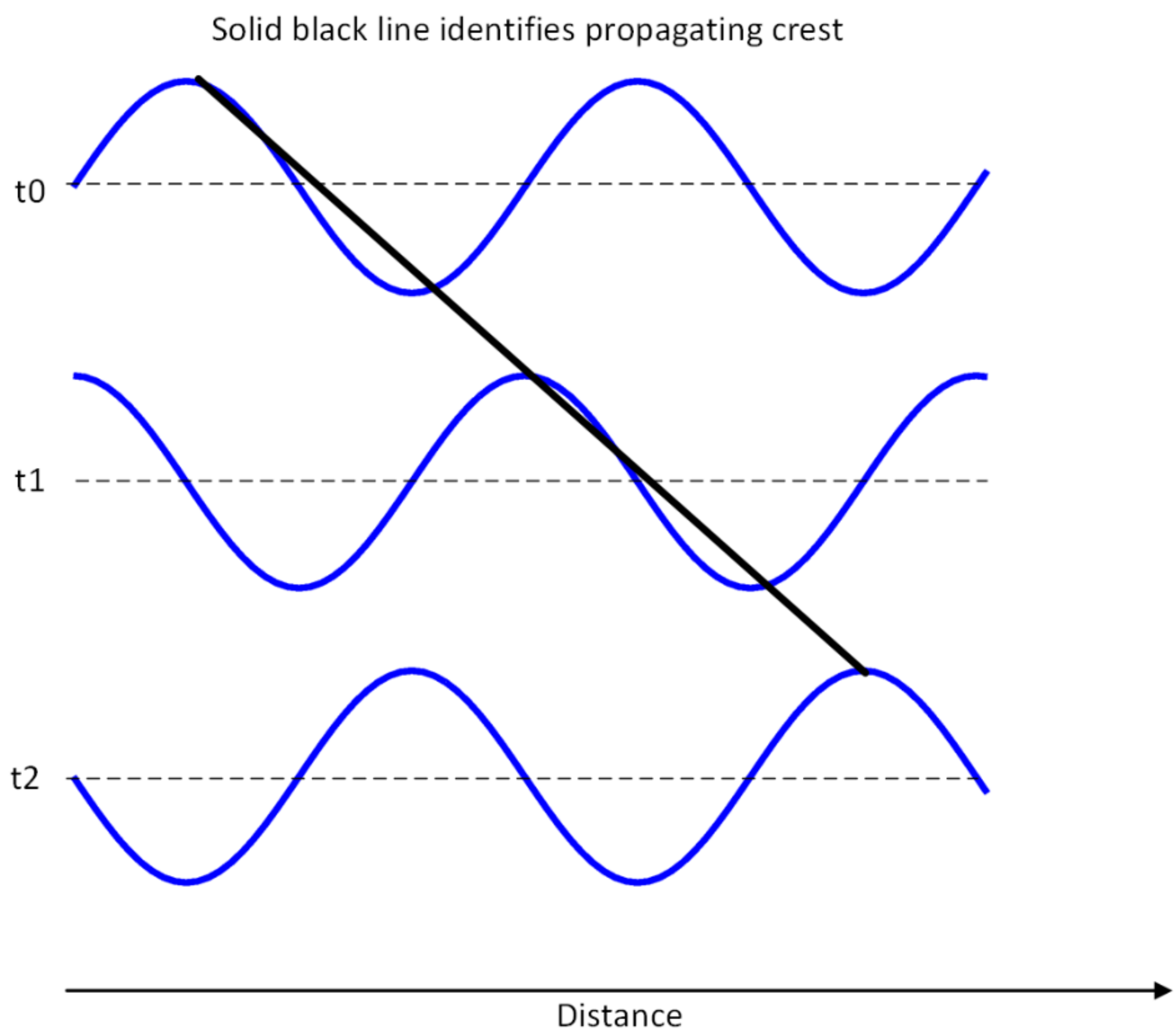


Figure 6. Schematic showing the propagation of a wave crest

The wave celerity, similar to the wavelength, also varies with water depth. This should be obvious based on equation (8). Celerity can be determined using the wavelength equations and/or the MakingWaves.xlsx (tab: Wavelength) to determine the wavelength. Then, using equation (8) and the estimate of wave period (where wave period is estimated using the procedures developed previously) determines the celerity.

Module 4 Experiment and Worksheet

1) Recall the definition of wavenumber (k) and angular frequency (σ) following equation (2). How can the celerity be written in terms of k and σ?

2) What is the wave speed for a deep water wave with a period of 20 s? For a shallow water wave with the same period?

3) A wave has a wavelength (L) of 100 m. It has a frequency (f) of 0.1 Hz. What is the wave speed (C)?

4) Waves are travelling with a speed (C) of 5 m/s. The wavelength (L) is 50 m. If the waves crash on a seawall, how often does the seawall get wet?

5) A wave has a wavelength (L) of 200 m and a speed (C) of 10 m/s. What is the wave period and frequency?

6) Make a plot of the wave speed variation as a function of h from deep water to shallow water for a 10 s wave. The spreadsheet MakingWaves.xlsx (tabs: Wavelength and Wave Speed) may assist in this problem.

7) At the wave flume, devise a way to measure the wave speed for waves with two different paddle frequencies. Use the methods devised earlier to determine the period and wavelength and subsequently the wave speed.

8) Compare your measurement of wave speed to that identified from your estimates of wavelength and period. Do they differ? If so, by how much? Postulate some reasons why there may be differences.

9) Compare your measurements to the theoretical wave speed (using MakingWaves.xlsx [tab: Wavelength] and estimated wave period). Do they differ? If so, by how much? Postulate some reasons why there may be differences.

Module 5 – Particle Trajectories

It was stated earlier that for small amplitude deep water ocean waves there is no net displacement of mass only energy in the propagating waves. That means for sinusoidal wave shapes, the water particle trajectories create closed circular orbits that decay in diameter with depth (Figure 7). Water particle motion for deep water waves decays exponentially with depth and wavelength. Thus, wave motion does not always reach the sea bed. In fact, it only generally does so as waves approach the shoreline and water depth decreases. In intermediate water, the trajectories become elliptical with a larger distance travelled horizontally than vertically. In shallow water, the trajectories are only identified by back and forth motion with no vertical displacement. The movie, wavemotion.avi (played in Windows Media Player) shows theoretical water particle motions for an intermediate depth wave with two trajectories identified by blue and pink curves showing the nearly circular orbit near the surface and the elliptical orbit lower in the water column.

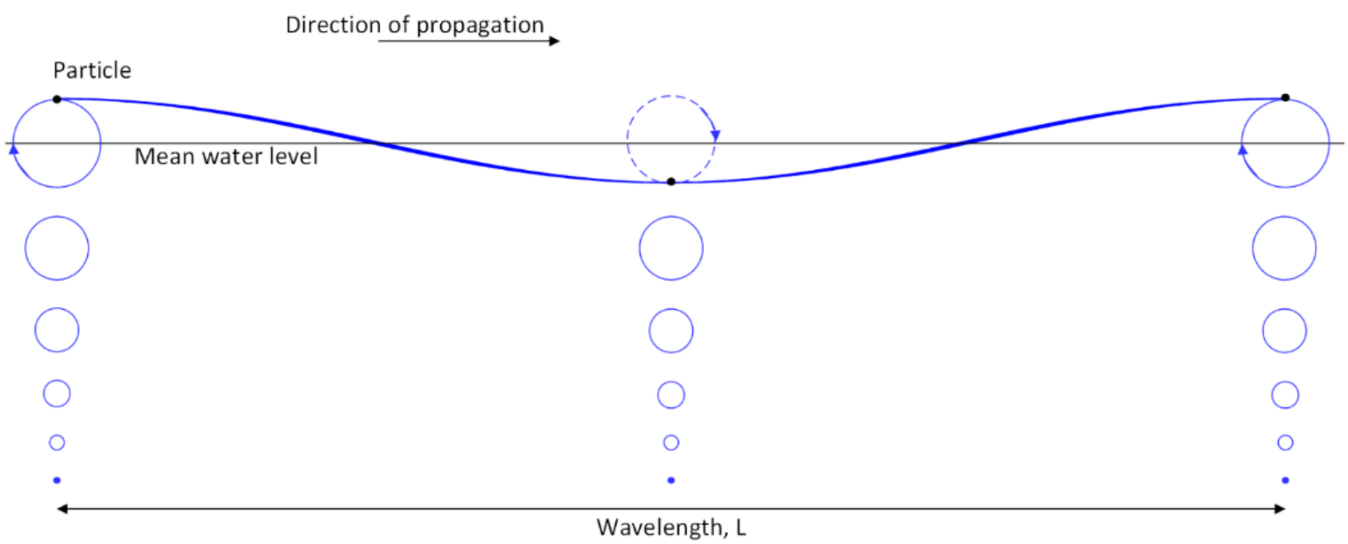


Figure 7. Schematic showing water particle trajectories for a sinusoidal wave and how they decay with depth.

Module 5 Experiment and Worksheet

1) Place a ping-pong ball in the wave flume and turn the wave paddle on. Describe what happens to the ball. Can you roughly trace the orbits on the flume glass using a dry erase marker? Is it circular? Do the orbits close? What might your findings mean for real world applications?

2) Redo question #1 with a different paddle frequency. What is different about the trajectories? Does the difference make sense with respect to the wave type?

3) Use the impeller current meter to measure the velocity just below trough level, in the middle of the water column and again near the bed. Discuss your results on the **maximum velocities** recorded at the various elevations. Students can identify by eye the data from the LoggerPro program, use the statistics button in the LoggerPro window, or copy paste data from the three different locations into the spreadsheet MakingWaves.xlsx (tab: Max Orbital Velocities).

Module 6 – Wave Energy

Wave energy consists of two forms: 1) The kinetic energy associated with the particle motion; and 2) the potential energy associated with the particles being displaced from their mean position. Each energy form constitutes half of the total energy contained in propagating oceanic waves. The importance of both types of energy is termed the equipartition of energy with the total energy defined as:

$$E = \frac{1}{8}\rho g H^2 \,, \tag{10}$$

where E is the energy (joules per m squared), ρ is the water density (kg/m^3) and H is the wave height (m). The important aspect from equation (10) is that the energy is proportional to the wave height squared.

Module 6 Experiment and Worksheet

1) A wave height is doubled. How does the wave energy change?

2) Determine the wave energy for a 1 m high wave (use $\rho = 1025$ kg/m^3).

3) Determine the wave energy for a 3 m high wave (use $\rho = 1025$ kg/m^3).

4) Discuss why/how storm waves can be so destructive to coastlines and infrastructure.

5) At the wave flume, record surface elevation data for two different paddle speeds using the acoustic sensor or estimate the surface elevation by eye from approaches used earlier. Using either approach, determine the wave height and the corresponding wave energy. Discuss the findings.

Module 7 – Tsunami

Tsunamis (Figure 8) can be large waves (when near shore) and are most commonly caused by underwater earthquake activity or volcanic eruptions. They can also be caused by underwater landslides, surface landslides where a portion of cliff or mountain plunges into the ocean, meteorites and atmospheric disturbances (termed meteotsunamis). Tsunamis are often incorrectly referred to as tidal waves. But, they do not result from tidal forcing mechanisms (sun and moon).

Figure 8. Photo showing a tsunami propagating near the shoreline (credit: jobsletter.org.nz).

Tsunami height in the open ocean may be as small as 0.1 – 1 m high but the wavelength might be up to 500 km. The wave period may be up to an hour. The water depth to wavelength ratio considering a typical ocean basin depth of 4000 m and the potential wavelength of 500 km is 0.008 << 0.05; implying tsunamis are shallow water waves.

As a tsunami propagates toward shore the wavelength decreases. The wave height must therefore increase to maintain the energy flux contained in the wave. This process is called shoaling and happens for wind-generated waves as well. The increase in tsunami height can be estimated using:

$$H = H_o \left(\frac{h_o}{h}\right)^{\frac{1}{4}}, \tag{11}$$

where H is the onshore wave height, H_o is the offshore wave height, h_o is the offshore water depth and h is the onshore water depth. So, a tsunami with 0.5 m height in 4000 m of water depth will have a 2.7 m height in 5 m water depth.

Pre-Module 7 Questionnaire

1) What causes tsunamis?

2) Is a tsunami considered a deep or shallow water wave?

3) What are typical speeds for a tsunami wave?

Module 7 Experiment and Worksheet

1) What causes tsunamis?

2) Is a tsunami considered a deep or shallow water wave?

3) What are typical speeds for a tsunami wave?

4) How long will it take a tsunami to cross the Atlantic Ocean (assuming a width of 2800 km and depth of 4000 m)?

5) A tsunami struck a small island in the Pacific Ocean about 5 hours after an earthquake. Assuming a water depth of 4000 m, estimate how far the island is from where the tsunami was generated.

6) Generate a tsunami in the flume using the supplied 2 x 4 board. See the video entitled tsunami.MOV for a demonstration on how to do this. A plastic bucket placed on the floor at the far end of the flume can be used to catch spillage.

7) Use the acoustic sensor to determine the tsunami height and use the impeller placed near mid water depth to determine flow velocities (compare both of these to any corresponding previous measurements using the wave paddle as the wave forcing mechanism). *A helpful hint is to stop the data logger after the tsunami impacts the beach. Data can be read straight from the LoggerPro window and/or use the statistics icon as described earlier.*

8) Generate another tsunami, this time using some means to estimate the tsunami speed. Compare that speed to the theoretical estimate for a shallow water wave.

9) Generate several more tsunamis by varying the speed of the 2 x 4. Discuss the differences you see and identify with collected data. How do they compare to the board speed used to generate the tsunami?

   Note, the tsunami likely altered the beach. We will return to tsunami effects on beaches in module 10.

Module 8 – Beach Profiles and Basic Theory

The beach profile is the "shape" of the beach and represents the change in elevation (or depth) as a function of distance offshore (Figure 9). For example, the elevation usually decreases (depth increases) with distance farther offshore. The profile on a natural beach is generally measured along a transect perpendicular to the shoreline and from the dune to an offshore location where the elevation changes little over time (called closure depth). Measurements on the dry portion of the beach profile are collected using a global position system (GPS; Figure 10). Those in the submerged portion of the beach profile are generally collected from a vessel using a GPS and a sonar device that determines the depth (Figure 11). GPS devices can also be used from some portions of the submerged profile on shallow sloping beaches. There are other methods to collect beach profiles but these tend to be the most common.

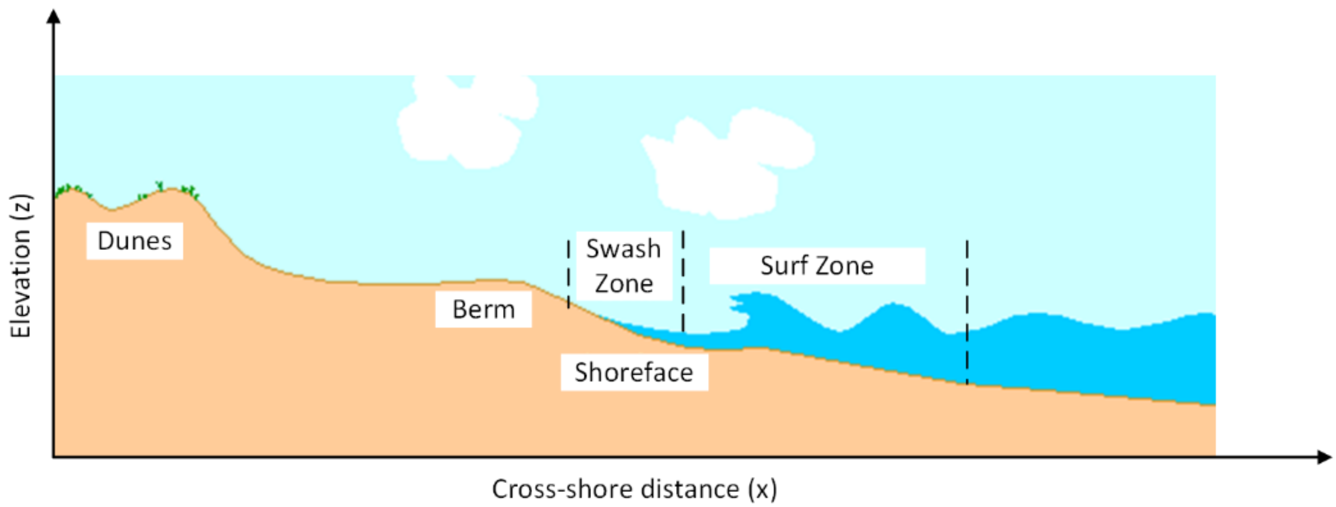


Figure 9. Schematic of the cross-shore beach profile (modified from Columbia.edu).

Figure 10. Student surveying a beach profile using a low-cost push cart and high grade GPS equipment. The antenna is at the top of the pole.

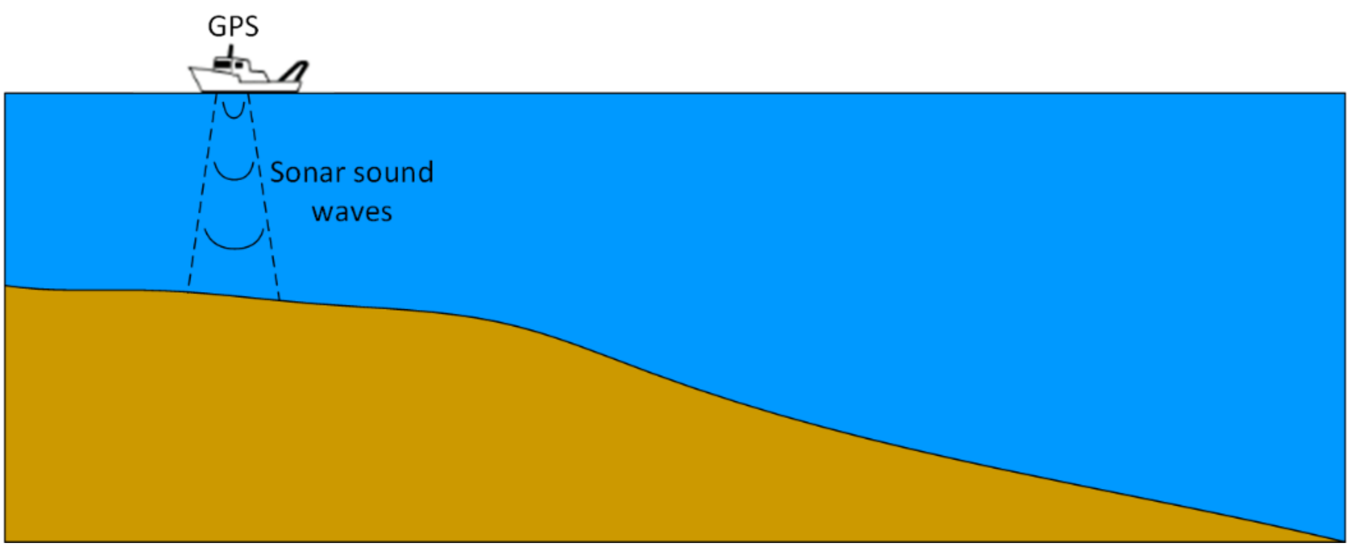


Figure 11. Schematic showing a survey vessel with GPS and sonar device for offshore beach profile measurements.

The beach profile changes on time scales as short as the wave motions with larger scale changes occurring on the time scales of storms or seasons. Coastal Engineers, Coastal Scientists and Military Planners are interested in understanding how the beach profile varies under particular wave conditions and then developing computer models to predict future beach profiles based on offshore wave conditions. Figure 12 shows an example of the seasonal change in beach profiles in southern California. The picture on the left shows a steeper beach with an ample amount of sand. This type of profile is sometimes termed a summer profile because small, longer period waves tend to drive sand onshore during the calmer summer months. The picture on the right shows a shallower sloping beach with the sand replaced by cobbles. This type of profile is sometimes termed a winter profile because large shorter period waves tend to drive sand offshore during the stormier winter months. Changes in the beach profile in the wave flume can be simulated by varying the paddle speed mimicking these summer and winter conditions.

Figure 12. Picture from southern California showing examples of beach change during summer and winter (adopted from coastalchange.ucsd.edu).

A basic theory for beach profiles suggests the shape takes the analytical form of

$$h = Ax^{\frac{2}{3}}, \tag{12}$$

where *h* is the water depth measured relative to the mean (still) water level, *x* is the distance offshore of the still water intersection with the beach, and *A* is called the profile scale parameter and is related to the size of sand on the beach. Equation (12) is known as an equilibrium beach profile. Values for *A* vary from roughly 0.05 to 0.25 for sand sized particles on natural beaches. The depth in equation (12) is positive but is often plotted as an inverse (negative) so the plot shape resembles the beach profile seen by eye. Figure 13 shows some example theoretical beach profiles for different scale parameters. The beach profile becomes flatter as the scale parameter (and associated sand size) decrease.

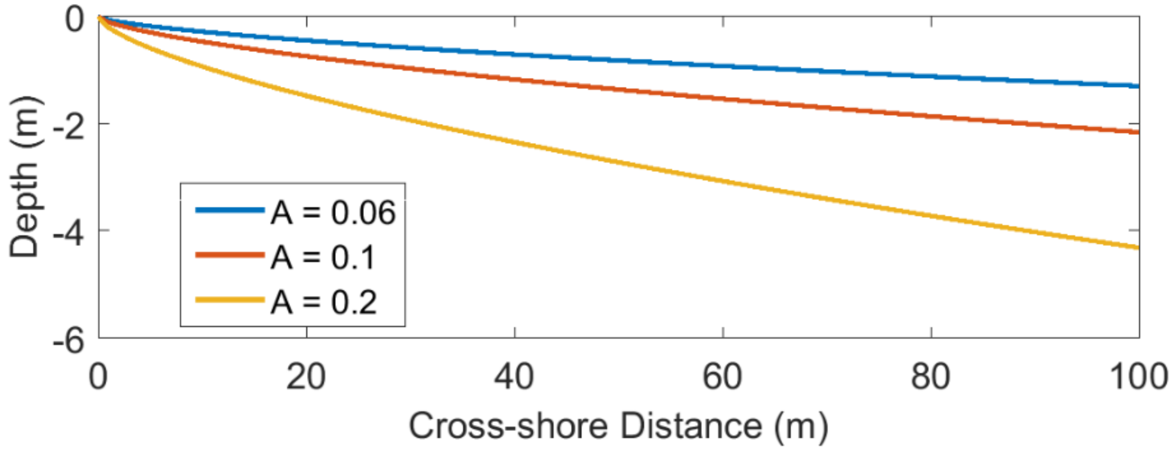


Figure 13. Example equilibrium beach profiles for different profile scale parameters.

Pre-Module 8 Questionnaire

1) What is a beach profile?

2) What are some ways researchers can measure the elevation or depth of a location on the beach?

Module 8 Experiment and Worksheet

1) What is a beach profile?

2) What are some ways researchers can measure the elevation or depth of a location on the beach?

3) At the wave flume, run waves at a particular paddle frequency for at least 3 minutes. Turn waves off. Devise a way to measure the beach profile elevation and record data on the spreadsheet MakingWaves.xlsx (tab: Beach Profile Theory). **MAKE SURE TO COLLECT A DATA POINT OF THE PROFILE AT STILL WATER LEVEL (x_{swl},z_{swl}).** Suggested cross-shore spacing for the profile is 0.02 or 0.04 m.

4) Put the (x_{swl},z_{swl}) values in the labeled cells of the spreadsheet MakingWaves.xlsx (tab: Beach Profile Theory).

5) Plot the beach profile (z or h) as a function of cross-shore distance (MakingWaves.xlsx; tab: Beach Profile Theory will also do this).

6) Does the profile shape look like it follows the simple theory of $h = Ax^{\frac{2}{3}}$?

7) Use the following steps to have Excel identify the scale parameter, *A*, through a technique known as least squares regression.

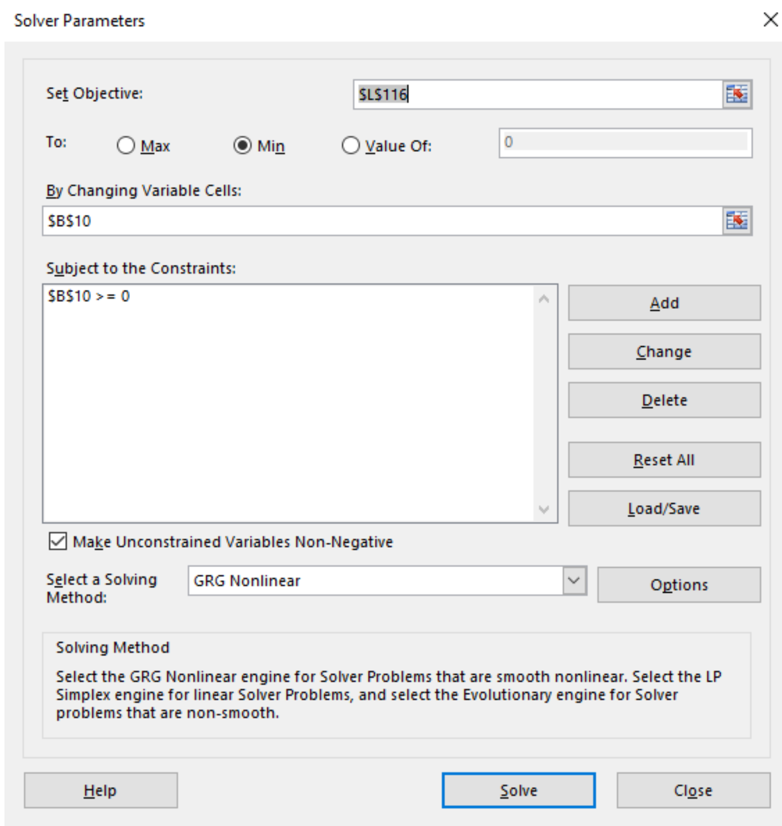
   a) Enter a guess of the A parameter into the cell identified as “Value for A” in MakingWaves.xlsx (tab: Beach Profile Theory). Suggested guess of 0.15.

   b) Highlight cell L116 in the L.S.R (least squares regression) column.

   c) Click on the Data tab at the top of the page. Click on the Solver Tab to the far right. If the solver tab is not visible follow these steps (click File, click Options, click Add-ins on the left panel, at the bottom drop down menu, select Excel Add-ins and click Go, select analysis ToolPak and Solver Add-in, click OK).

   d) In the solver window (screenshot shown here): Set Objective to L116, set By Changing Variable Cells to B10, Add a Subject to constraint B10>=0 if not already identified. Check the Make Unconstrained Variables Non-Negative, Select a solving Method should be set to GRG Nonlinear. Click Solve.

   e) The Least Squares A parameter will be returned to cell B10.



Now, compare the measured profile to the theoretical profile as shown on the graph. Describe what you see. How can you quantify the differences? MakingWaves.xlsx (tab: Beach Profile Theory) can also provide some quantification (The total squared error shown in cell L116).

Module 9 – Application: Beach Slope and Slope Predictions

The beach slope identifies the steepness of the beach profile (rise/run) and can be defined between any two locations on the beach profile. The beach slope is important for a variety of reasons:

1) It helps govern the type of breaking wave through variations in wave shoaling (where the term shoaling refers to a change in wave height with water depth). Figure 14 shows a schematic and examples of the different types of breakers one may expect on different sloped beaches. Surging breakers occur on steep beaches and/or small amplitude long period waves. The wave does not break per se but rolls onto the beach. Plunging breakers occur on more moderately sloped beaches. Spilling breakers occur on gently sloping beaches with breaking beginning at the crest of the wave and tumbling down the wave face.

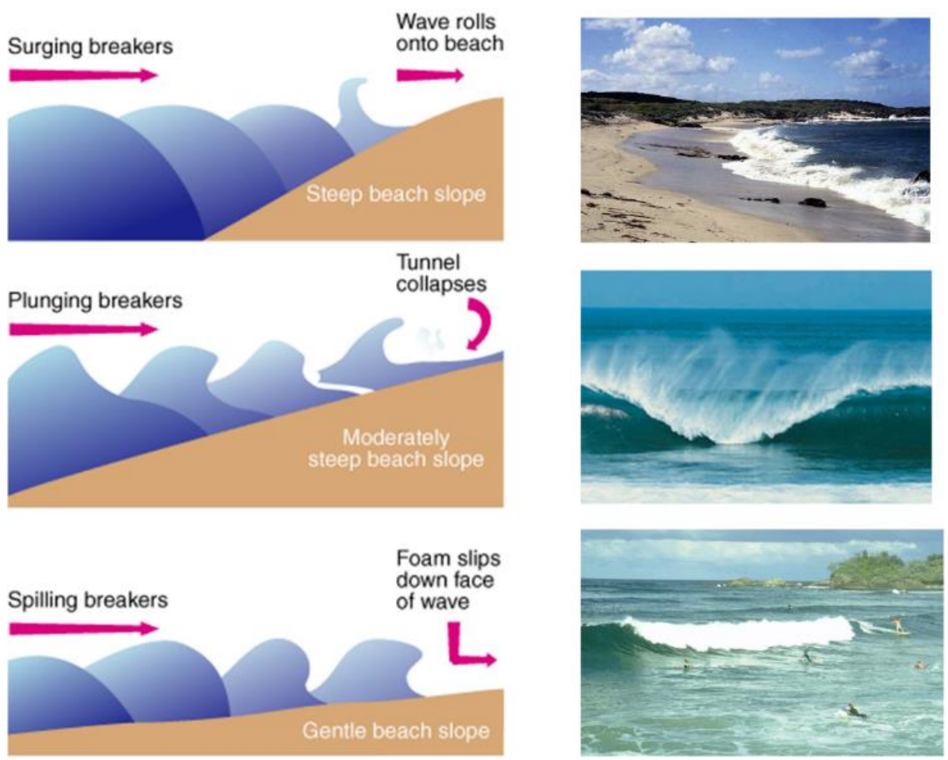


Figure 14. Schematic and associated image of different breaker types related to beach slope.

2) The beach slope near the shoreline is largely governed by swash zone processes of runup and rundown and is related to the grain size. Larger grain sizes tend to have steeper beach slopes.

3) Amphibious military activities often require the insertion of personnel from the ocean to the land. Some vehicles may have difficult traversing over a steep beach near the shoreline (Figure 15A) or if the beach slope is too shallow a vessel may be stranded far from the shoreline (Figure 15B). In addition, knowledge of the breaker type is beneficial for operators prior to landing.

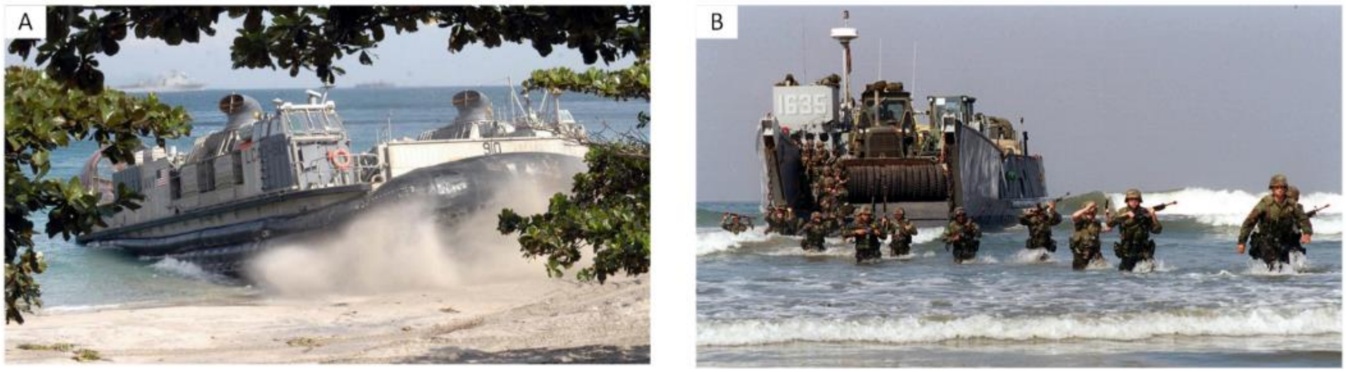


Figure 15. A) Landing Craft Air Cushion (LCAC) approaching a steep beach face. B) Military personnel exiting a landing craft that was restricted from farther landward motion due to the shallow beach slope.

There are numerous theoretical formulations for estimating the beach slope, *S*. Indeed, the derivative of equation (12) provides one estimate as

$$S = \frac{2A}{3x^{\frac{1}{3}}}. \qquad (13)$$

But, this formulation causes the slope to go to infinity as the shoreline is approached (small *x*). The interest is often the slope near the shoreline, S_0, and many other empirical estimates exist (Table 3).

Table 3. Different formulations for the beach slope near the shoreline.

Researcher	Formulation	
Rector	$S_0 = 0.3\left(\frac{H}{L}\right)^{-0.3}$	(14)
Sunamura (lab)	$S_0 = 0.26\left(\frac{D}{H}\right)\left(\frac{H}{L}\right)^{-0.6} + 0.15$	(15)
Komar and Gaughan	$S_0 = 0.25\left(\frac{D}{H}\right)^{0.25}\left(\frac{H}{L}\right)^{-0.15}$	(16)

- Where *H* is the wave height, *L* is the wavelength and *D* is the Acetal bead diameter.

Module 9 Experiment and Worksheet

This exercise will test the different formulations for beach slope near the shoreline provided in Table 3.

1) Measure the Acetal bead particle diameter.

   For three different paddle speed settings, do the following:

2) Run the waves for a minimum of 3 minutes.

3) Devise a way to quantify the beach slope near the shoreline.

4) Estimate the offshore wave height by collecting data with the acoustic sensor or using a measuring device on the flume wall (as was done previously).

5) Estimate the wave period from stopwatch measurements or from the acoustic sensor data (as was done previously).

6) Use the spreadsheet MakingWaves.xlsx (tab: Wavelength) to determine the wavelength (using the known water depth and period).

7) Plot the measured beach slope (y-axis) as a function of the theoretical slope (x-axis) for the three different slope estimates. Spreadsheet MakingWaves.xlsx (tab: Beach Slope) can assist with this plot.

8) Do the results match your expectations? What do the plots suggest about the theoretical estimates? If not, discuss some reasons why the theory breaks down for the wave flume measurements.

Module 10 – Beach Erosion

Engineers, scientists, municipality managers and insurance agencies (among others) have an interest in how the beach changes over time as it can affect property and infrastructure loss. The change of most interest/concern is beach erosion (Figure 16) where sand is removed from the landward portion of the beach profile and carried offshore or alongshore. Many times this sand or some fraction of it will return to the beach under calmer conditions, but that is not always the case. Beach erosion processes can be studied by measuring the profile before and after erosive conditions (e.g. storm) occur. The difference in profile elevation at each cross-shore position provides the local change. Integrating those changes across the profile yields the total volume change in the beach profile.

Figure 16. Picture from Mid-Atlantic beach showing severe beach erosion (coastalcare.org).

As mentioned, total volume changes can be determined by integrating the measured elevation changes across the profile. Integration is another term for summation or finding the area under a curve from some location x_1 to another location x_2. Volume is obtained by multiplying this area by some distance along the beach (the flume width for the Making Waves program). Let's assume that elevation measurements were made at two different times on the same beach profile; perhaps pre- and post-storm (Figure 17). The integrated volumetric changes can be determined by finding the area under the pre-storm curve (black shading) and subtracting the area under the post-storm curve (blue shading).

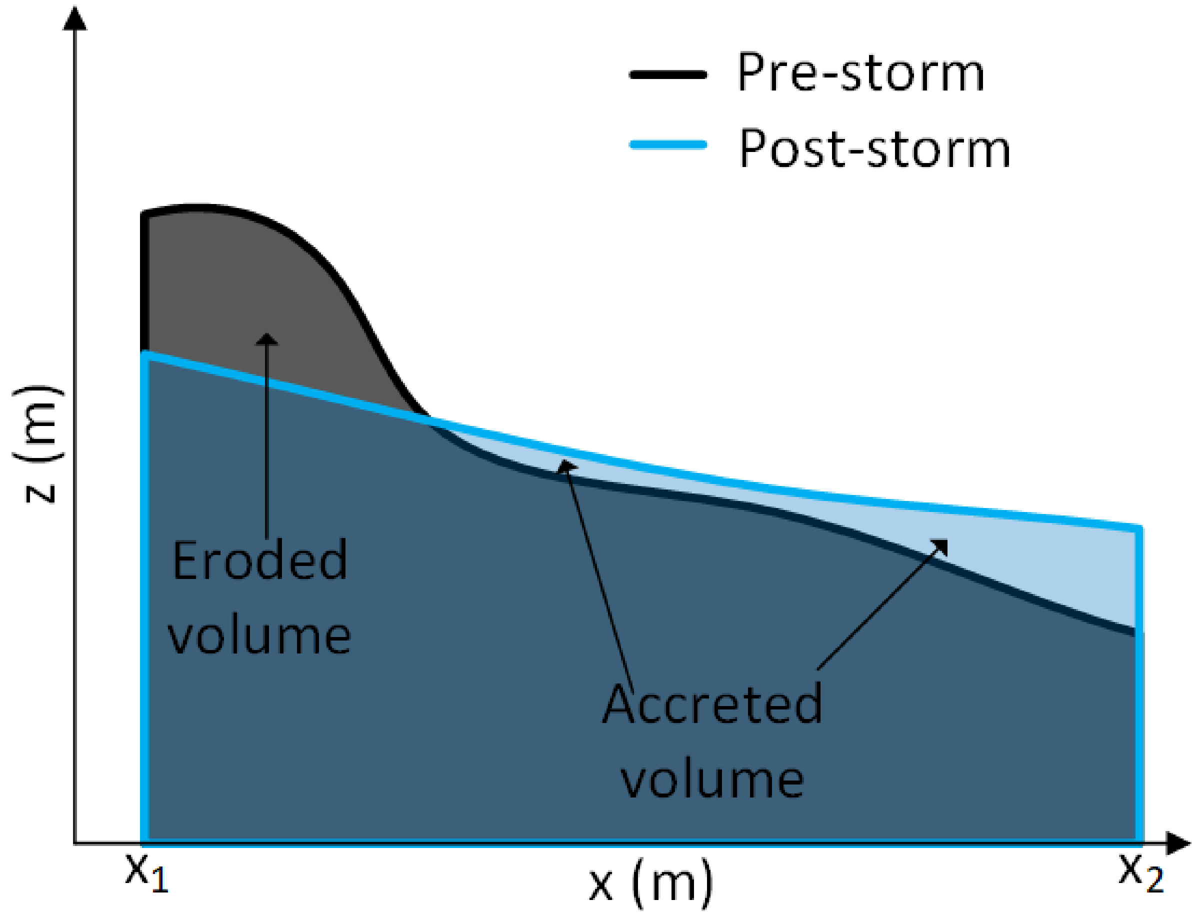


Figure 17. Schematic showing the areas under the curve determined through integration and eroded and accreted volumes from pre- and post-storm measurements.

The integration can be approximated by many different procedures:

<u>Left-point rule</u> (Figure 18): The Left-point rule "chops" the integral into a summation of rectangular shapes. The rectangles are identified with the width being the horizontal distance between the location of two known measurements and the height being the elevation at the left edge of the rectangle. The equation for a <u>single</u> rectangular shape within the summation between locations x_2 and x_1 is:

$$Area = (x_2 - x_1) * z_1. \tag{17}$$

Equation (17) is multiplied by flume width to obtain volume for that segment. The procedure is repeated for all segments and the individual volumes are added to obtain the total volume.

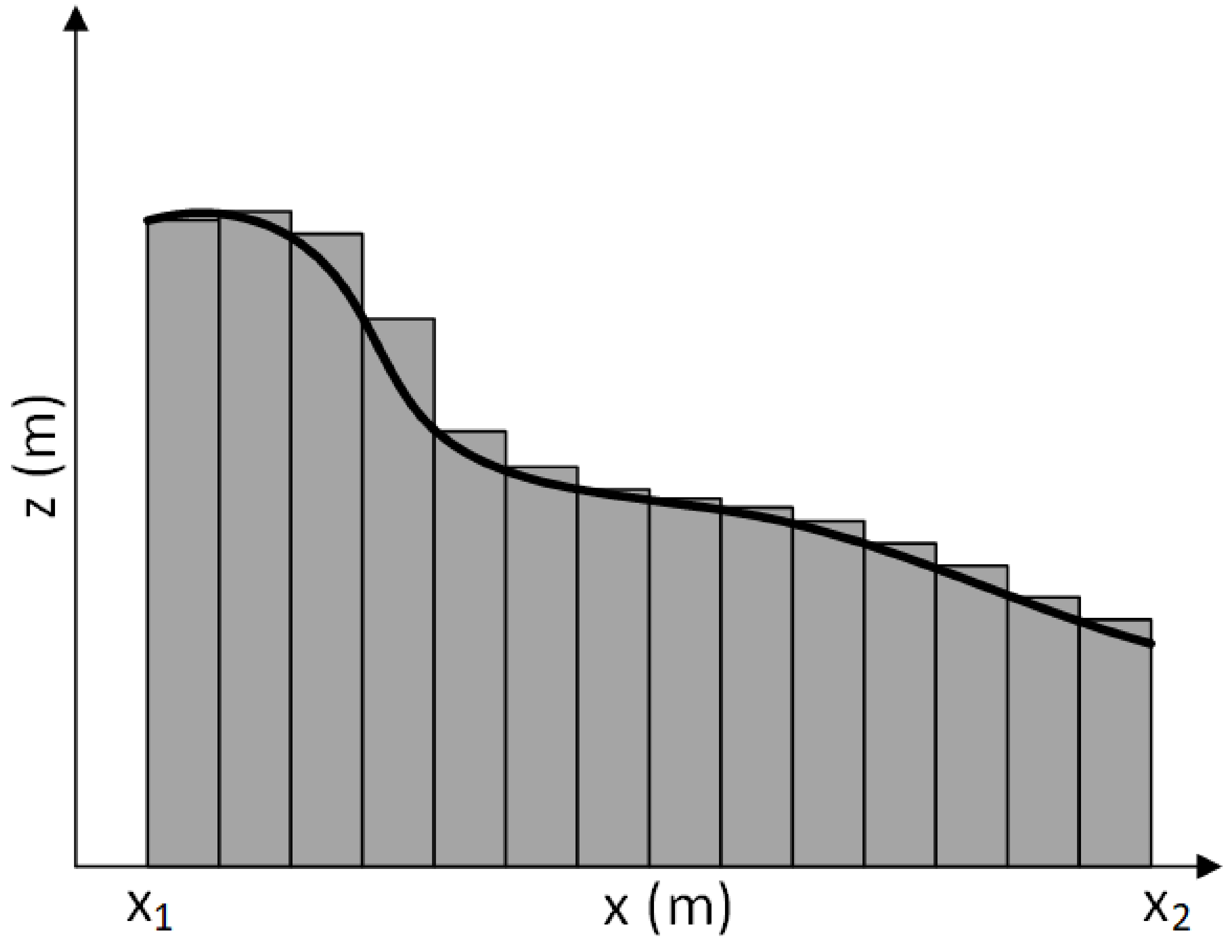


Figure 18. Schematic showing the left-point rule for integration for area under the curve.

Trapezoidal rule (Figure 19): The Trapezoidal rule "chops" the integral into a summation of trapezoidal shapes. The trapezoids are identified with the width being the horizontal distance between the location of two known measurements and the heights being the elevations at those two locations. The equation for a single trapezoidal shape within the summation between locations x_2 and x_1 is:

$$Area = (x_2 - x_1) * \frac{1}{2}(z_2 + z_1). \tag{18}$$

Equation (18) is multiplied by flume width to obtain volume for that segment. The procedure is repeated for all segments and the individual volumes are added to obtain the total volume.

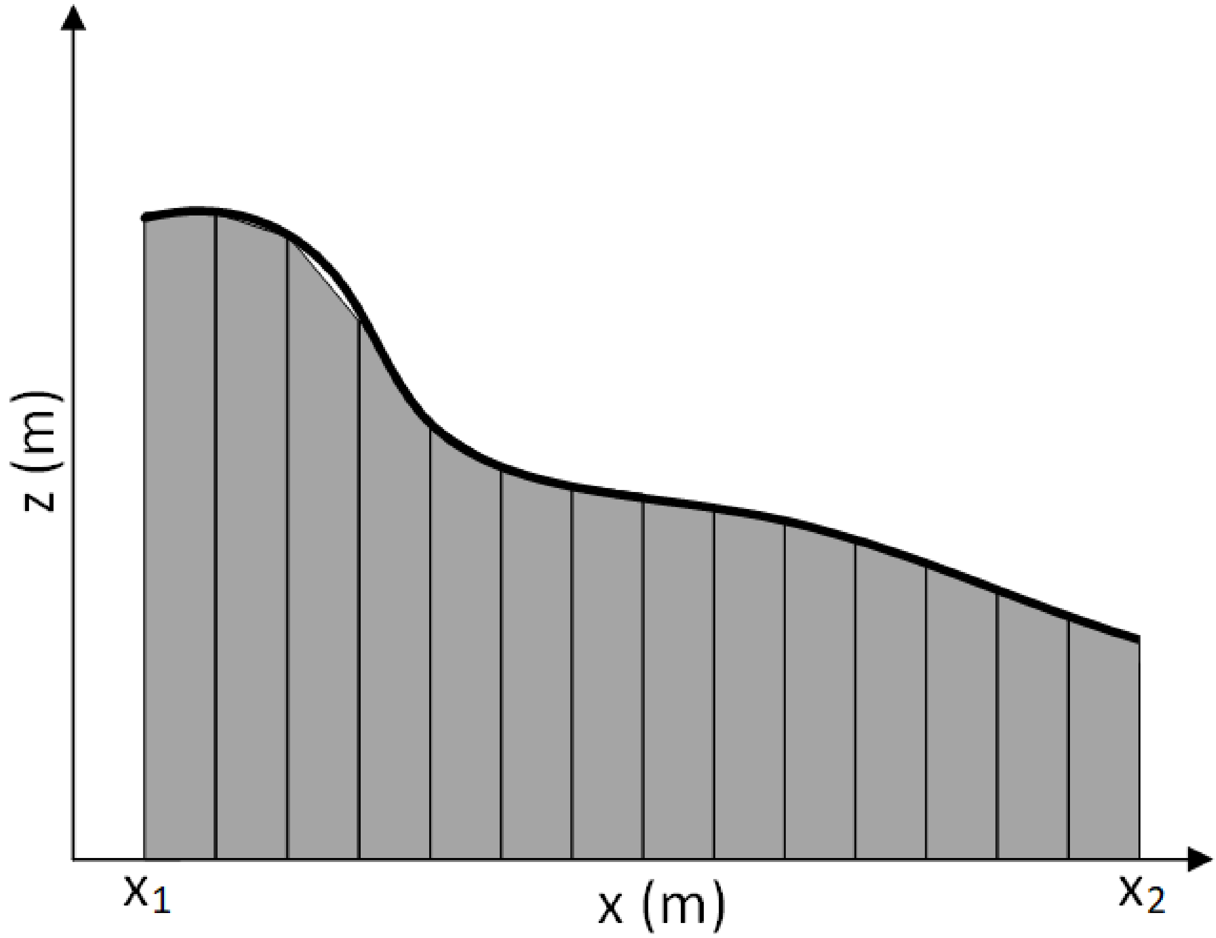


Figure 19. Schematic showing the trapezoid rule for integration for area under the curve.

<u>Simpson's rule</u>: Simpson's rule also breaks the integral into a summation of shapes but tries to maintain some curvature for each section of the summation using parabolic interpolation rather than using a horizontal or angled line as in the left-point and trapezoid rules respectively. The equation for Simpson's rule is not provided as it is beyond the scope of the exercise. However, results from Simpson's rule and the other approximations are presented in MakingWaves.xlsx (tab: Beach Erosion).

Module 10 Experiment and Worksheet

1) At the wave flume, run the waves with a slow paddle speed creating "summer" conditions. Run the waves for at least 5 minutes and then turn the paddle off.

2) Carefully trace out the "summer" beach profile using the pin striping tape by adhering it to the flume wall.

3) Run the waves with a high paddle speed creating "winter" conditions. Run the waves for at least 5 minutes and then turn the paddle off. Notice the difference in the time it takes for the beach to respond to "winter" waves vs. "summer" waves? Explain why the beach changes faster for "winter" waves.

4) Carefully trace out the "winter" beach profile using the pin striping tape (different color) by adhering it to the flume wall.

5) Use the technique from module 8 to measure the "summer" and "winter" beach profiles and record your data either directly into the spreadsheet entitled MakingWaves.xlsx (tab: Beach Erosion) or on a printout of the same sheet. **Make sure to use the same cross-shore coordinates for both profiles. Suggested spacing is 0.02 or 0.04 m.**

6) Enter your data into the spreadsheet if a hard copy was used

7) The spreadsheet will automatically plot the two beach profiles and estimate the net volumetric change using several different estimates for integrating across the profile.

8) Do you expect there to be a net volumetric change in the beads that constitute the beach profile? Why might the net result be non-zero?

9) Return to the wave flume and generate a tsunami using the approach described in module 7. What do you think will happen to the profile relative to the "winter" condition?

10) Trace out the beach profile after tsunami generation and enter data into the spreadsheet entitled MakingWaves.xlsx (tab: Tsunami Erosion) or on a printout of the same sheet. Make sure to obtain measurements at the same cross-shore positions as was done for the "winter" profile.

11) Enter your tsunami data into the spreadsheet if a hard copy was used.

12) Copy the "winter" data from MakingWaves.xlsx (tab: Beach Erosion) to MakingWaves.xlsx (tab: Tsunami Erosion).

13) The spreadsheet will automatically plot the "winter" and tsunami beach profiles and estimate the net volumetric change using several different estimates for integrating across the profile. Did the beach change match your expectations? What was the effect on the landward portion of the beach profile?

Module 11 – Application: Beach Nourishment

It is estimated that nearly 25% of sandy beaches worldwide are eroding. Beaches provide a protective buffer from extreme events and also provide recreation opportunities that attract tourists and support many local economies. Thus, it might be important to mitigate erosion because the financial and protective benefits tend to far exceed the cost. There are a variety of methods used to protect coastlines in an effort to minimize erosion with the two most common being: 1) hard structures such as jetties, groins, or sea walls (See Module 13); and 2) beach nourishment. The latter is now the most common approach, especially in the United States and is sometimes referred to as the "soft" solution.

Beach nourishment is the process whereby sand from a borrow source, usually far offshore, is dredged and delivered to the coast via barge or vessel. The sand is pumped onto the beach and moved into position with heavy machinery. The initial beach shape, called the template, is steeper than what is expected for that particular shoreline so that natural processes can redistribute the sand. It should be noted that in other countries sand is pumped into the surf zone rather than on the beach for nourishment in the hopes that waves will eventually move the sand onshore. Figure 20 shows a pre- and post-nourishment image from Rehoboth Beach, Delaware. The dredge delivering sand to the beach can be seen in the upper image. Tide levels are roughly the same in both images. The outflow pipes (structures running across the beach) and the steps down to the beach from the boardwalk provide excellent perspective with regard to the nourished beach where the pipes are covered and the steps are no longer needed as a dune was built up against the boardwalk.

Figure 20. Before and after images of beach nourishment at Rehoboth Beach, DE.

The most basic beach tenet of beach nourishment is to increase the dry beach width by some amount. The theory to identify the required volume uses the concept of equilibrium beach profiles (equation 12) for the original and nourished beach profiles. The volume (V, per meter length of beach) of required sand for a particular desired additional dry beach width Δx is given as:

$$V\ per\ meter\ length\ of\ beach = (h_* + B)\Delta x, \tag{19}$$

where h_* is the closure depth; location where the beach profile is expected to change little, and B is the berm height (refer to Figure 21). The total volume is then obtained by multiplying equation (19) by the project length. In a natural setting, the length may be on the order of kilometers. In the Making Waves in the Classroom exercises the project length is the internal flume width.

The original beach profile is assumed to have an equilibrium profile shape (Module 8). The nourished profile is shifted upward and seaward maintaining the same equilibrium profile shape if the diameter of the nourishment sediment is the same as the original, the case for Making Waves in the Classroom exercises. The closure depth, as described previously, is the depth where there is expected to be little change in elevation over time. This depth is limited in the wave flume due to the flume dimensions.

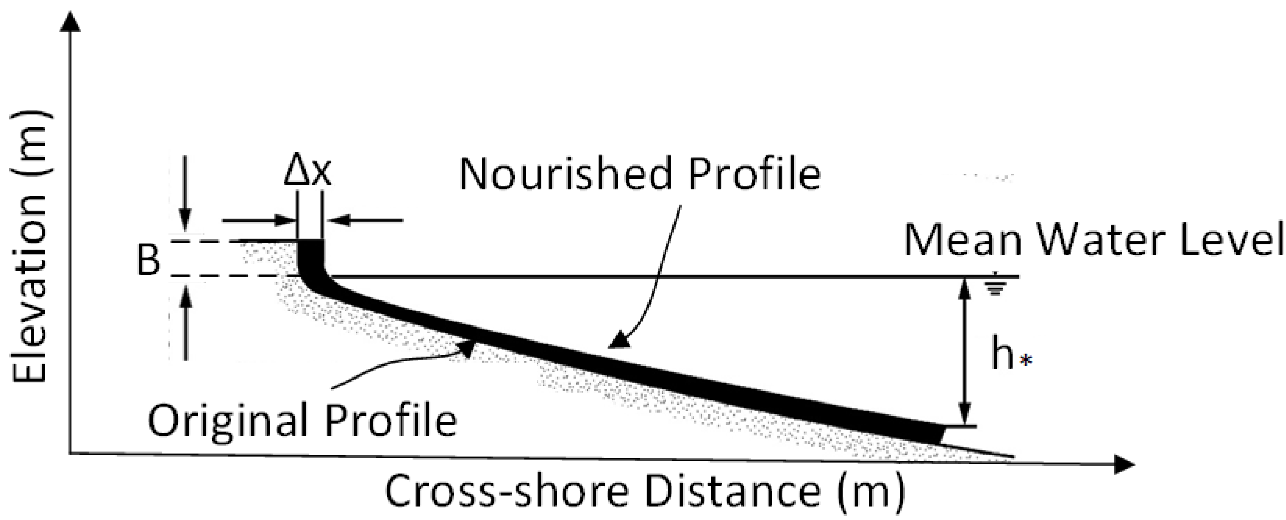


Figure 21. Schematic showing the original beach profile and the nourished beach profile providing the additional dry beach width, Δx.

Module 11 Experiment and Worksheet

1) At the wave flume, run the waves with a slow paddle speed creating "summer" conditions. Run the waves for at least 5 minutes and then turn the paddle off.

2) Carefully trace out the beach profile using the pin striping tape by adhering it to the flume wall.

3) Estimate the berm height (in meters).

4) Estimate the closure depth based on your beach profile measurements from module 10. The value may essentially be the distance from the still water level to the bottom of the flume.

5) Identify a desired additional dry beach width for a nourishment (suggested values between 0.05 and 0.1 m). The smaller value of the range is recommended.

6) Determine the required volume of material for the beach nourishment using equation (19) and the internal flume width.

7) The volume of beads can be measured using the provided plastic beakers. Otherwise, the mass can be estimated using the known bead density of 1420 kg/m3 and the required volume in cubic meters. Note that the density does not consider the voids between the particles (roughly 30%). Thus, the required mass is really 70% of the calculated mass (the voids do are already considered if bed volume is used). Use the provided scale to measure the required mass of beads for the beach nourishment. The scale can measure in units of grams requiring kilograms to be converted to grams first (by multiplying by 1000).

8) Place the nourishment beads on the beach face near the mean water line. Run the waves for 5 minutes with the paddle speed unchanged from step 1. Describe what you see happening.

9) Turn the waves off and carefully trace out the beach profile using the pin striping tape (different color) by adhering it to the flume wall. Describe the differences in the two profiles. You can measure the beach profiles and put the data into the spreadsheet MakingWaves.xlsx (tab: Beach Nourishment) to plot the profiles and investigate volumetric changes.

10) What is the final dry beach width gained? Does it match the desired width? Why might there be a difference between the desired and actual dry beach width gained?

11) If time permits, remove the nourished volume of beads from the flume. Perform the experiment again from the beginning, but this time place the nourishment beads in the surf zone.

Module 12 – Sea Level Rise – Effect on Beaches

Sea level rise occurs when landlocked ice sheets melt releasing their water to the oceans and through the warming of oceanic water causing it to expand. Global sea level rise is estimated at roughly 30 cm per century (Figure 22) and may accelerate over time. Sea level rise has important implications for low-lying coastal areas where infrastructure can become impacted more frequently (Figure 23). In addition, sea level rise enhances coastal erosion by allowing oceanic processes to impact regions farther landward (Figure 23).

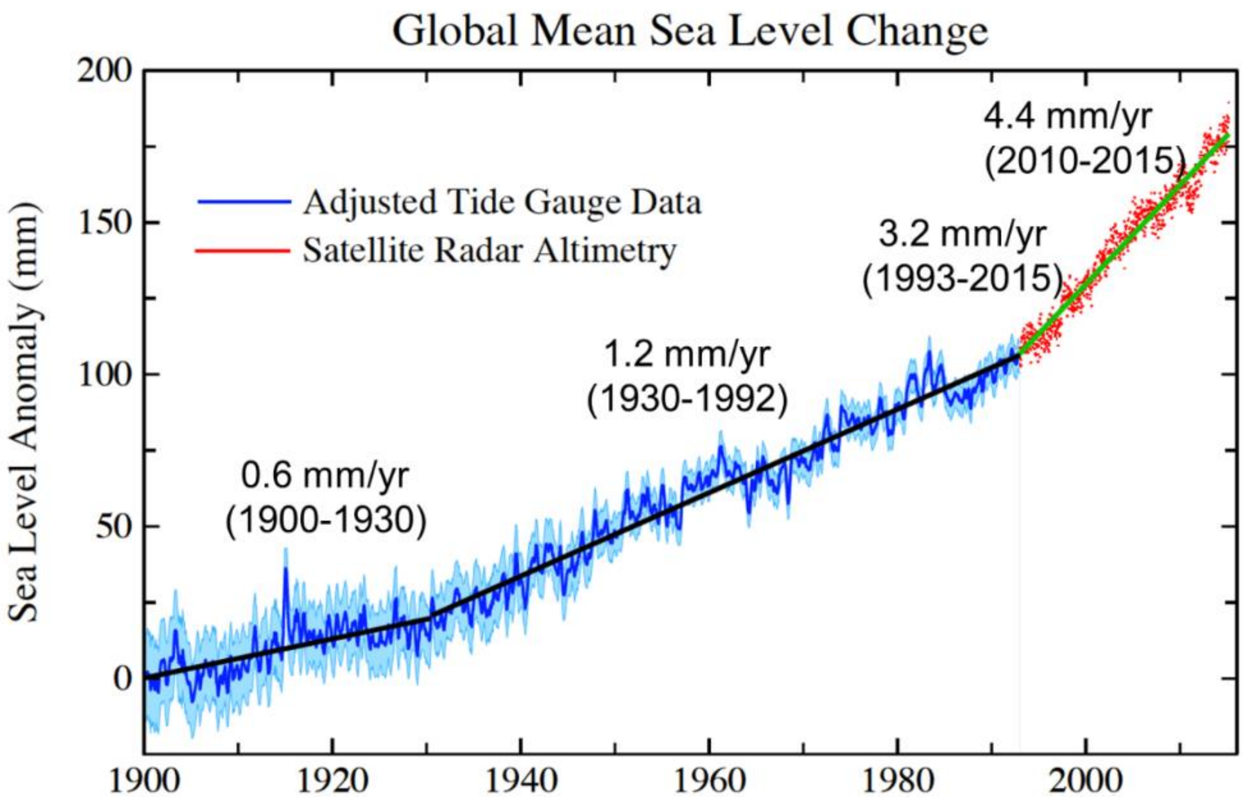


Figure 22. Estimate of global mean sea level rise for the last century (Hawaii.gov).

Figure 23. Image showing the effects of sea level rise with impacts on infrastructure and beach erosion (climatecentral.org).

Pre-Module 12 Questionnaire

1) What is sea level rise and what causes it?

2) What is a rough estimate of global sea level rise per century?

3) How can sea level rise affect coastal communities?

Module 12 Experiment and Worksheet

1) What is sea level rise and what causes it?

2) What is a rough estimate of global sea level rise per century?

3) How can sea level rise affect coastal communities?

4) At the wave flume, run the waves with a slow paddle speed creating "summer" conditions. Run the waves for at least 5 minutes and then turn the paddle off.

5) Carefully trace out the beach profile using the pin striping tape by adhering it to the flume wall.

6) Collect "before" sea level rise beach profile data using the approach from module 8. Paste your data into the spreadsheet MakingWaves.xlsx (tab: Sea Level Rise).

7) Decide on a sea level rise value for the wave flume (suggested values are 3, 4 or 5 mm). These values are large for the scaled wave flume but should allow some beach changes to be observed.

8) Estimate the volume of water needed to be placed in the flume to generate the sea level rise chosen

9) Put the volume of water into the flume and run the waves with the same paddle speed as in step 4. Run the wave for at least 5 minutes. Turn the waves off.

10) Carefully trace out the beach profile using the pin striping tape (different color) by adhering it to the flume wall.

11) Collect "after" sea level rise beach profile data using the approach from module 8. Make sure to collect data that the cross-shore positions as the "before" nourishment profile. Paste your data into the spreadsheet MakingWaves.xlsx (tab: Sea Level Rise).

12) How did the profile change after raising sea levels but keeping the wave forcing the same?

13) What are some ways that this change can be quantified? Elevation measurements can be placed in the spreadsheet MakingWaves.xlsx (tab: Sea Level Rise) to plot the profiles and investigate volumetric changes, if desired.

14) Postulate what would have happened if the sea level rise chosen was half or double what was actually used. Time permitting, add additional water volume to test the effect of doubling sea level rise.

Module 13 – Application: Protecting the Beach

Beach nourishment was shown as one mechanism to protect the beach. Other mechanisms do exist including the use of offshore breakwaters (Figure 24A), gabion structures (Figure 24B), seawalls (Figure 24C), and possibly living shorelines (although not common on open ocean sandy coastlines).

Figure 24. Examples of methods to protect beach using hard structures. A) Offshore breakwater, B) Gabion structures, C) Seawall.

Module 13 Experiment and Worksheet

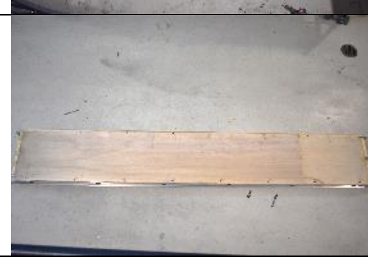
Select some structure for beach protection from the choices available (rocks, seawall) and conduct an experiment placing the structure somewhere on the beach profile and recording the change in the beach profile and corresponding wave conditions where applicable. Record the results and generate plots to discuss the effect of the chosen structure. Time permitting, choose another structure or alter the same structure (use more, use less, change orientation, change location, change burial depth etc.) and redo the experiment. Record the results and generate plots to discuss the effect of the chosen structure.

The spreadsheet MakingWaves.xlsx (tab: Beach Protection) can be used to investigate pre- and post-structure placement beach profiles. No solutions are given the open-ended nature of the experiment.

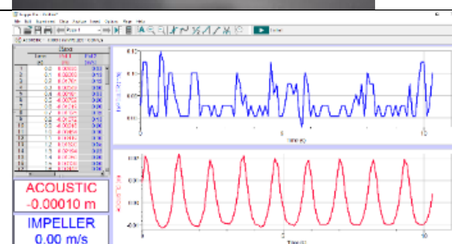
Appendices

Wave Flume Parts List

The flume consists of:

Part	Where Purchased	Image
Two 8' sections of acrylic that mate in the center using draw latches	Fabricated by CHPT manufacturing in Georgetown, DE	
Scaffold stand parts CB72: 7' x 2' cross brace	Scaffoldingdepot.com	
Scaffold stand parts CB102: 10' x 2' cross brace	Scaffoldingdepot.com	
Scaffold stand parts 81G: screw jack with base plate, solid	Scaffoldingdepot.com	
Scaffold stand parts B7: 7' aluminum plank with wood deck	Scaffoldingdepot.com	
Scaffold stand parts B10: 10' aluminum plank with wood deck	Scaffoldingdepot.com	

Scaffold stand parts SPL: 2' x 3' scaffold frames, Vanguard	Scaffoldingdepot.com	
DC gear motor (3XA78)	Grainger.com	
DC voltage controller (5X412)	Grainger.com	
Motor housing	Fabricated at the University of Delaware, (see plans below for description)	
Acetal copolymer 9 Melt Natural, (PPR-POM01)	Premierplasticresins.com	

Impeller current meter MiniWater6 Micro, (MIWA0611)	Omni Instruments	
Banner ultrasonic distance meter (current version; S18UIAQ)	Walker Industries	
Vernier LabQuest Mini Logger (LQ-MINI)	Vernier.com	
Vernier LoggerPro 3 (LP)	Vernier.com	
Vernier analog breadboard cable (BB-BTA)	Vernier.com	
Two Sciencent Support Stand 8" x 5", Coated Base Size - 24"	Amazon.com	
Dell Laptop	Amazon.com, but any recent Windows based laptop will work	

Digital kitchen scale	Amazon.com, but any small digital scale will work	
Range of beakers	Amazon.com, but any beakers will work	
Bestty 120 inches Double Scale Soft Tape Measure	Amazon.com, but any hard or soft tape measure with metric units will suffice	
Two stopwatches	Amazon.com, but any stopwatch or timer will work	
Ping pong balls	Amazon.com	
Pin striping tape	Amazon.com	
Plumbers putty	Lowes	
Plumbers tape	Lowes	
Ruler	Amazon.com	
½” wrench	Mcmaster.com	
Phillips head screwdriver	Mcmaster.com	
Beach protection structure elements: bag of small rocks, bag of aluminum blocks, plastic sheet (seawall)	Lab surplus, any similar items will work	
2 x 4 (2 feet long)	Lowes	
Fish net	Amazon.com	

Wave Flume Set Up

Scaffold Stand

Set up the scaffolding frame using the frame stands and the screw jacks

Figure A1. Pictures showing frame stands and jack screw set up.

Install the cross-braces by places the brace opening over the pin on the scaffold stand

Figure A2. Pictures showing cross brace installation.

Place the scaffold planks on the scaffold stands being careful not to pinch fingers. **Note the long scaffold plank will contain the motor stand. It has the outline marks for the flume and motor stand.**

Figure A3. Pictures showing installation of the scaffold planks.

Adjust the level of planks using the arms on the jacks. In most situations, the jacks will only require a turn or less to level.

Figure A4. Pictures showing jack screw adjustment.

Wave Flume

Place the motor end of the flume on the longer scaffold plank.

Figure A5. Picture showing motor end of flume on scaffold plank.

Place the other end of the flume on the shorter scaffold plank. It will hang off the plank.

Figure A6. Picture showing beach end of flume hanging off scaffold plank.

Take a small amount of plumber's putty and roll into a narrow diameter "snake" about the diameter of a pencil.

Figure A7. Pictures showing use of plumber's putty.

Place the putty onto the inner vertical and horizontal surfaces of the end of the flume mating section; the surfaces WITHOUT the orange rubber seal.

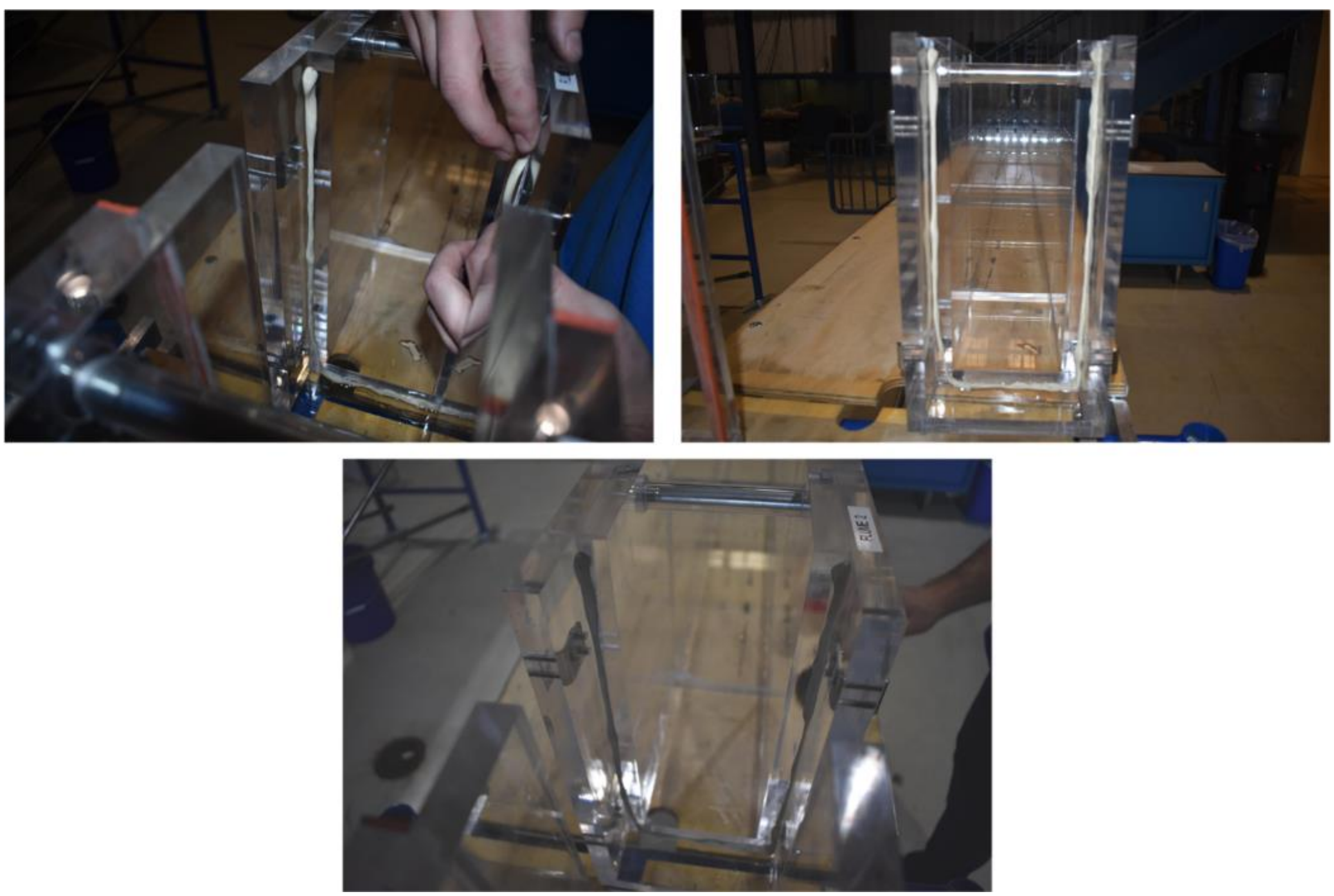


Figure A8. Pictures showing placement of plumber's putty on the interior flume face.

Slide the two flume halves together. DO NOT wiggle the two halves side-to-side as this may crack the acrylic. Once the sides are nearly seated use the draw latches to adhere the two halves together. Use the grasp of the draw latch to adjust the tension. The latch should shut tight but there is no need to have it extremely tight.

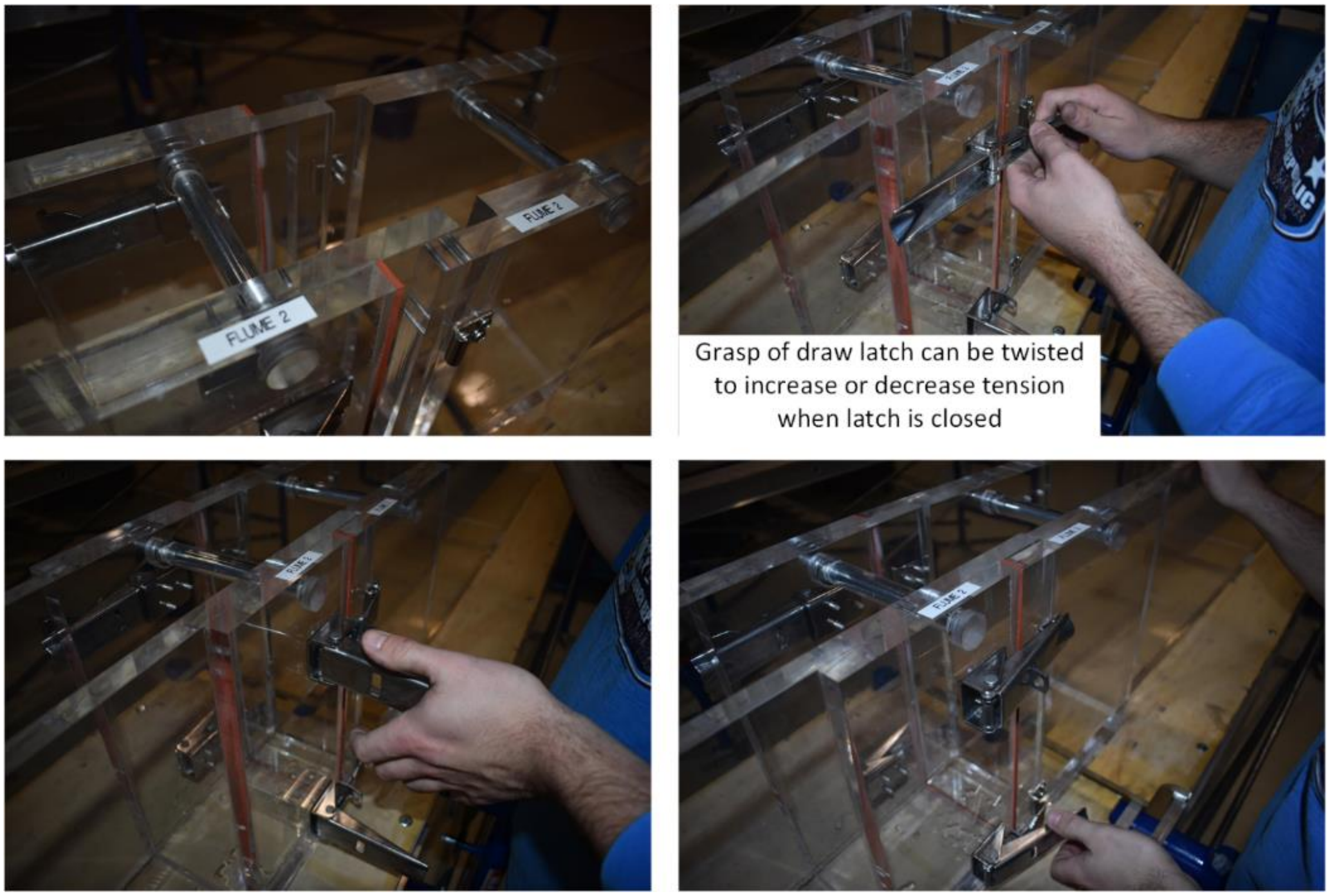


Figure A9. Pictures showing mating of flume halves and adjustment and closing of draw latches.

The plumbers putty should squeeze up into the gap between flume halves flume and create and additional watertight seal. Remove any excess plumbers putty.

Slide the entire flume so it aligns with the marks on the scaffold planks.

Figure A10. Picture showing flume alignment on scaffold plank marks.

Screw the NPT drain plug into the threaded opening on the beach side of the flume (if not already done). There is no need to overtighten this cap. MAKE SURE the cap is not cross-threaded when tightening. The first few turns should be easily done by hand. Plumbers tape may be needed for a tight seal.

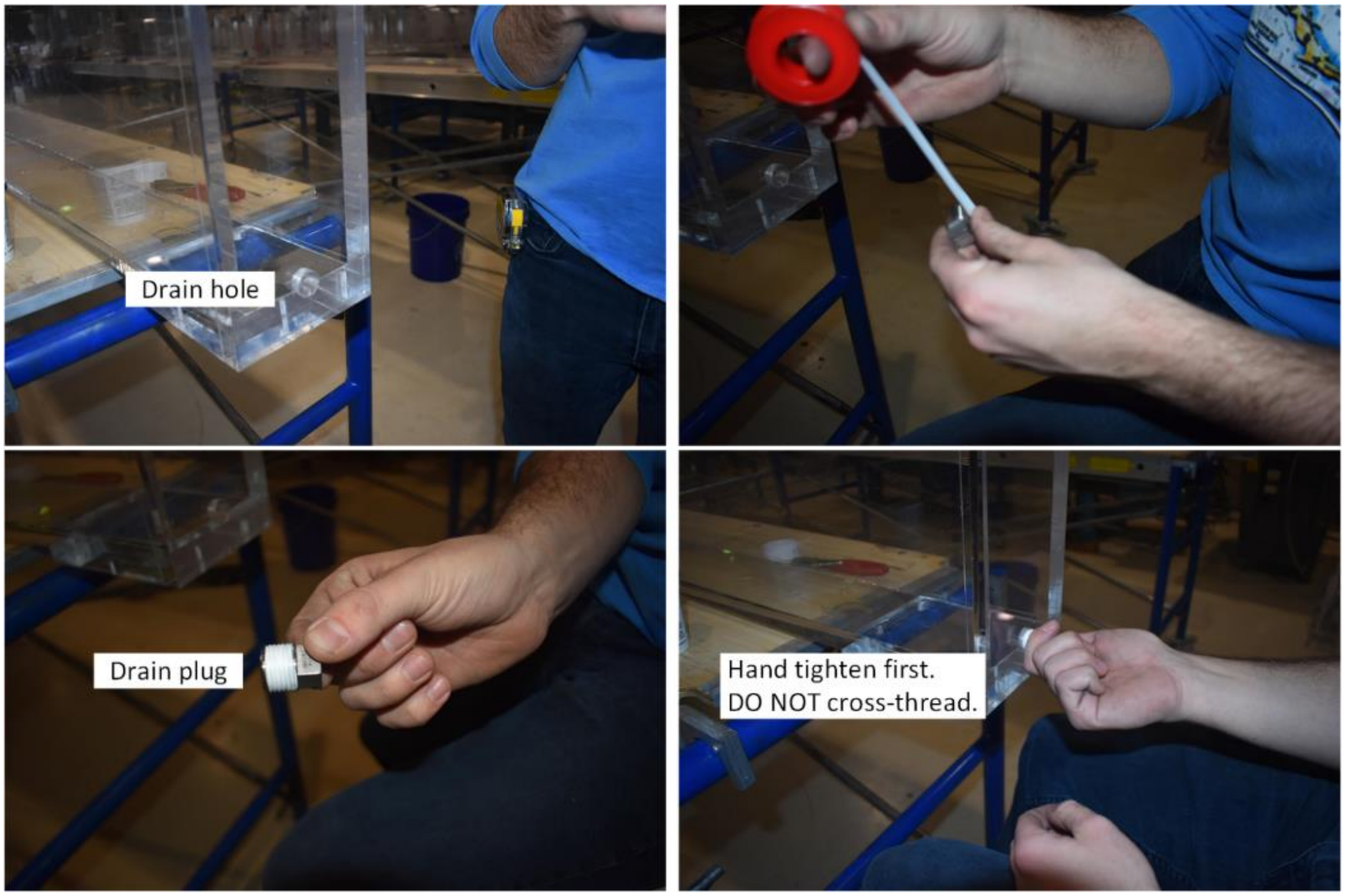


Figure A11. Pictures showing drain hole and drain plug.

Motor Assembly Stand

Place the motor assembly stand on the scaffold plank at the wave paddle end of the flume. Align the stand with the marks and the L-brackets with the existing holes. Insert wood screws using a drill with Phillips bit or the supplied screwdriver to hold the motor stand fixed.

Figure A12. Pictures showing motor assembly stand and stand placement on scaffold plank.

Attach the linkage arm to the paddle by threading the bolt into the opening on the paddle arm. Use the supplied ½" wrench to tighten the bolt to the paddle arm. Attach a 5/16" nut to the bolt and tighten using the supplied ½" wrench.

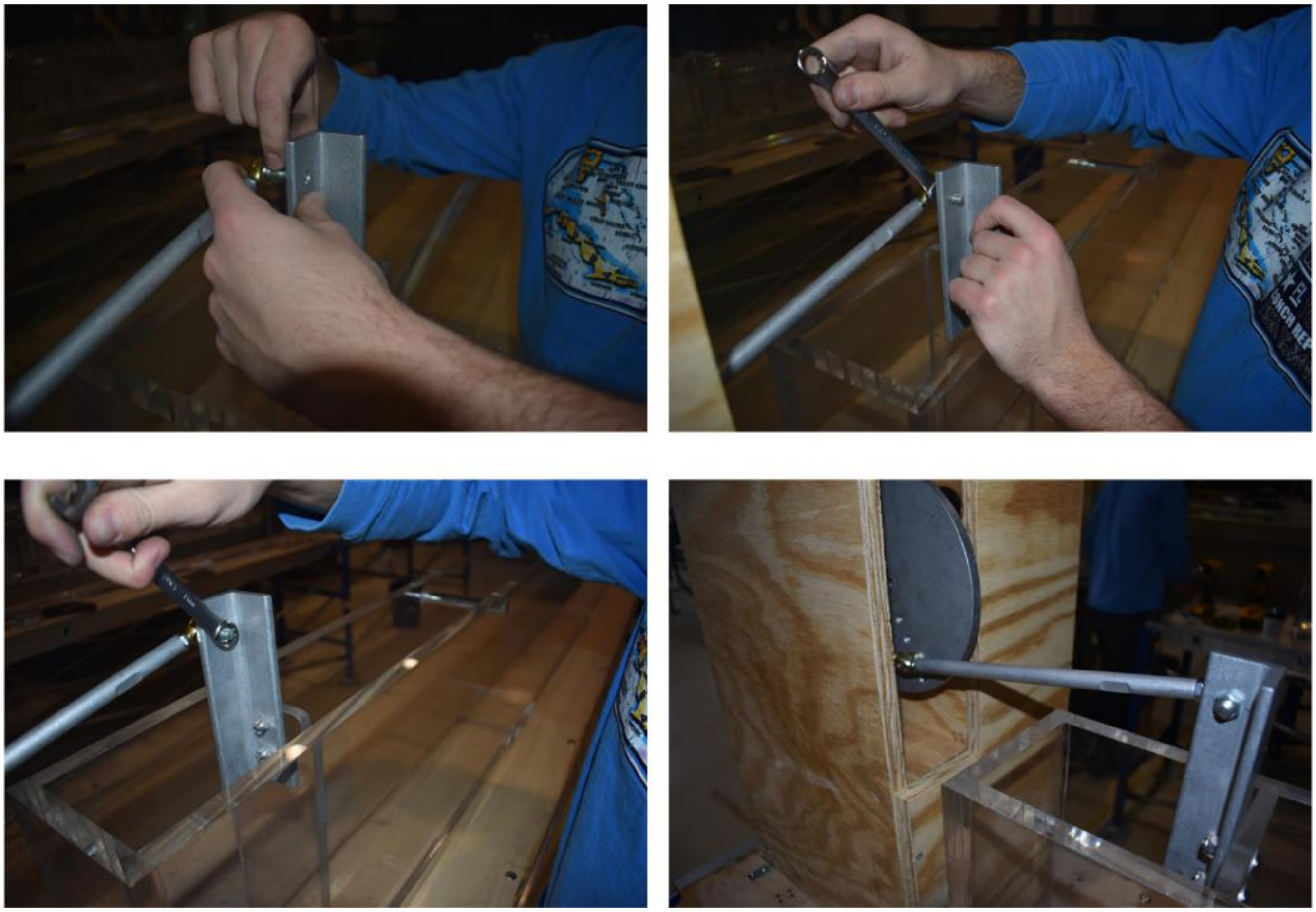


Figure A13. Pictures showing attachment of linkage arm to wave flume paddle arm.

Connect the short power cord from the DC controller to the power receptacle on the motor stand. Connect the longer power cord into a wall outlet to provide power to the system.

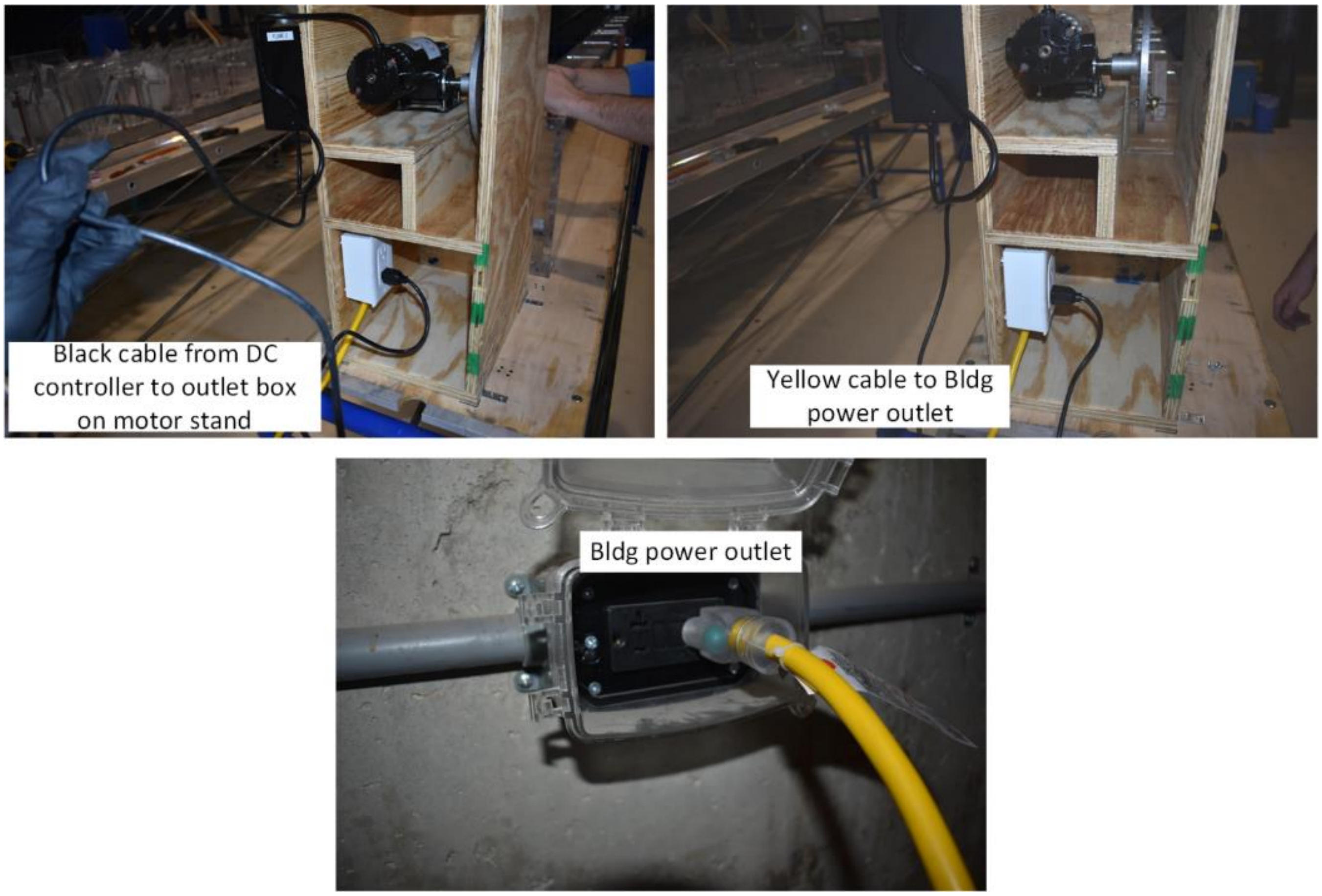


Figure A14. Pictures showing power connection cables.

Using the Flume

Fill the flume with water until roughly 0.05 m deep and check for leaks at the flume midsection and the at the drainage plugs.

If leaks occurs:

1) Check that the draw latches are holding the flume halves together tightly
2) If necessary, drain flume, pull apart and redo the plumbers putty procedure described above
3) Verify the drainage plugs are in and seated several threads. Pipe thread tape may be needed to improve sealing.

Once the flume is leak free:

Add 1.5 to 2 buckets of Acetal beads at the beach end (opposite paddle). Spread the beads over roughly 1 to 1.5 m in an approximate triangular shape (Figure A15).

Figure A15. Initial beach set up in a roughly triangular shape.

Fill the flume to a depth of 0.14 to 0.18 m.

Plug in the yellow extension cable to building power. Turn the controller power switch to on. Waves are made by adjusting the control knob to change the paddle frequency (Figure A16).

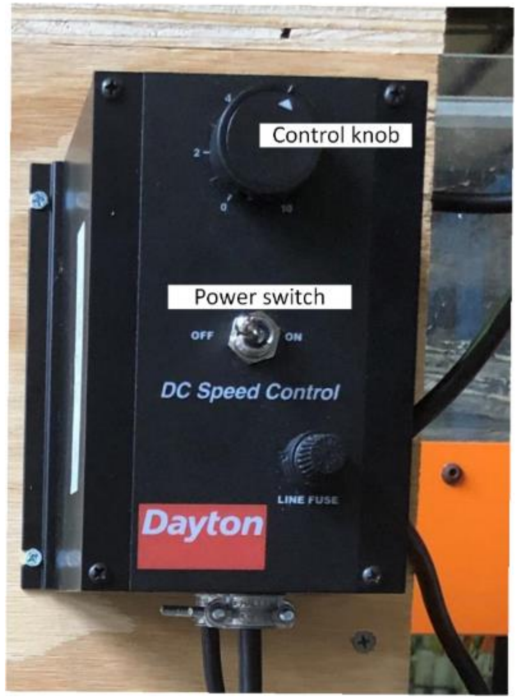


Figure A16. DC controller showing power switch and speed control knob.

DO NOT turn power on with control knob above 3.

DO NOT turn the control knob beyond 7.

The flume should be cleaned periodically. Placing a small amount of bleach in the water will help mitigate growth.

Wave Flume

The wave flume was fabricated by CHPT Manufacturing in Georgetown DE. The flume consists of two 8' sections of acrylic that mate in the center using draw latches. Scaled drawings of the flume are provided below with description on putting the flume together provided earlier.

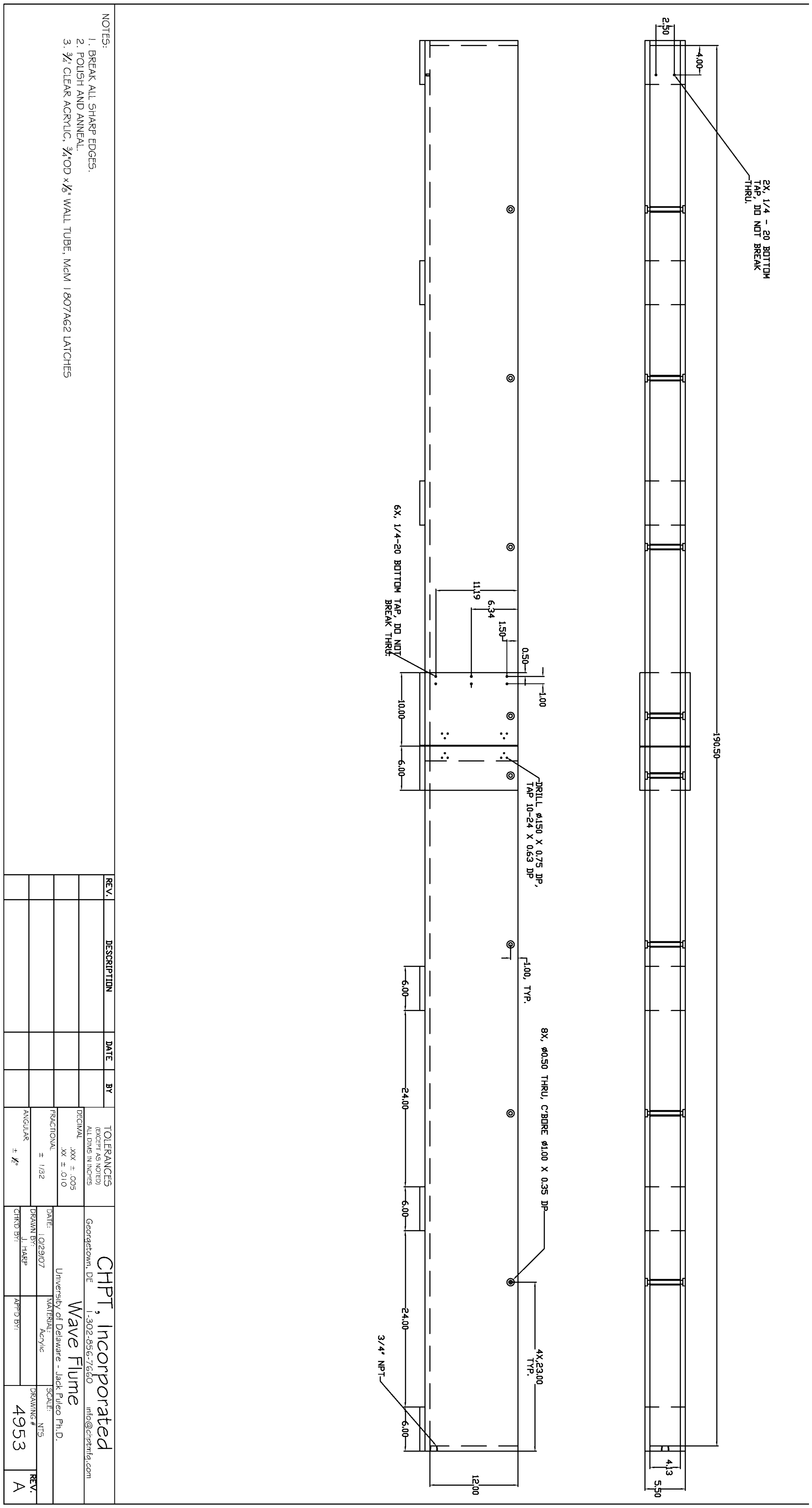


Figure A17. Snapshot of CAD drawing for the wave flume. A PDF version of the file is available upon request.

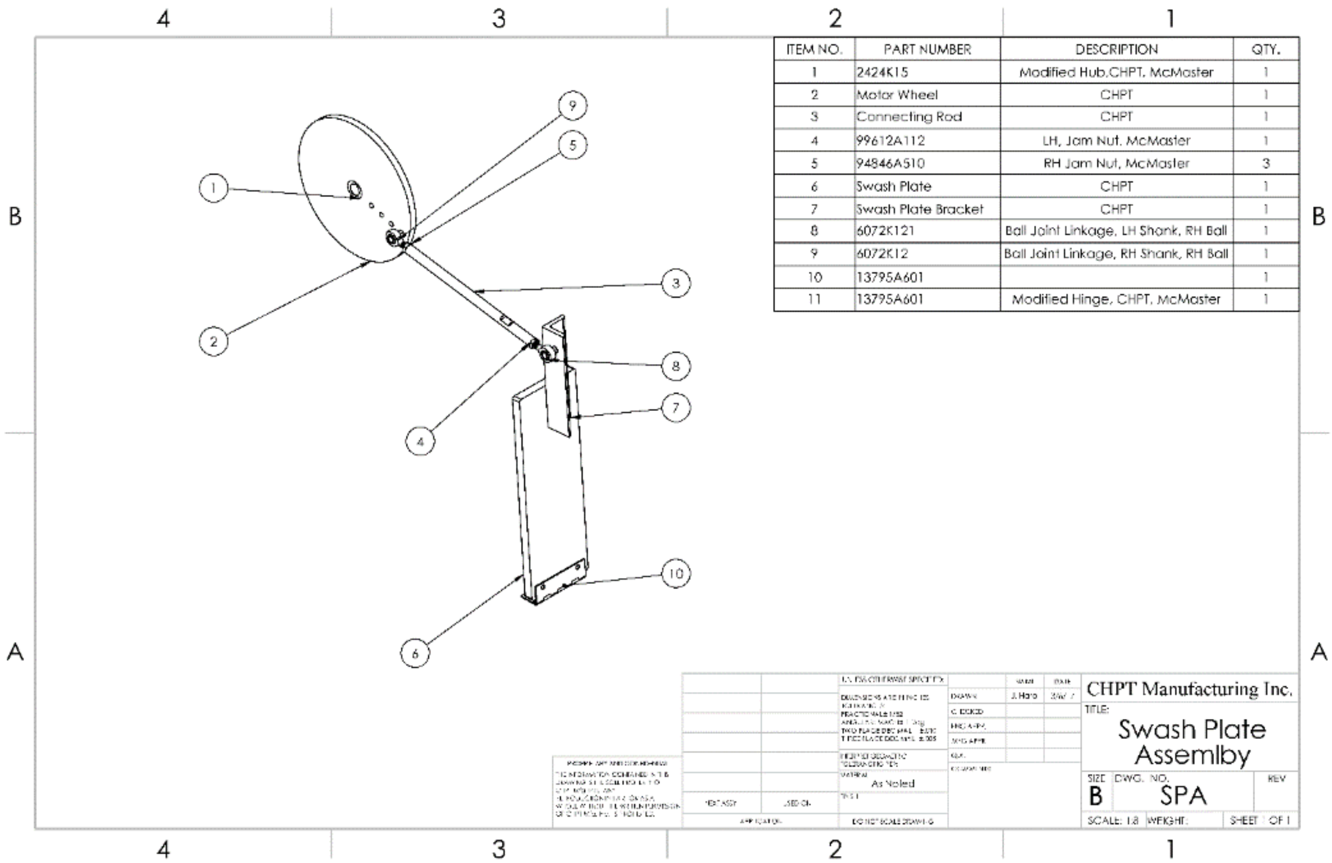


Figure A18. Snapshot of CAD drawing for the wave paddle and motor wheel. A PDF version of the file is available upon request.

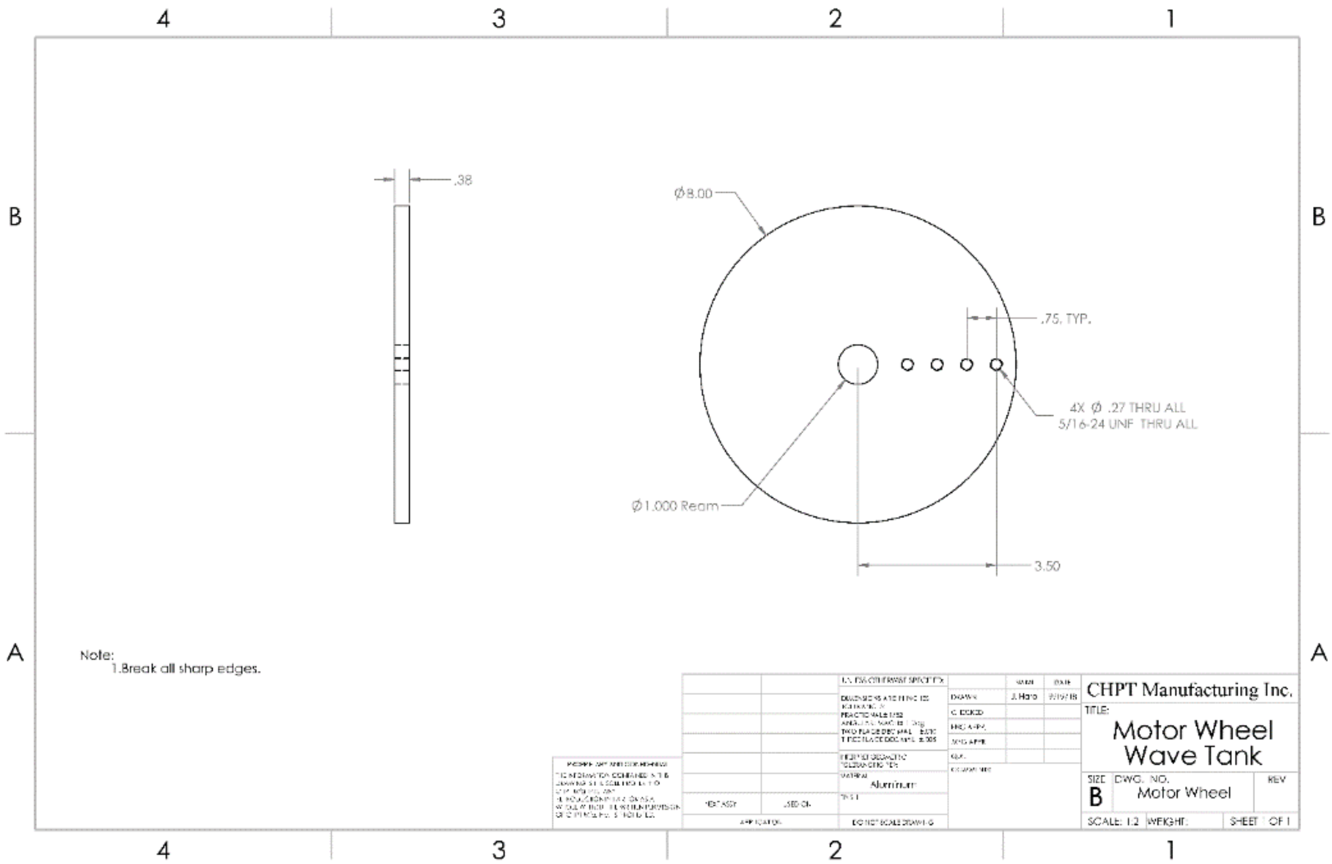


Figure A19. Snapshot of CAD drawing for the motor wheel. A PDF version of the file is available upon request.

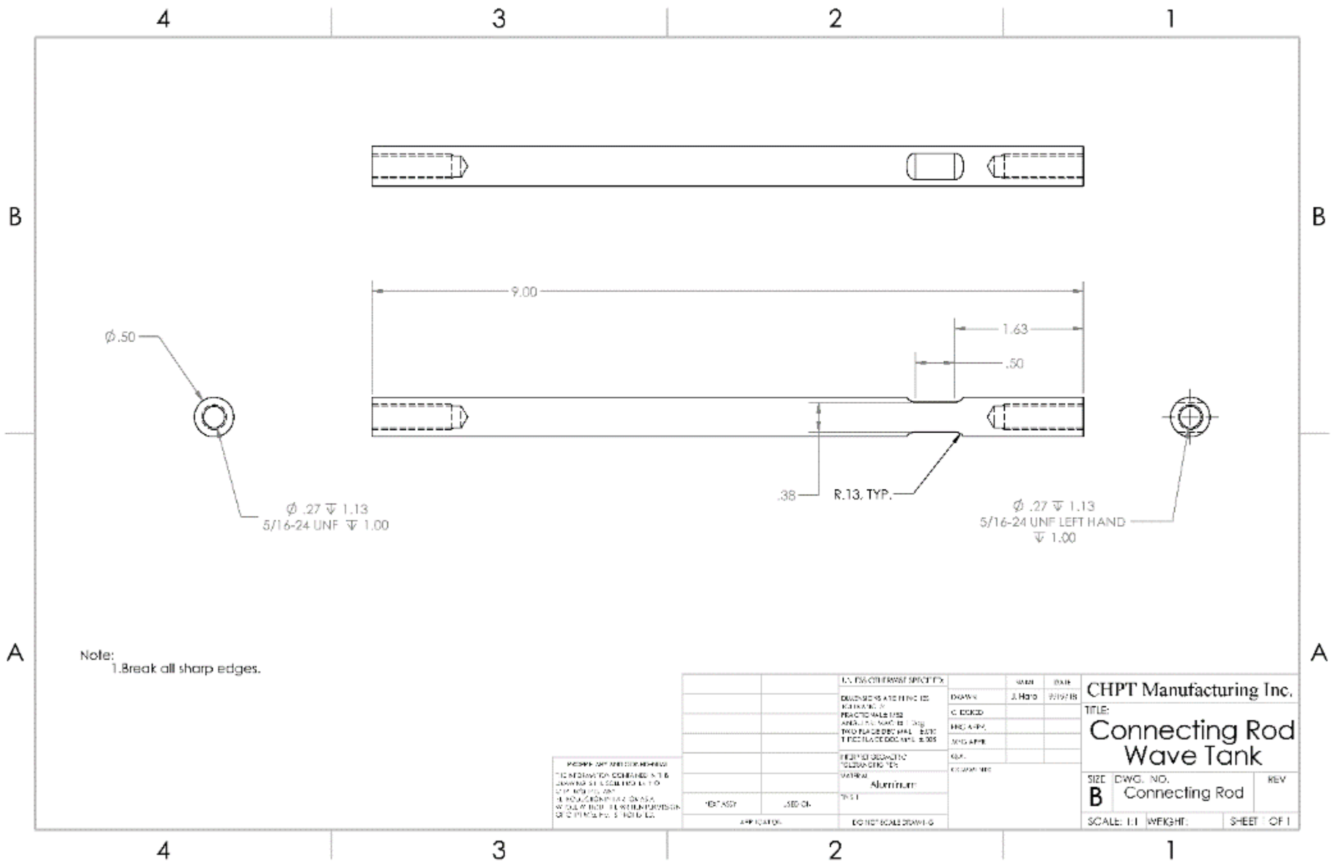


Figure A20. Snapshot of CAD drawing for the linkage arm. A PDF version of the file is available upon request.

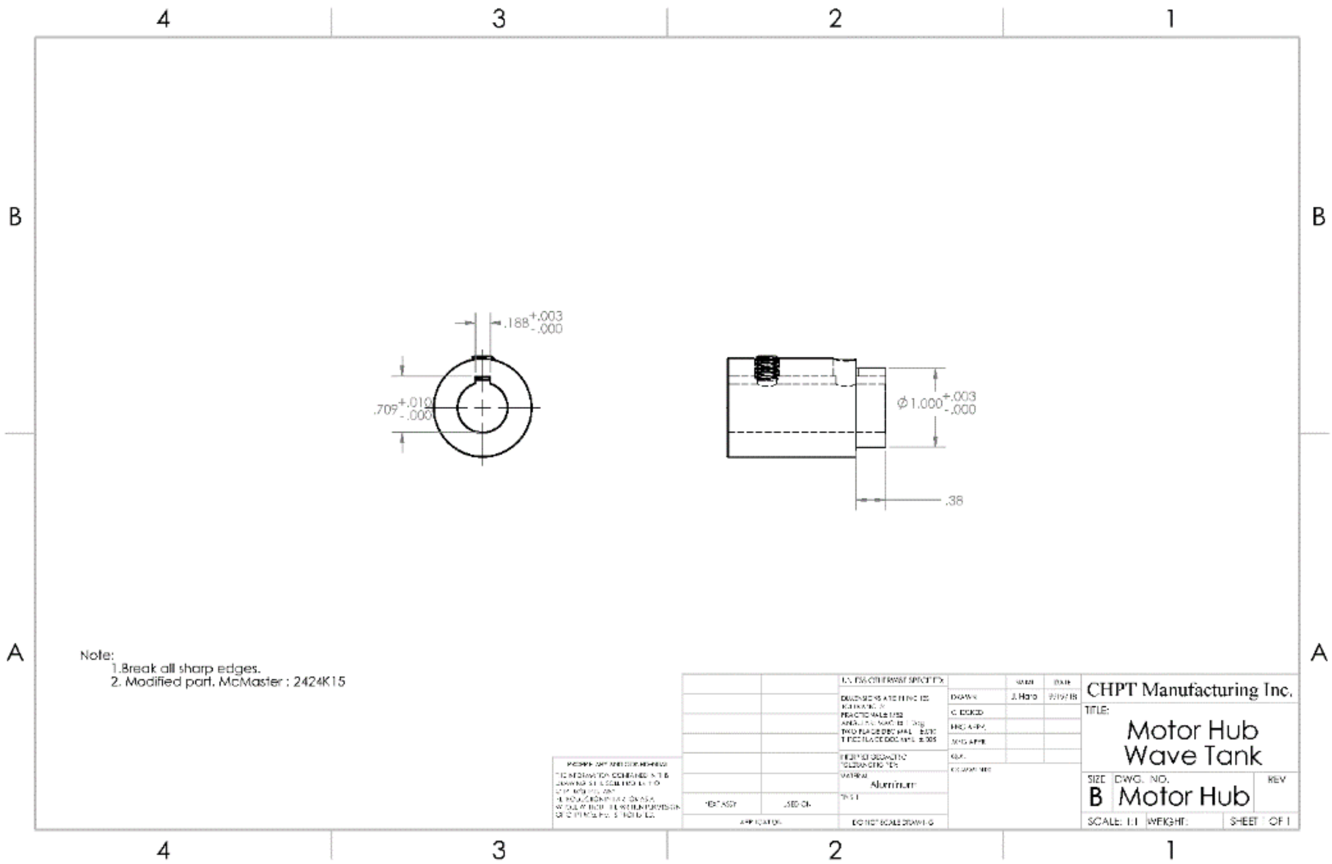


Figure A21. Snapshot of CAD drawing for the motor hub. A PDF version of the file is available upon request.

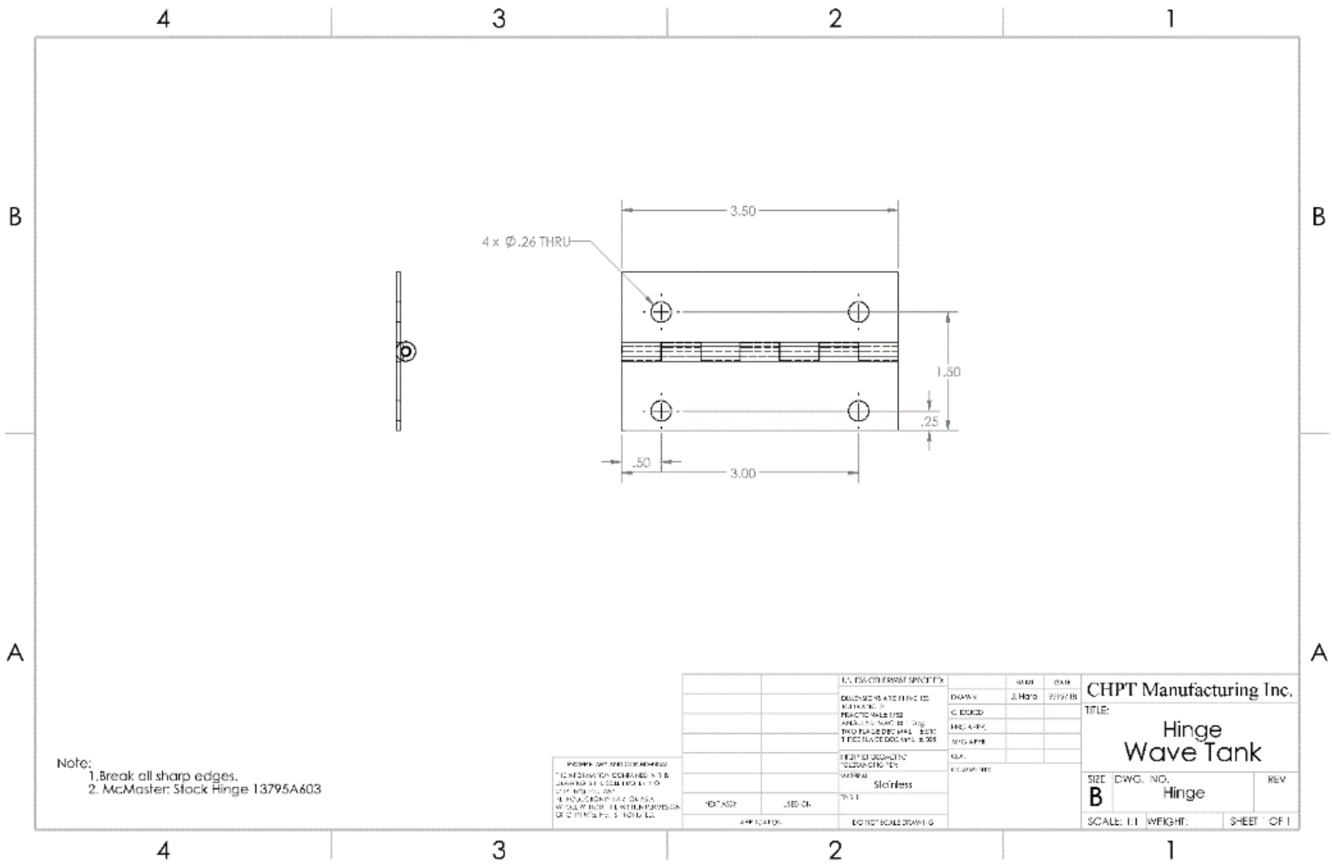


Figure A22. Snapshot of CAD drawing for the hinge connecting the wave paddle to the flume. A PDF version of the file is available upon request.

Sensors

There are two sensors included with the wave flume:

1) Banner Acoustic Distance Meter (current version with model number: S18UIAQ) with Euro-style quick disconnect (model number: MQDEC2-530). The current version requires a resistor (470 Ω) in the current loop to change to voltage for data logger recording. The sensor measures time of flight for sound waves over a range of 30 to 3000 mm. The sensor is clamped into a lab stand and placed above the flume roughly centered between the flume walls. The distance from the face of the sensor to the still water level should be between 0.08 and 0.1 m.

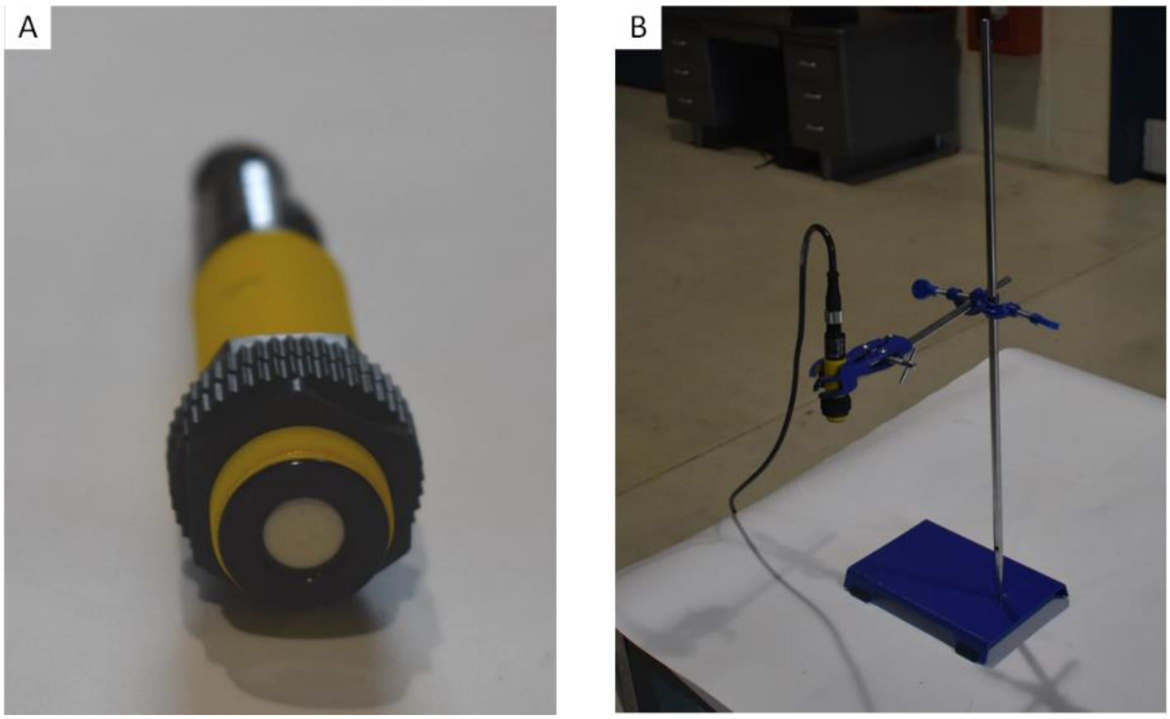


Figure A23. A) The Banner Acoustic Distance Meter. B) The acoustic sensor in the lab stand.

2) An Omni Instrument Impeller Current Meter (MiniWater6 Micro, model number: MIWA0611). The sensors measures fluid speed from 0.04 to 5 m/s with a 0 – 1 V output. The sensor is first taped or cable tied to the ¼" diameter stainless steel tube and then clamped into the lab stand. The sensor is meant to generally measure higher flow speeds than are recorded in the flume and cannot differentiate flow direction. Thus, the sensor is largely used to identify flow magnitudes at different cross-shore positions and elevations.

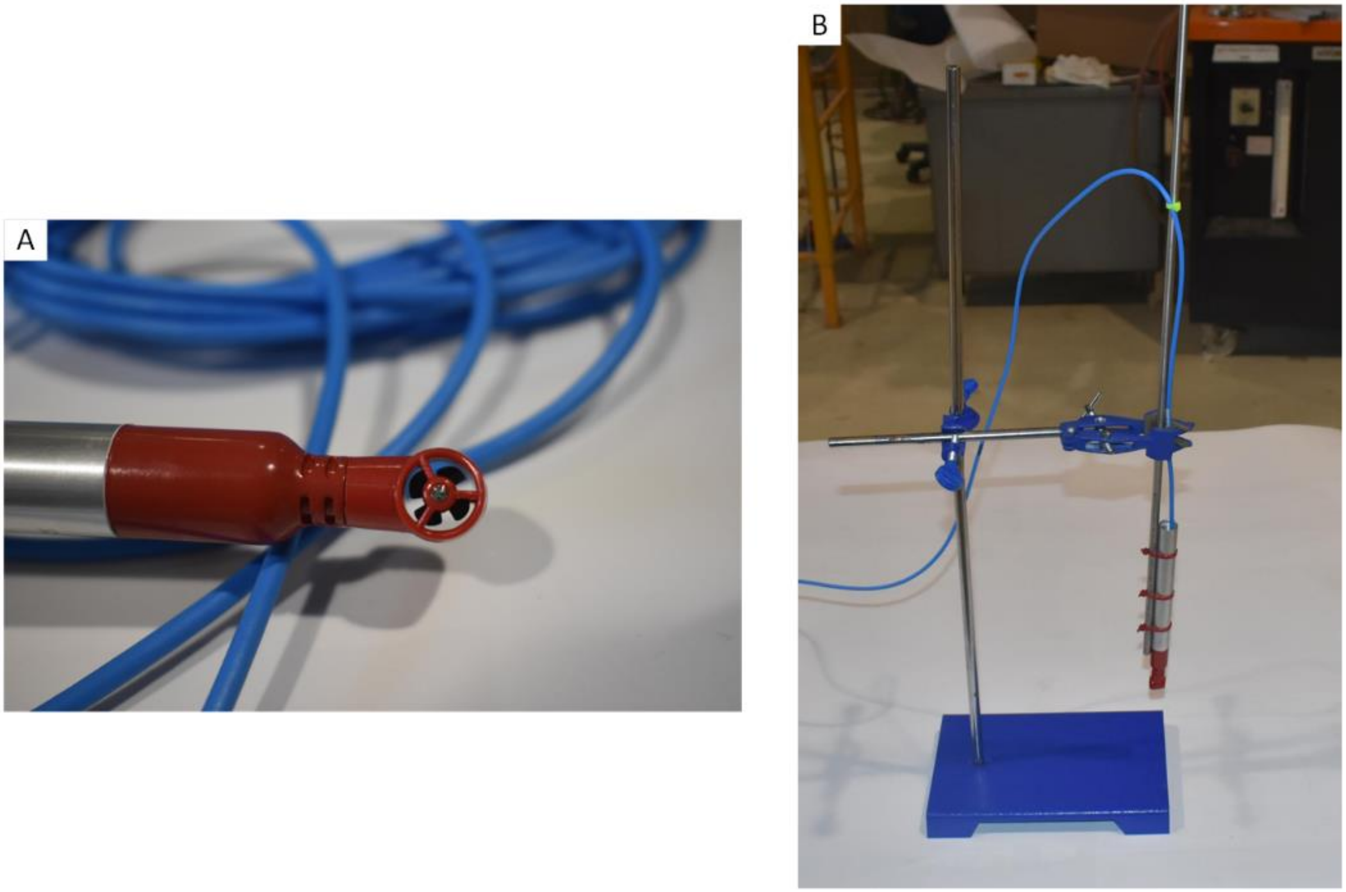


Figure A24. A) Close up view of the Omni Instruments Impeller Current Meter. B) The impeller attached via cable ties to a ¼" diameter stainless steel tube and affixed in the lab stand.

Vernier LabQuest Mini Logger

The LabQuest Mini logger is a low cost data logger used in many high school physics and chemistry classes. The generic voltage inputs on the data logger are used to collect data from the sensors used in the wave flume. Logger connections are described in the following section. Here, data logger usage is presented:

- Double click on the Making Waves icon on the desktop.

This is the icon that will run the LoggerPro software and automatically open the interface to work with the supplied sensors.

- A window will open up named ‘Sensor Confirmation’
- To connect sensors, click ‘Connect’ for both CH.1 and CH.2 in the section named “Connect Non-AutoID Sensors” (series of screen shots below):

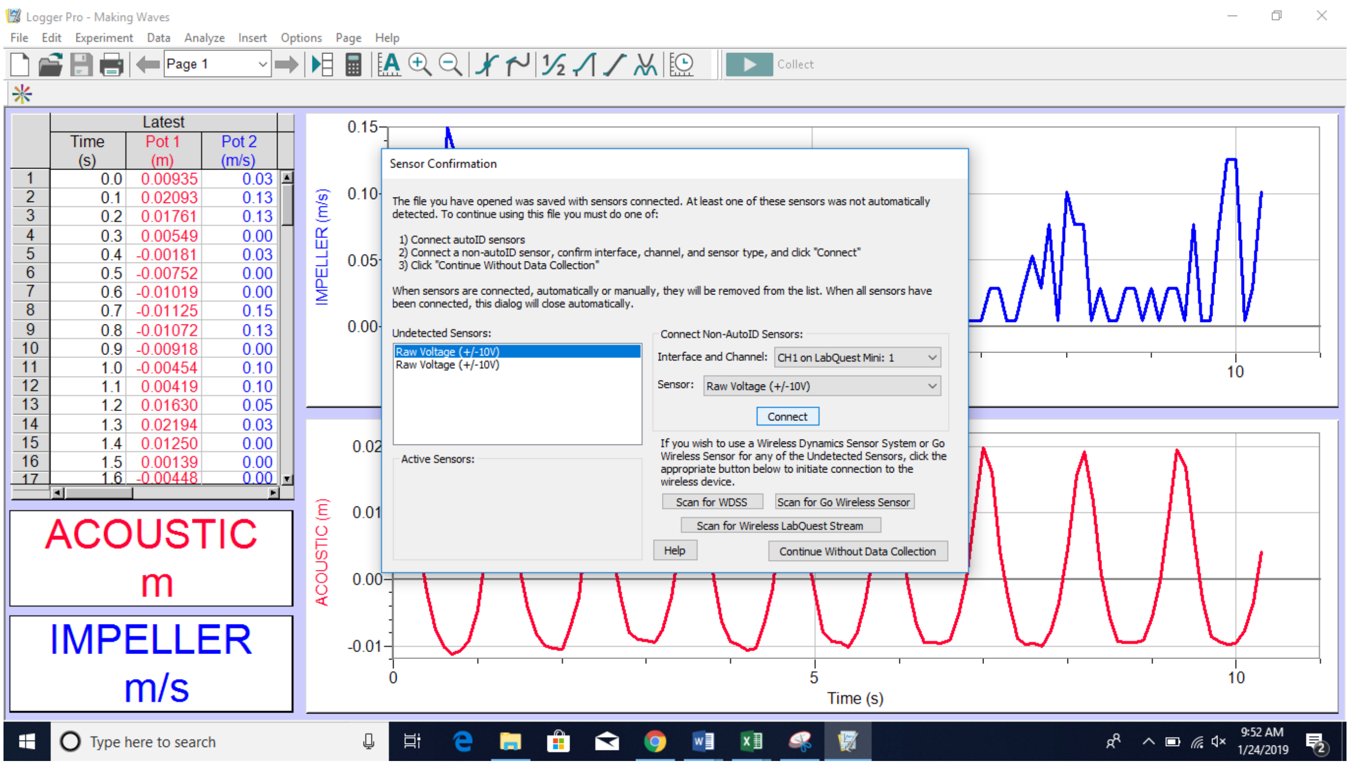


Figure A25. LoggerPro screenshot for connecting channel 1.

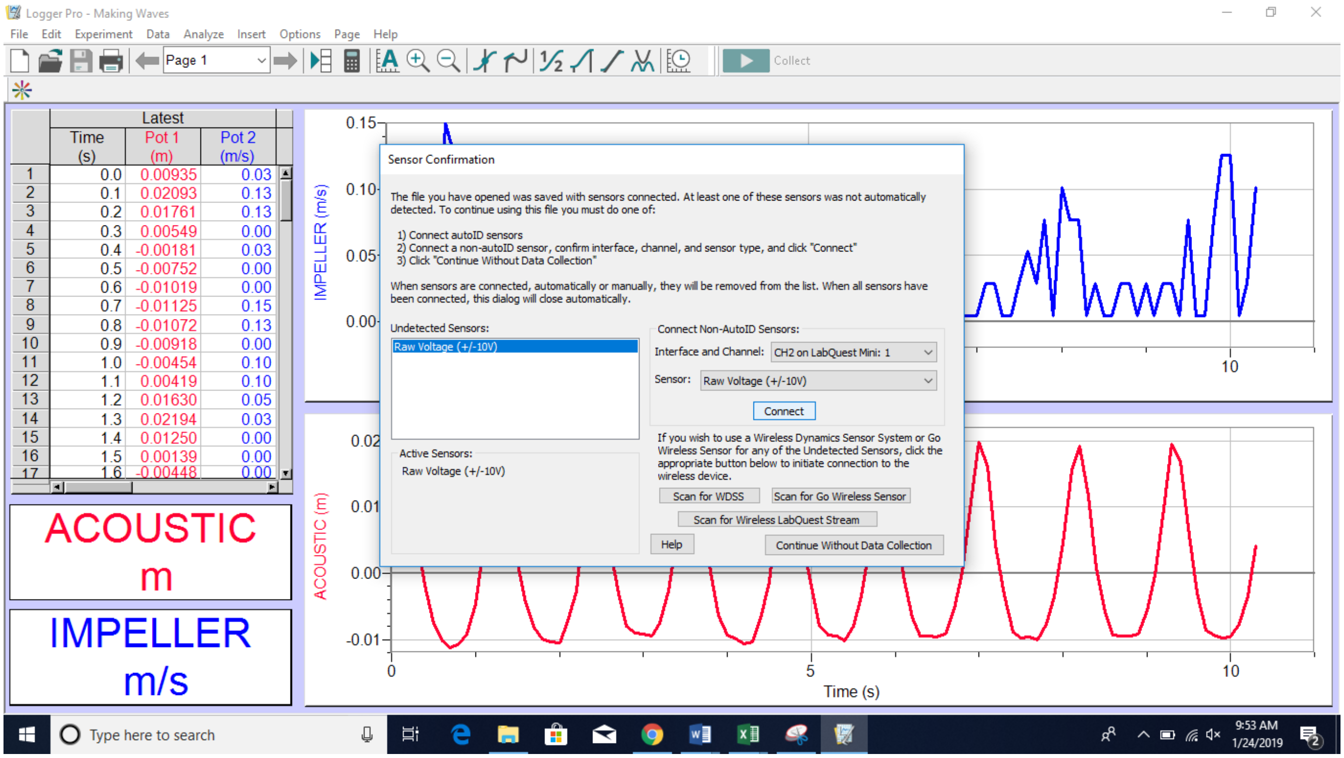


Figure A26. LoggerPro screenshot for connecting channel 2.

- The LoggerPro is now ready to collect data. In general, if the 'Collect' icon at the top of the screen darkens when the mouse hovers over it, the LoggerPro is ready to collect data.

- Before any data are collected, make sure to **zero the sensors** when the motor is completely turned off and the water is still. To do this, click 'Experiment' at the top of the page. Then, click 'Zero..'. (Figure A27):

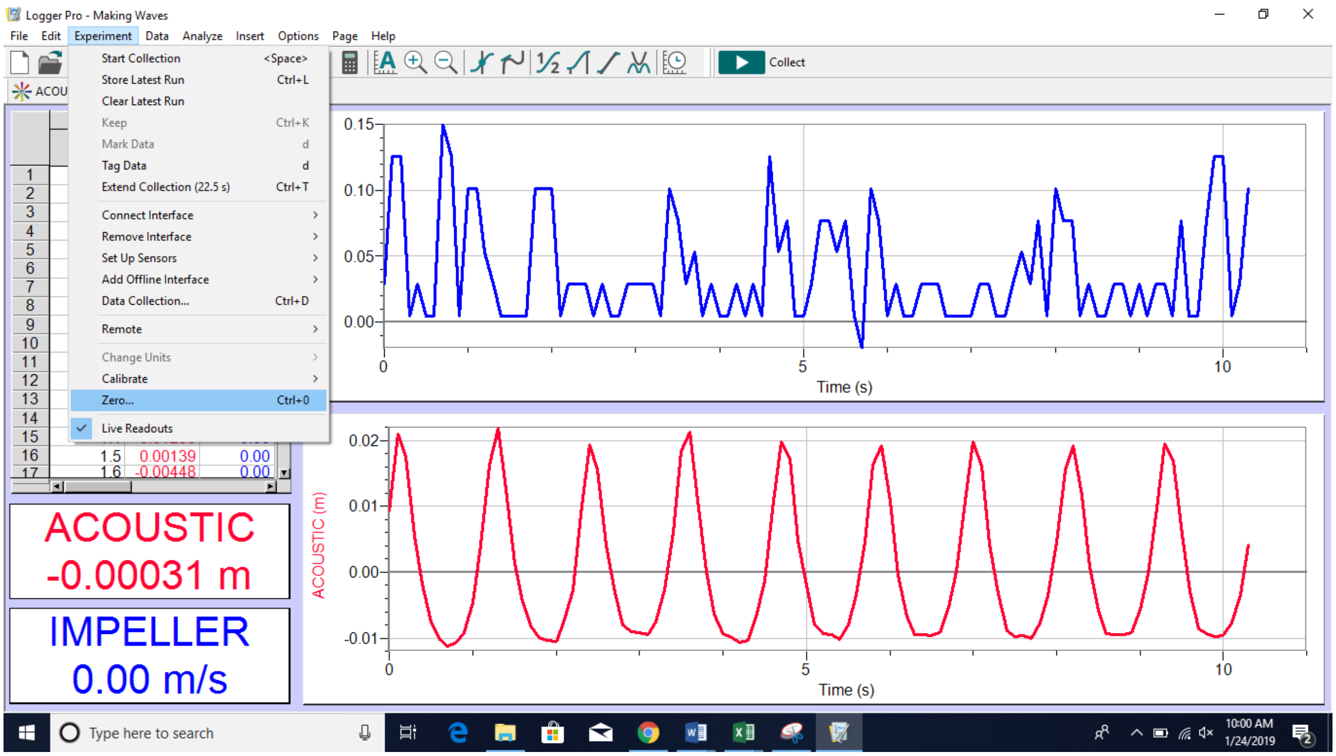


Figure A27. LoggerPro screenshot for zeroing sensors.

- A ‘Zero Sensors Calibration’ window will open. Make sure both channels have checkmarks in their respective boxes and then click “OK” (Figure A28):

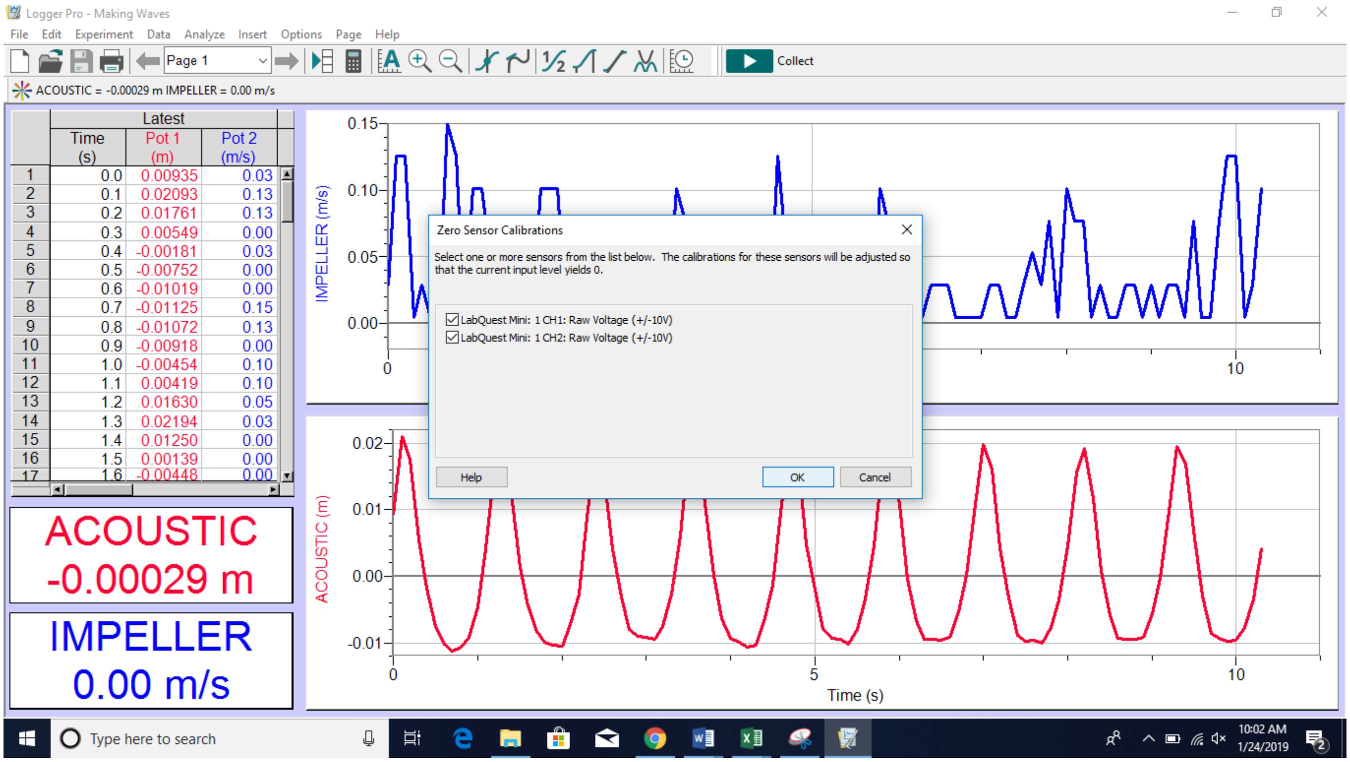
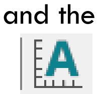
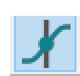


Figure A28. LoggerPro screenshot for zeroing sensors.

- To obtain the best results, turn motor on for a couple of seconds to generate waves before clicking “Collect”.
- Data will be graphed in real time.
- If data are being collected and the screen only shows a horizontal line near zero, click this icon at the top of the screen: 
- This icon is called ‘AutoScale Graph’ and it will zoom in so that data can be more easily seen. For these modules, waves will only be a couple centimeters high, and speeds will only reach a maximum of roughly 0.20 - 0.25 m/s.

- To quickly find the max or min of a data set, click the ‘Statistics’ icon on the top of the screen: 

- Once this icon is selected, small windows will open up on each graph displaying relevant statistical information.

- To quickly find data points on the graphs, click the ‘Examine’ icon: 

- Once this icon is selected, one can hover over the graph at each point and see the values of that data point.

- For many of these modules, data will need to be imported into the Making Waves spreadsheet for further analysis. **It is important that students copy and paste data into the Making Waves spreadsheet or export data as a CSV file after every successful collection.**

- Once data are entered in the Making Waves spreadsheet or saved as a CSV file, students can click 'Collect' again to record another data set. A new graph will be displayed, and a new table will start recording data. **Again, make sure to zero the sensors before every collection with the motor turned off and the water completely still.**

- For example, in Module 3, Deep vs. Shallow Water, students collect data three times. After each collection, students should copy and paste data into the Making Waves Spreadsheet or export data as a CSV file. Copy and pasting the data is easier, but CSV files can be used if a student is absent and wants to analyze data at a later date.

- To copy and paste data, click on the column heading of the data that is desired. Acoustic data are in red, and the impeller data are in blue. Units are displayed on the column headings to further identify the data. All the data in that column will be highlighted. Right click to copy, and then go to the Making Waves spreadsheet to paste (Figure A29).

-

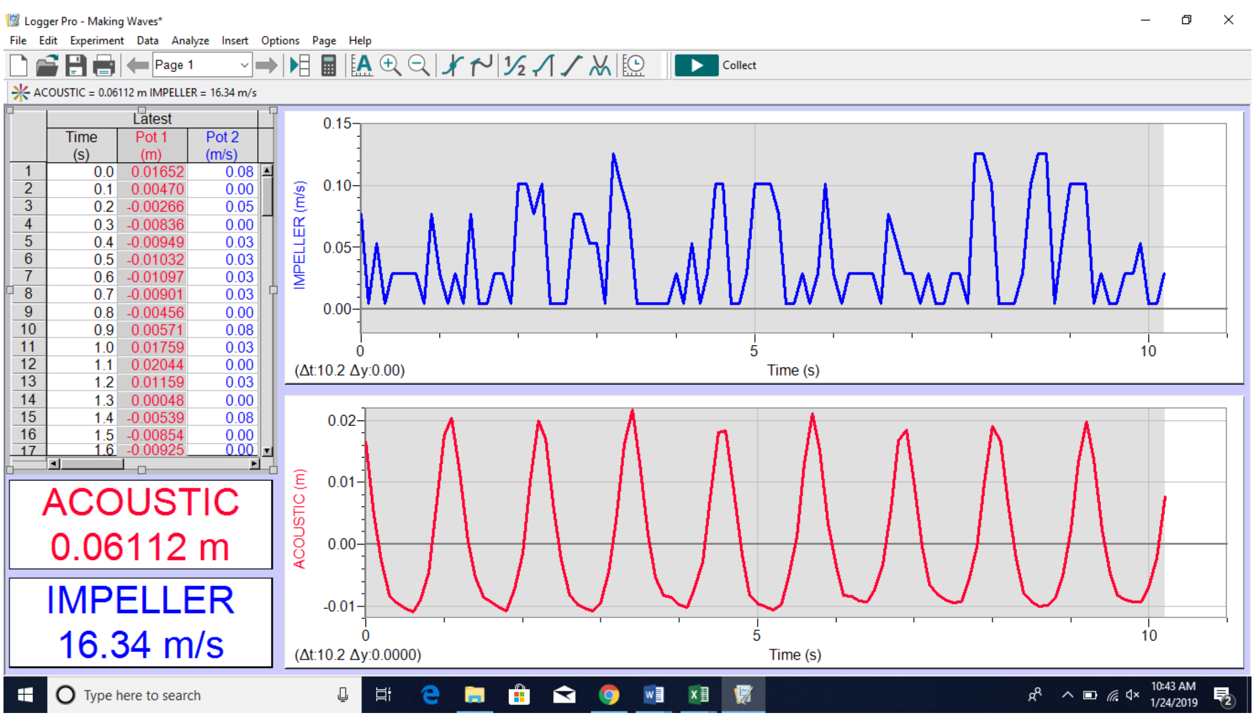


Figure A29. LoggerPro screenshot showing highlighting of sensor data for copying into an Excel spreadsheet.

- To save data as a CSV file:
  - Click "File" at the top of the page
  - Click "Export As.."
  - Select "CSV.."
  - Name the file and then save to an easy location such as the Desktop.

- ○ Students can then open up the CSV file and then copy and paste data into the Making Waves spreadsheet, or perform other calculations on the data in Excel.
- Students can save the Making Waves LoggerPro file before exiting the program, but this is not necessary as the same beginning steps outlined previously will need to be followed when opening the file again.
- If, for whatever reason, the calibration of the sensors seems off, teachers can manually input the calibration equations again by following these steps:
  - Click "Experiment" at top of screen.
  - Select "Set Up Sensors" then LabQuest Mini 1.
  - A new window will open (Figure A30).

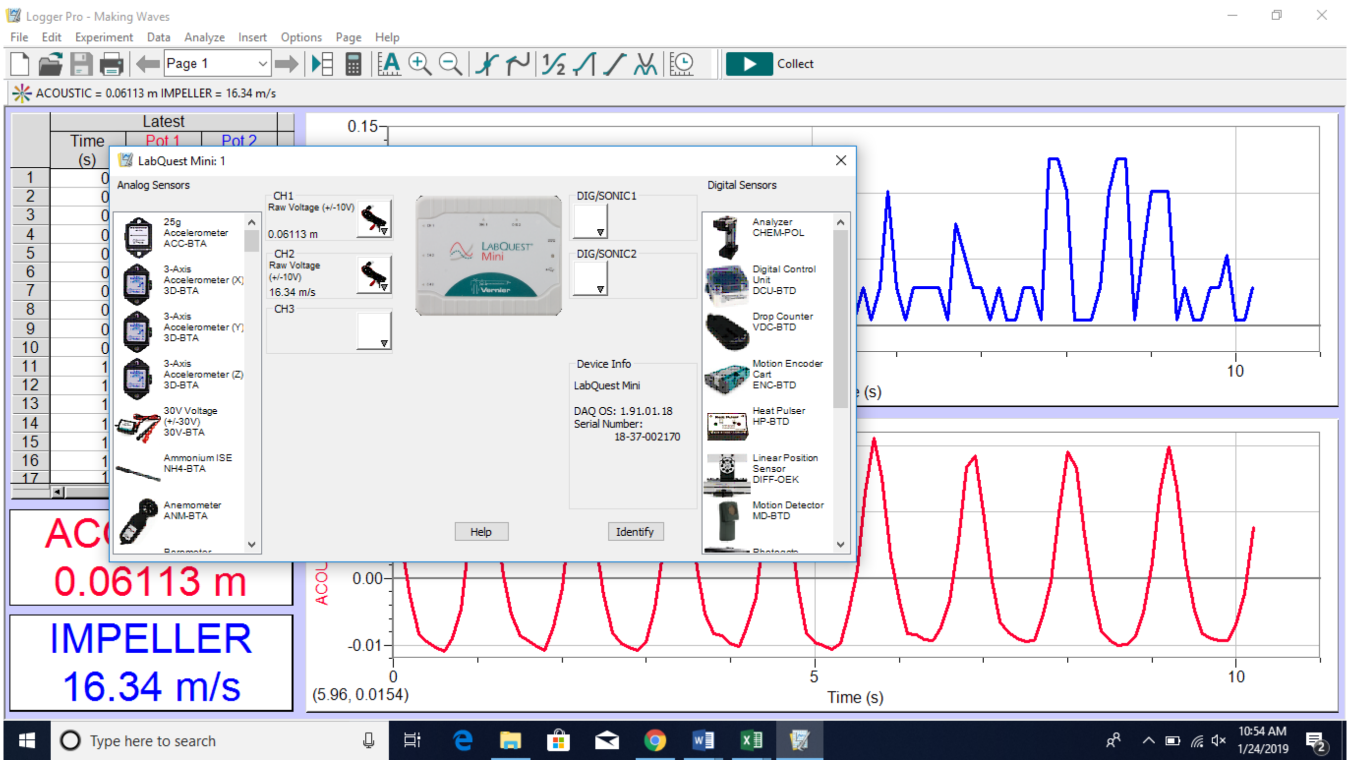


Figure A30. LoggerPro screenshot showing options for setting up sensors (ONLY IF NEEDED).

- Next, click on the icon of either of the sensors and then click calibrate. Click the "Equation Tab" (Figure A31).

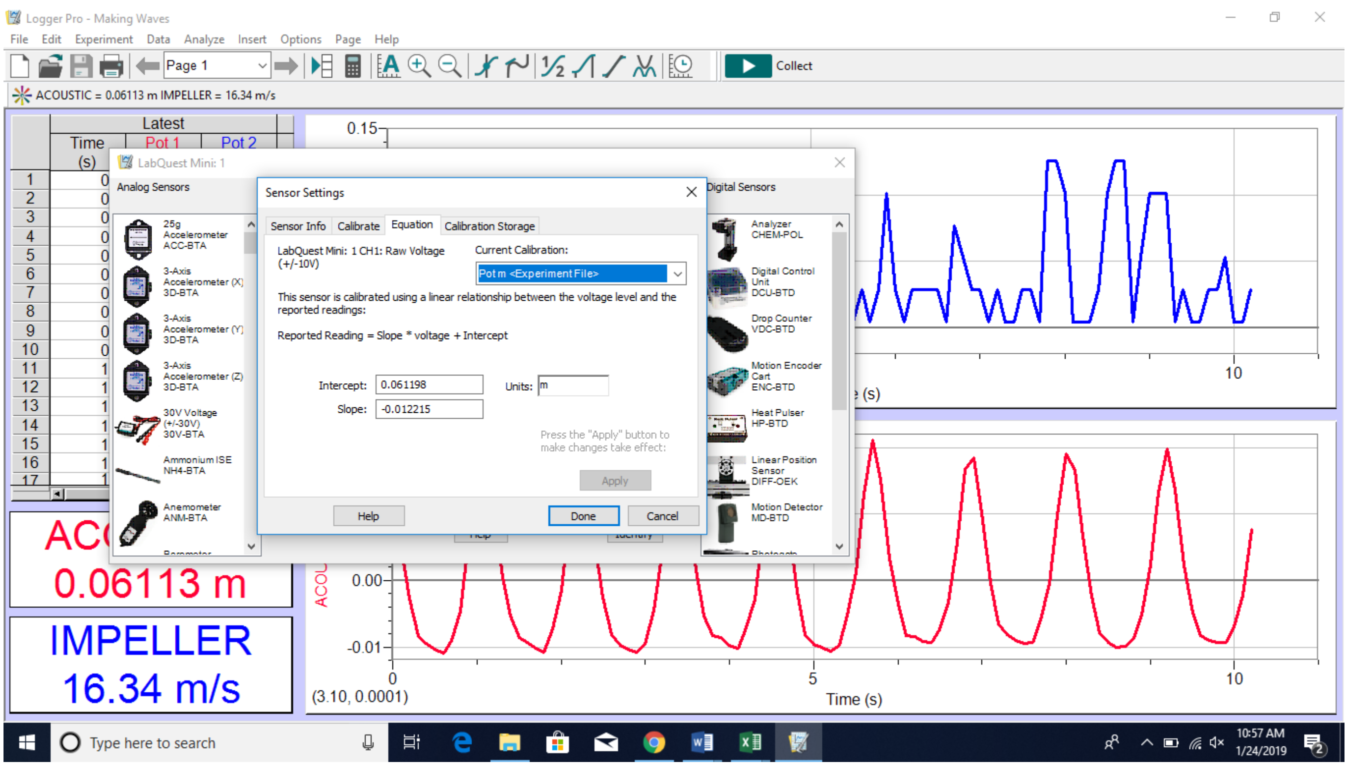


Figure A31. LoggerPro screenshot showing options for setting up sensors – equations tab (ONLY IF NEEDED).

- The sensors are displayed as "Raw Voltage". To collect data, raw voltage is applied to a calibration equation which then transforms the voltage into a measurement that can be useful, such as free surface elevation or water speed.
- Calibration equations can then be re-entered for each sensor. Use the following table to determine which equation corresponds to your flume based on the flume number. Note, the Impeller has the same calibration for all flumes.

Flume number	**Banner Acoustic Sensor (yields units of m)**	**Impeller Current Meter (yields units of m/s)**
FLUME01	y = -0.012215x - 0.002871	y = 4.96x + 0.04
FLUME02	y= -0.025865x + 0.02066	y = 4.96x + 0.04
FLUME03	TBD	y = 4.96x + 0.04
FLUME04	TBD	y = 4.96x + 0.04
FLUME05	TBD	y = 4.96x + 0.04
FLUME06	TBD	y = 4.96x + 0.04
FLUME07	TBD	y = 4.96x + 0.04
FLUME08	TBD	y = 4.96x + 0.04
FLUME09	TBD	y = 4.96x + 0.04
FLUME10	TBD	y = 4.96x + 0.04
FLUME11	TBD	y = 4.96x + 0.04
FLUME12	TBD	y = 4.96x + 0.04

- Once the correct equations are entered, click "Apply".
- To save calibrations, click "Calibration Storage" tab and then select the calibration equations to be saved in the experiment file (Figure A32).

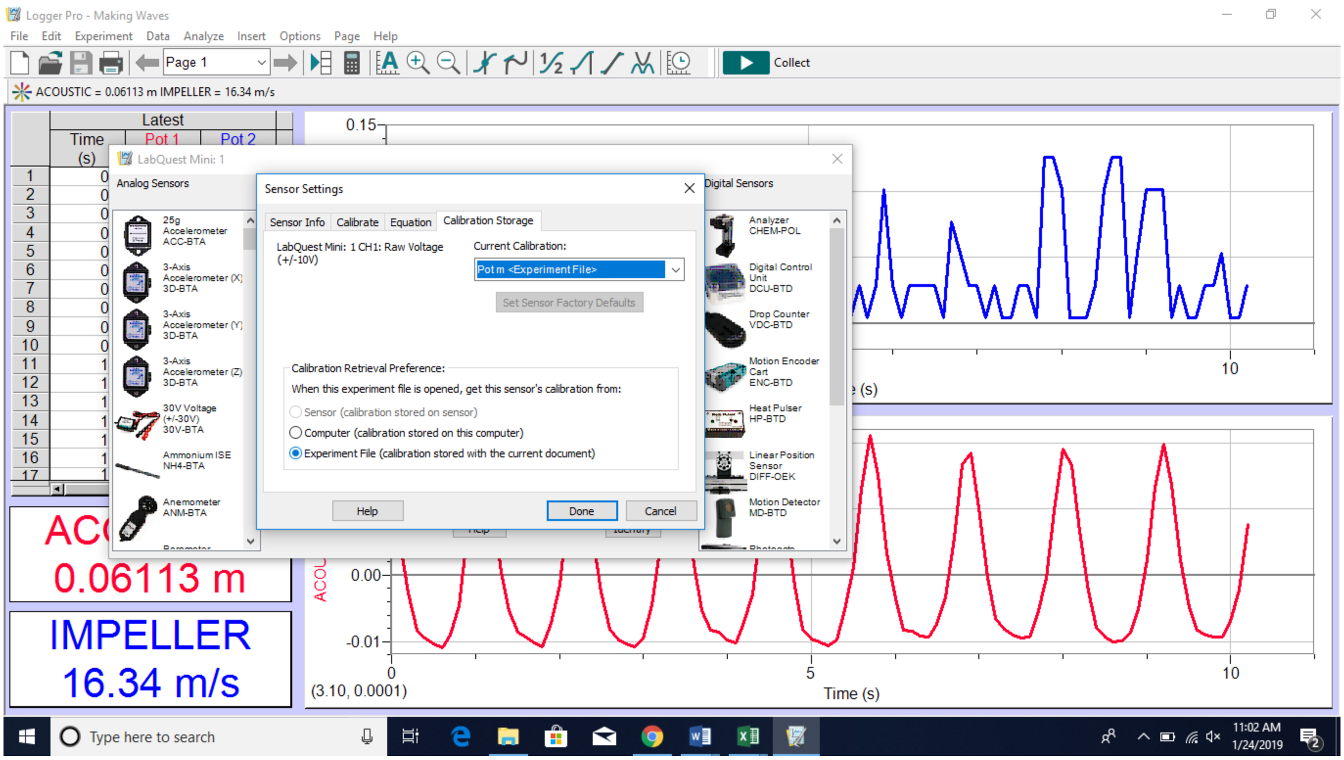


Figure A32. LoggerPro screenshot showing options for setting up sensors – calibration storage (ONLY IF NEEDED).

- Re-Entering calibration equations should not be necessary unless the Making Waves.cmbl file became corrupted.

Electronics Box and Computer

An electronics box has been fabricated to power the data logger and sensors and send signals from the sensors to the data logger. A full description of the logger box is provided using Figures (A33 and A34) as guides.

Power is supplied by an inexpensive 12 volt DC power supply. The power cable is plugged into main building power and powers the electronics box and the sensors. The USB cable coming out of the LabQuest LoggerPro Mini is plugged into the USB port on the supplied laptop. Both cables pass through 1 ¼" thread size cable glands (mcmaster.com: 69915K73). The cables have been thickened using water resistant heat shrink tubing to allow the cable gland to compress around the cable and provide strain relief. Power output from the power supply (Power +, black; Power -, red) is connected to a terminal strip. The first three terminal sections are connected through metal jumpers. Similarly, the last two terminal sections are also connected with jumpers.

The acoustic and impeller sensors are terminated in a Subconn underwater connector (MCIL3M; available from MacArtney.com) with locking ring (MCDLS-F). These connectors are more expensive and robust than needed but provide excellent strain relief at the connection point. The connection point is a Subconn bulkhead (MCBH3F; available from MacArtney.com) with flying leads on the inside of the electronics box. Unfortunately, the conductors inside the acoustic and impeller cables differ in color from the conductors inside the subconn connector cable. The diagram (Figure A34) shows which colors are mated. In addition, standard color convention (black for negative and red or white for positive) are not maintained due to color variations from the logger connection end (refer to Figure A34). Voltage input cables for the LabQuest LoggerPro Mini (BB-BTA) allow for data collection by the logger. The cables come with a small breadboard attached. The breadboard is removed and the leads from the bulkhead are soldered directly to the leads from the logger input cables.

<u>Acoustic sensor</u>: The green conductor from the bulkhead goes to positive power; the black conductor goes to negative power; and the white connects to the yellow conductor from the logger input cable for channel 1 (Acoustic). The acoustic sensor is in a current loop configuration and requires a 470 Ω resistor across the yellow and black conductors from the logger input cable. The resistor converts the amperage to voltage.

<u>Impeller sensor</u>: The green conductor from the bulkhead goes to positive power; the black conductor goes to negative power; and the white conductor connectors to the yellow conductor from the logger input cable for channel 2 (Impeller). The black conductor from the logger input cable goes to negative power.

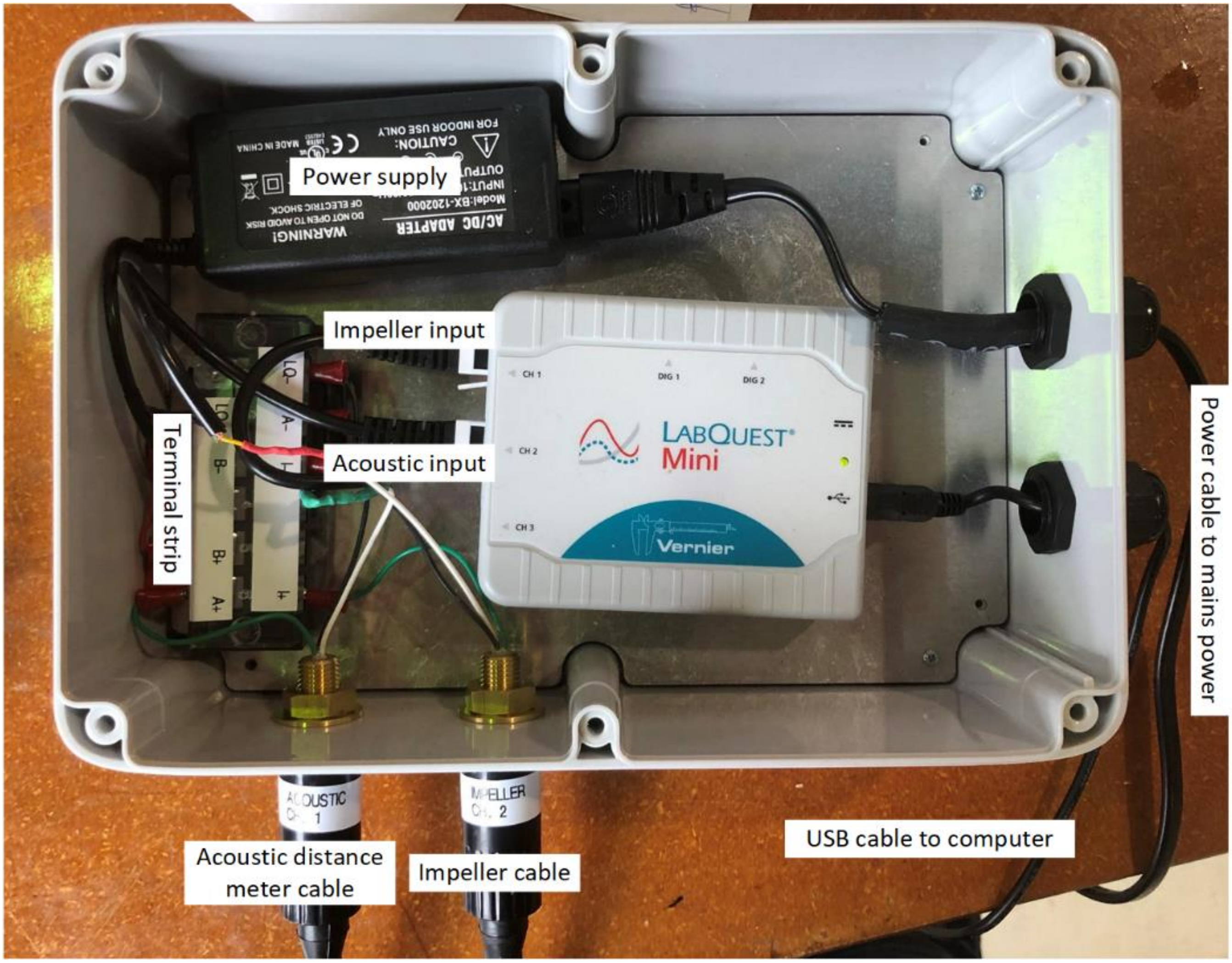


Figure A33. A picture of the electronics box showing the main components.

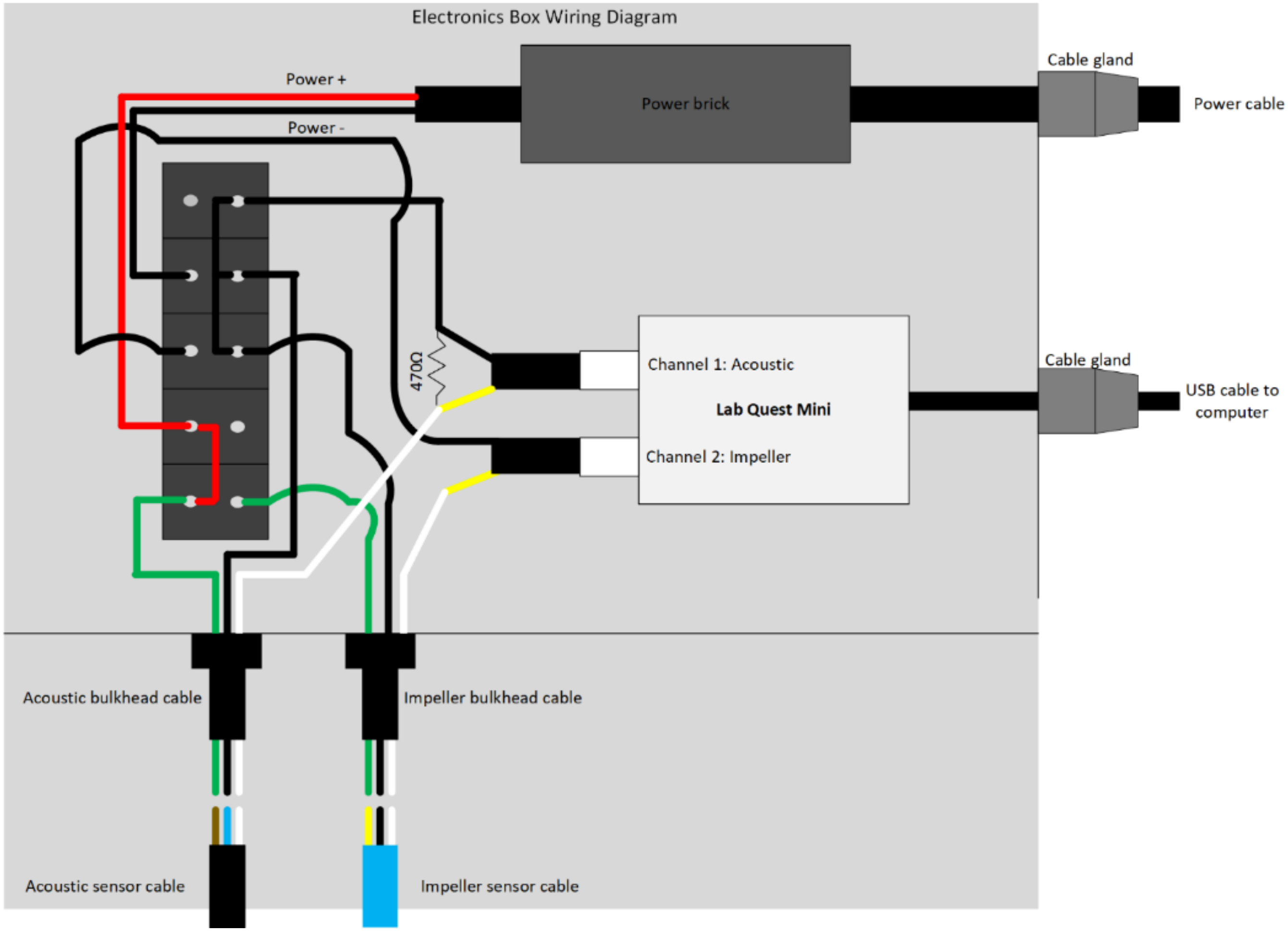


Figure A34. A wiring diagram for the electronics box.

Motor Assembly and Motor Assembly Stand

The motor assembly stand is made from 3/4" plywood cut on table and chop saws. The table saw is also needed for making dado cuts into several of the stand pieces. Figure A35 shows the pieces that are required with corresponding measurements and locations of the dado cuts. Boards are fastened together using 1 1/2" exterior wood screws. Holes at connections were pre-drilled (5/64" bit) prior to screwing together to reduce chance of wood splitting. Pieces are labeled A-I and the corresponding pieces are labeled in images of the finished motor assembly stand (Figure A36). **Note: Attach the motor to piece E (Shelf 1) (see below) BEFORE attaching all the motor assembly stand pieces together. Similarly, wire and attach the GFCI outlet BEFORE attaching all the motor assembly stand pieces together.**

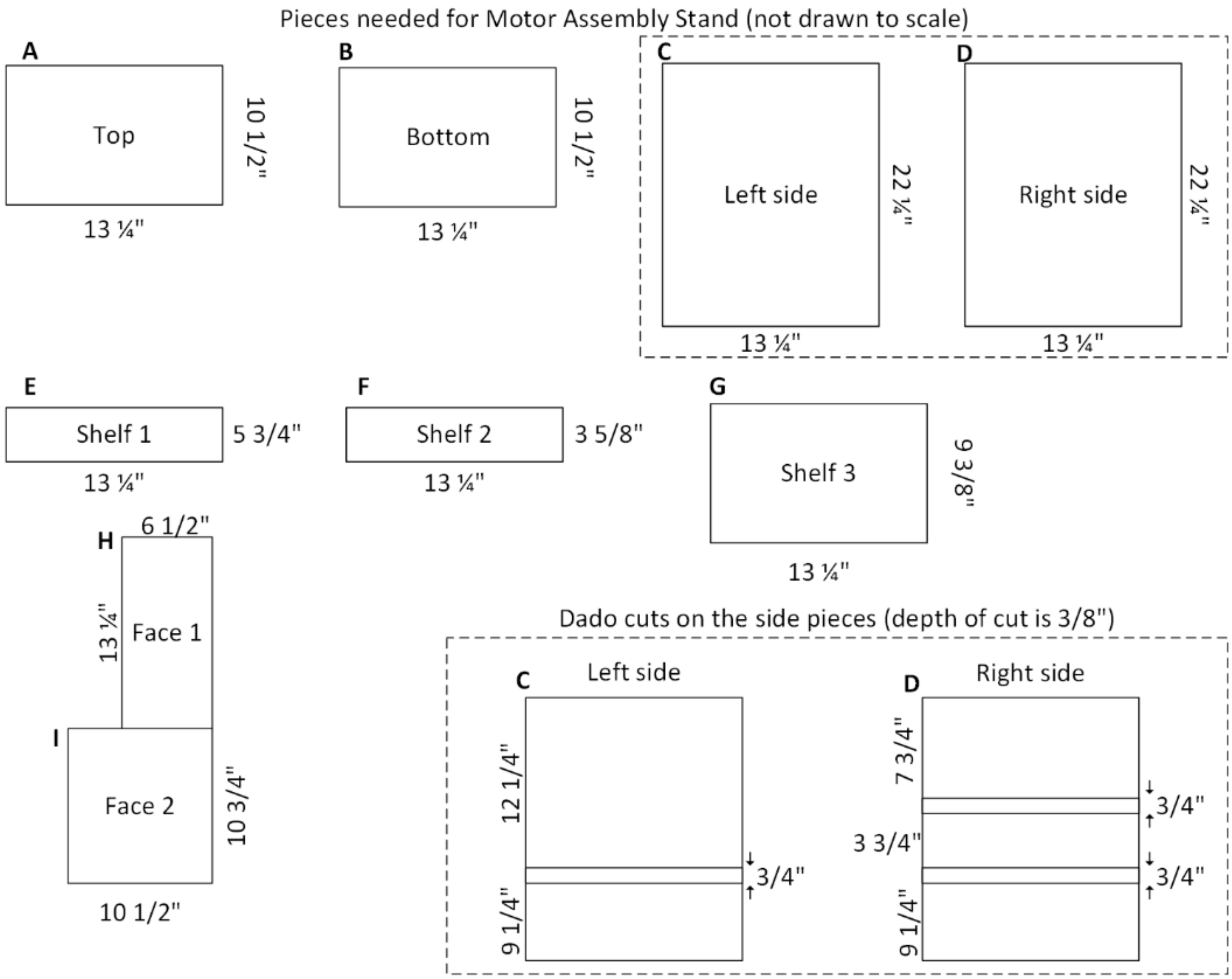


Figure A35. Diagram showing pieces, dimensions, and dado cuts for motor stand assembly. Letters correspond to pieces of completed stand shown in Figure A36.

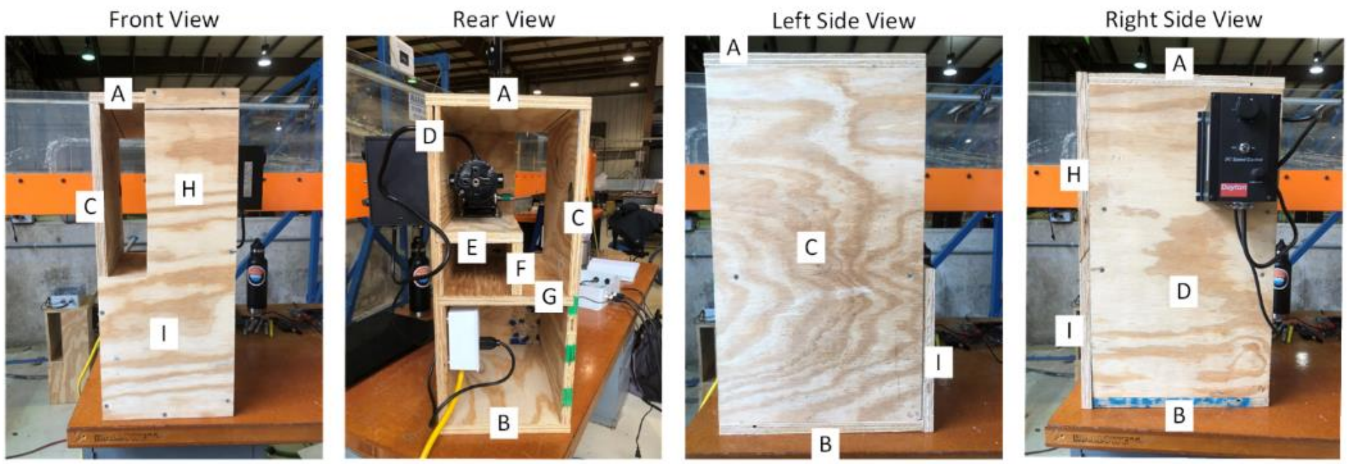
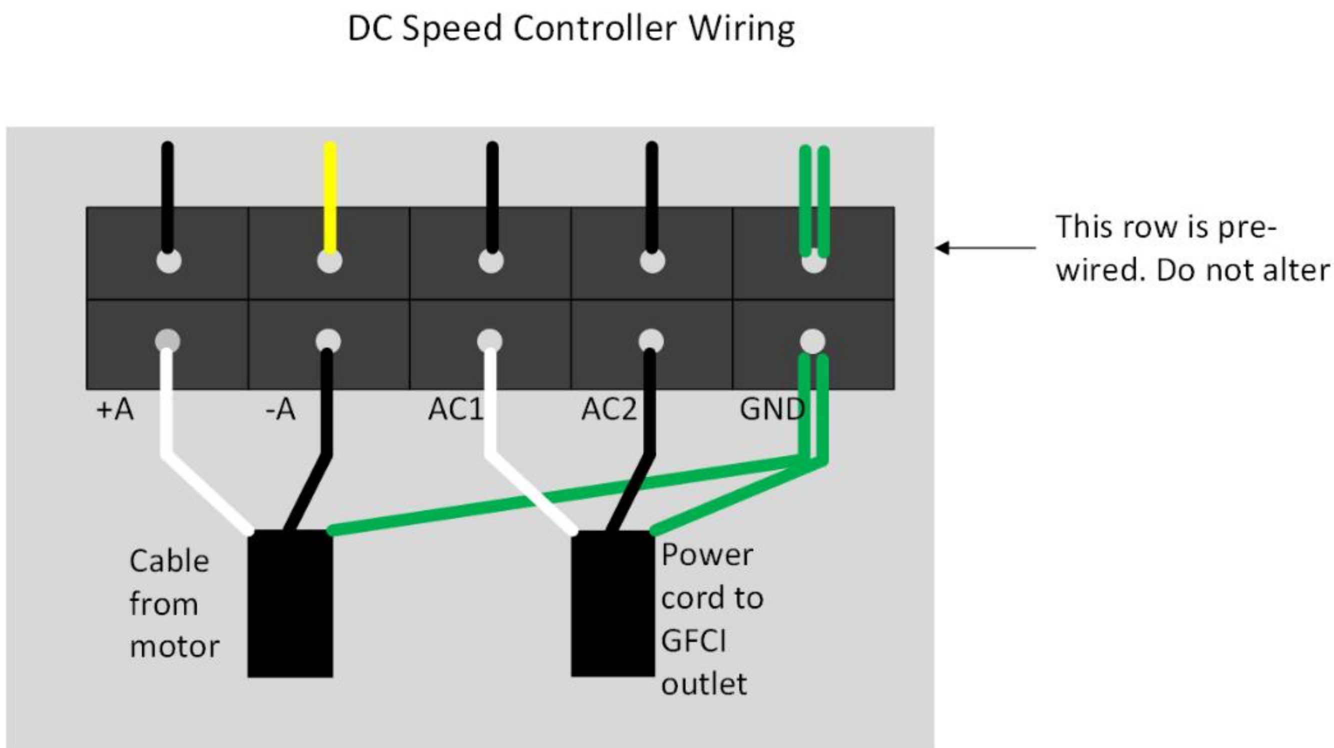


Figure A36. Completed motor stand assembly from different views. Letters correspond to pieces shown in Figure A35.

The motor is a 1/8 Hp DC gear motor (Dayton model number: 3XA78). It is much more powerful than is needed for the flume paddle, but has been used successfully in the past and so was kept in the present flume design. The motor attaches to the horizontal mounting board (item E in Figures A35, A36) using 1 ½" inch long ¼" x 20 bolts and nuts. An 8" diameter aluminum disk was fabricated with a collar and set screw on the rear side. The collar is affixed over the motor shaft and tightened with the set screw. A linkage arm (0.5" diameter x 9" long) is connected to the threaded hole on the disk and the other end of the arm attached to the threaded hole in the wave paddle using the supplied hardware (5/16" x 24). The ball joint ends of the linkage arm and hardware were purchased from mcmaster.com (RH Threaded Shank, RH Threaded Ball – 6072K12, LH Threaded Shank, RH Threaded Ball – 6072K121, LH Threaded Jam Nut – 99612A112, RH Threaded Jam Nut – 94846A510 [3 required]).

The motor cable is connected to a DC speed controller (Dayton model number: 5X412) that controls the motor rotation speed. The controller is attached on the upper right portion (facing motor) of the stand using 1.5" wood screws. Exact placement is not critical. The connections for the motor cable inside the controller are shown in Figure A37. An inexpensive 12 volt DC power supply was purchased and the cable cut to connect the controller to power (any three pronged power cord will suffice). Connections for this power cord inside the controller are also shown in Figure A37. The female end of a 25-foot extension cord is cut and the leads wired into a GFCI outlet (Figure A38). The outlet box is screwed to the lower left on the inside of the stand (orientation if facing motor back end) using 1.5" wood screws (see the white outlet box in the rear view of Figure A36). The GFCI outlet is attached to the outlet box using the screws provided with the outlet. The male end of the extension cord is connected to main building power. The male end of the controller power cord is connected to the GFCI outlet. Power connections were completed in this fashion for safety considering the motor and power connections are near water.



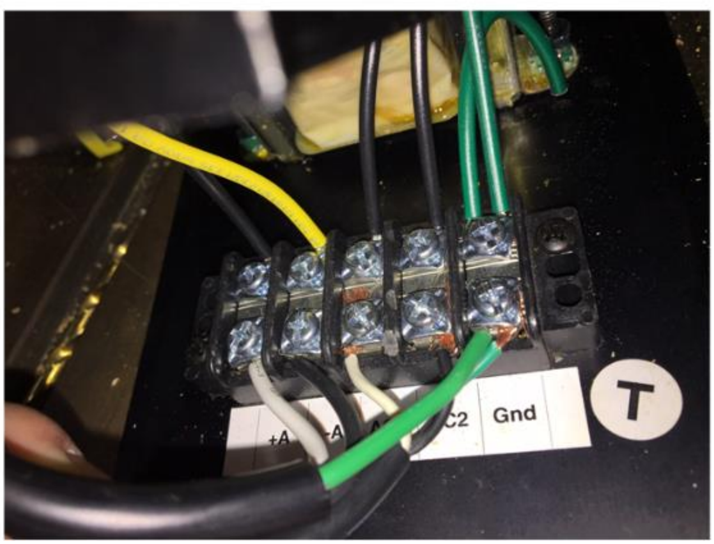


Figure A37. Wiring diagram and picture showing the wiring inside the DC speed controller.

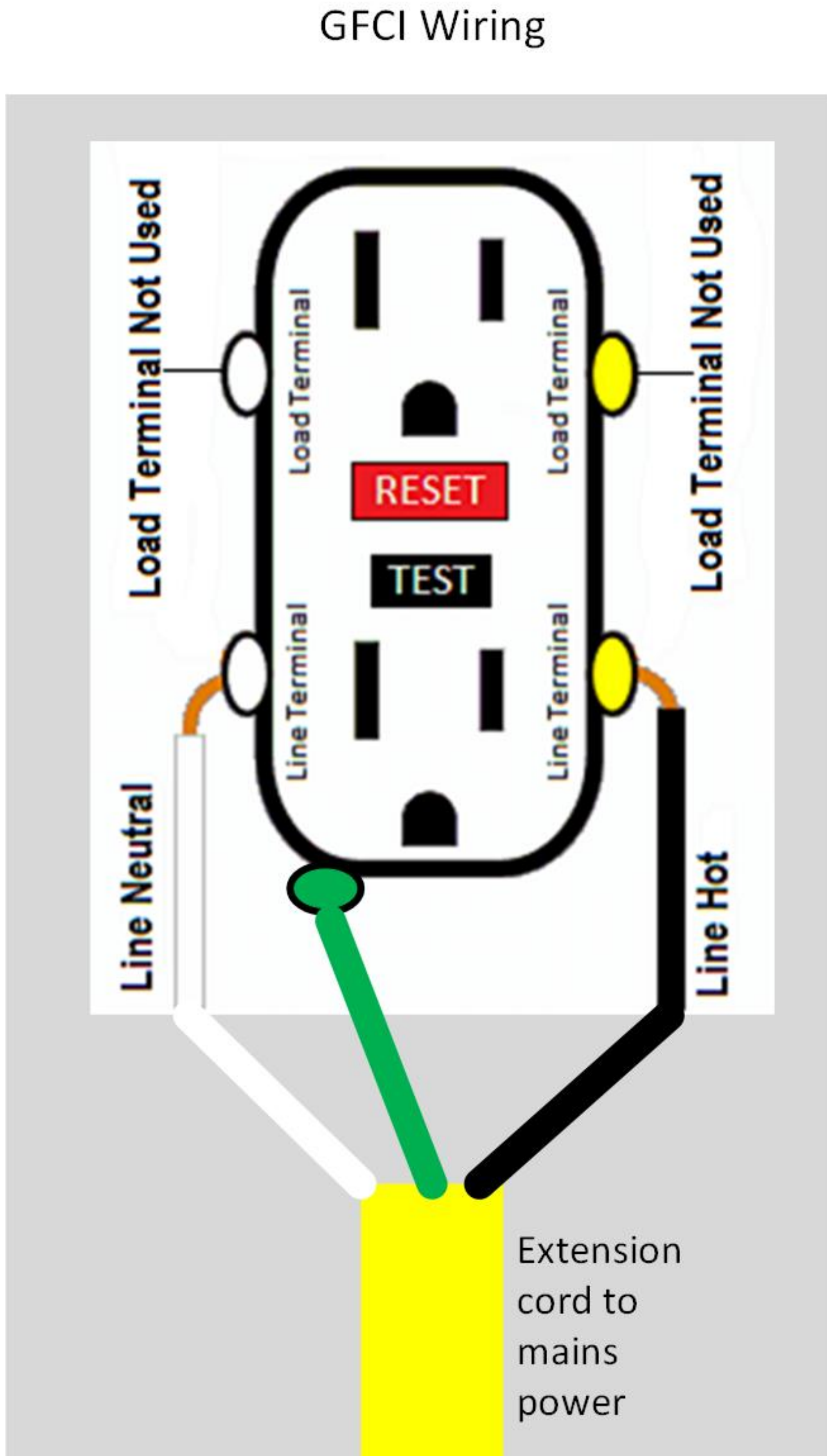


Figure A38. Wiring diagram for the GFCI outlet for the wave flume motor assembly stand.