The Effect of Pile Driving at the New NY Bridge on the Swim Bladder of Fish

Chloe Hutchins

Nyack High School

Chloe Hutchins

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Chloe Hutchins

Abstract

The growing amount of noise pollution affecting various bodies of water is becoming an increasingly problematic issue worldwide. Pile-driving is one of the many causes of the rising amount of noise pollution and is one that has become a major concern, especially because of the many studies which show that pile-drivers can cause the swim bladders of fish to shake and burst. This study looked further into the effects of the noise produced by pile-driving by using gel beads in rubber gloves that represent the fish, which are then used in order to assess the negative impacts of the noise created by the pile-drivers. The damage to the gel beads was then rated on a scale of 0-2 based on the amount of gel beads damaged. Overall the exposed groups were found to have much more damage than the control groups. Based on the damage that was found in the "fish models" it can be suggested that real fish may experience similar damages when exposed to the same noise levels. However, more tests into whether the 'fish models' accurately represent real fish will have to be done because it is a novel idea.

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Introduction

A growing problem throughout the world is the increasing amount of noise pollution from man-made sounds in the oceans and other bodies of water. There are many different types of anthropogenic noise produced in the oceans. Some of the most well-known are Navy Sonar, vessel noise, and seismic surveys. One noise which has recently begun causing more concern among researchers is pile driving. The loud underwater noises created by pile drivers have many negative effects on fish in the water around them, as well as humans and animals not in the water See Figure 1).

Figure 1- Noise Comparison Chart

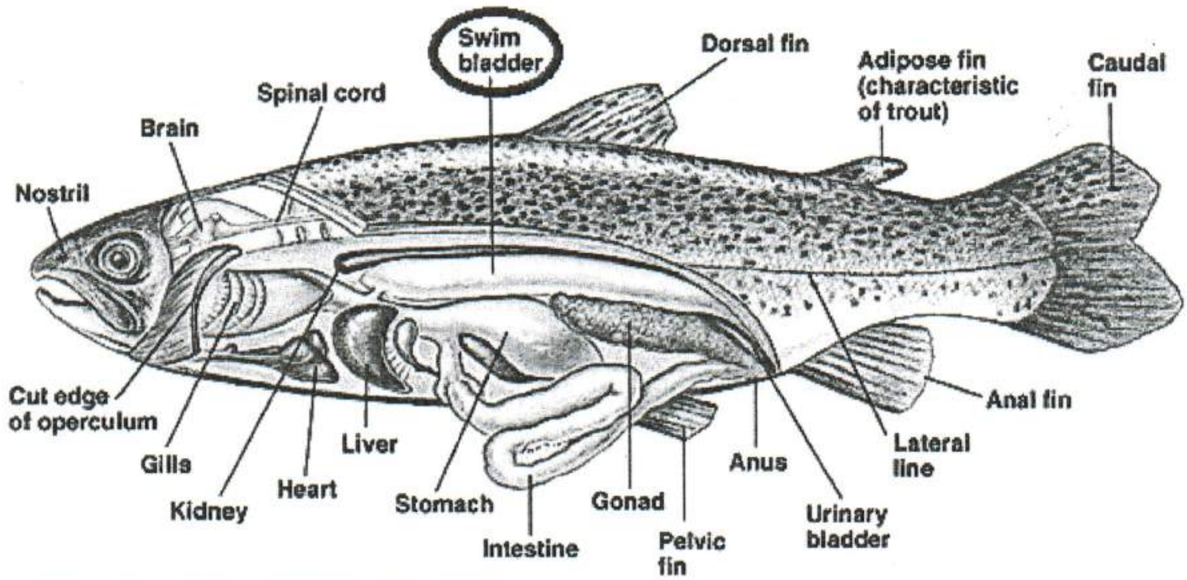
Sound Levels (dB)	Intensity (W/m^2)	Effect / Examples
0	1×10^{-12}	Threshold of hearing at 1000 Hz
10	1×10^{-11}	Rustle of leaves
20	1×10^{-10}	Whisper 1 m away
30	1×10^{-9}	Quiet home
40	1×10^{-8}	Average home
50	11×10^{-7}	Average office, soft music
60	1×10^{-6}	Normal conversation
70	1×10^{-5}	Noisy office, busy traffic
80	1×10^{-4}	Loud radio, classroom lecture
90	1×10^{-3}	Inside a subway train
100	1×10^{-2}	Noisy factory, siren from 30m
110	1×10^{-1}	Damage from 30 minutes exposure
120	1×10^{0}	Loud rock music, threshold of pain damage in seconds
140	1×10^{-2}	Jet plane at 30 meters, severe pain
160	1×10^{-3}	Bursting of eardrum

http://www.yale.edu/ynhti/curriculum/images/2008/5/08.05.07.06.jpg

What first sparked the interest of many into the impact that high underwater sound levels have on marine animals was the belief that Navy sonar activities were injuring whales. This is because sonar has been correlated with the strandings of whales and Navy sonar activities (Fernández, 2005). The mid-frequency sonar of Navy ships can reach up to levels of 237 dBs, which outside of water would be about 175 dBS, a level which is louder than the noise levels that can burst a human eardrum. The seismic surveys are marine geographical surveys where seismic arrays are towed around, and their loud sounds are emitted downwards to probe the sea bed for fossil fuels. The seismic survey's low frequency nature is especially troubling because of the large range that it can travel, up to thousands of miles (Hatch, 2007). Although vessel noise, or shipping noise, is not as intense as the levels of the sonar and the seismic surveys, they are a major contributor to the rise of noise in the oceans (Pirotta, 2012).

More recently, the effect of pile driving has become a concern, particularly regarding its impact on fish. Exposure to underwater noise from pile driving may also cause temporary or permanent hearing loss (Mueller-Blenkle, 2010; Popper, 2009), which can be damaging to the fish because they use sound in many different ways necessary for their survival. Many fish use sound for mating and hunting for food (Hastings, 2005; Popper, 2009; Popper, et al., 2014, Radford, et al., 2014). The behavioral effects range from direction change, to stopping or swimming faster (Mueller-Blenkle, 2010; Popper, 2009). Some research has shown that loud noises can make swim bladders, a gas filled sack in fish used for buoyancy, vibrate and cause damage to the bladder, the surrounding organs, and the tissue (Halvorsen, 2012; Hastings, 2005; Popper, 2009). The potential impact of underwater sound on a fish's swim bladder is the focus of this study.

Figure 2 – Swim bladder location in relation to other major organs

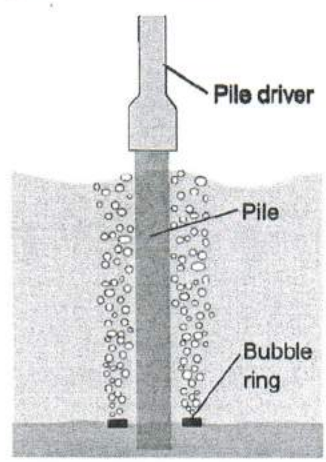


This study concentrated on how the size of the swim bladder and how the absence or presence of the swim bladder affected the injuries expressed in the fish as a results of exposure to underwater noise during pile driving. Past studies have indicated that the presence of a swim bladder seems to have an effect on the injuries expressed by fish, and the effect of their size has also begun to be questioned. One study found a greater hearing sensitivity for fish with larger swim bladders in comparison to those with smaller swim bladders (Schulz-Mirbach, 2012). It is likely that this hearing sensitivity could also be a sign of a greater physical impact of the sound on the fish. The different types of swim bladders, such as the physostomous swim bladder which can be used to easily manipulate the volume of the gas in the bladder, and the physoclistus swim bladder which cannot, may also affect the injuries expressed (Halvorsen, 2012). The physostomous swim bladder's ability to change the volume of air in it easily may allow it to lessen the effects from high sound levels. Other studies have revealed that some fish have developed other morphology specializations such as the anterior extension, which connect the inner ear and the swim bladder (Schulz-Mirbach, 2012). These extensions allow the sound more direct access to the inner ear through direct stimulation from the swim bladder. This, like other evolutions of the swim bladder, may change the way the swim bladder is affected by high sound levels.

The type of pile driver that this study examined regarding its effect on fish was an impact pile driver. Impact pile driving is a loud, impulsive sound that is repeated at a certain interval. Impact pile driving produces high sound pressures underwater, which is why many suspect it has a great impact on fish (Casper, 2012; Popper, 2009). The sound levels created by impact pile drivers depends on many factors such as pile size, type, water depth, hammer energy, and substrate type (Mueller-Blenkle, 2010; Stadler, 2009).

This study focused on the pile driving occurring during the construction of the New NY Bridge which connects Westchester and Rockland County across the Hudson River. At this bridge, noise pollution is a big concern because of the shortnose and Atlantic sturgeon, which are an extremely old endangered species that live in the Hudson River. The solution that the engineers came up with, which works to lessen the effects of pile driving, was an air-bubble curtain (See Figure 3). These air-bubble curtains increase the compressibility of the water and work to absorb the sound pressure waves from the noise, therefore causing the sound to lose energy, reducing its effects on fish (Domenicos, 1982; Popper, 2009; Stadler, 2009).

Figure 3- Air bubble



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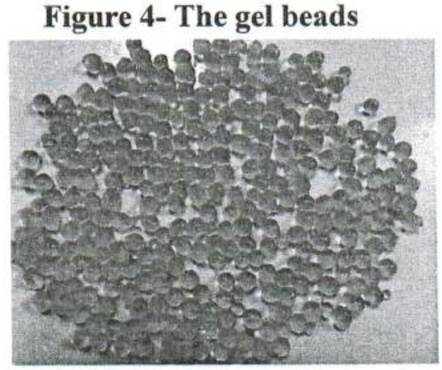
Recently, however, there has been a noted increase in the number of deaths of sturgeon in the Hudson River which have increased greatly since construction began. The number of sturgeon deaths went from a total of 6 over the three year period before construction began, to a total of more than 100 in the three year period after construction began. Of the sturgeon found dead, many were found to have died from blunt trauma, with injuries such as gashes and severed heads that were most likely caused by impacts from boat propellers. Due to these deaths, protective methods such as propeller cages and a slower speed limit at the construction area have been called for by local environmental groups (Foderaro, 2015).

Overall, this study will be looking into the effects of pile driving noise on fish swim bladders, in order to see just how damaging the sound exposure can be. A novel way of measuring the damage without actually injuring the fish was created for this experiment. Balloons of different sizes were filled with either air or water to represent the different swim bladders, and the damages that are inflicted were tested on gel beads to see if either one was more damaged by the pile driving. This study is intended to provide a better understanding of which swim bladders and fish are more affected by pile driving noise, and allows for a better protection of those fish. I hypothesized that the noise produced from the pile driving will be intense enough to burst the gel beads and possibly the 'swim bladder', this being the balloon. This study looked into the impact of presence of and type of swim on the damage to the gel beads after exposure to underwater pile driving sounds, assuming that the damage could be applied to the expected damage of underwater pile driving on real fish.

Methodology

The Making of the Gel Beads

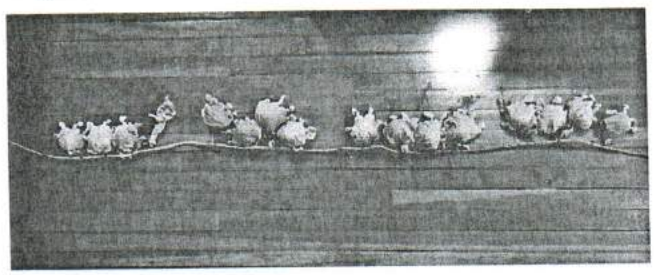
Figure 4- The gel beads



To assess the relative degree of injury caused by underwater noise on fish tissue and the swim bladder, sodium alginate gel beads were created to simulate fish tissue as well as to assess the damage from the pile driving, using the method described by Hock, et al., in (2002). A 2.0% sodium alginate solution was made by adding 10g of sodium alginate to 500mL of water. Then the sodium alginate was blended on the lowest setting for approximately 30 seconds and $1/8^{th}$ of a teaspoon of red food coloring was added. A 0.50% calcium chloride solution was made by adding 5g of calcium chloride to 1000mL of water. These two solutions were combined to make the gel beads by dripping the sodium alginate solution into the calcium chloride solution. Sodium alginate is a polymer and, when dripped into the calcium chloride solution, cross linking occurs, which chemically links the two, causing the drops to harden and form beads. The gel beads made in this experiment were 1/2 cm in diameter. Many different procedures were tested in order to produce the desired size and hardness of the gel beads.

The Making of the 'Fish Models'

Figure 5- The 'fish models' attached to the



The experimental treatments consisted of four different types of 'fish models' which were made from rubber gloves, gel beads, and balloons to model fish skin, muscle tissue and organs, and the swim bladder, respectively. Four different variations of the fish model were made: 1) a small balloon filled with air, 2) a small balloon filled with water, 3) a large balloon filled with air, and 4) a large balloon filled with water. The 'fish models' with air-filled balloons represented a fish that had a swim bladder and the 'fish models' with balloons filled with water were used to represent a fish that did not have swim bladder. The gel beads were used to simulate the surrounding tissue in fish as a way of assessing the damage from the pile driving. The small balloons were ~2 inches wide and the large balloons were ~3.5 inches wide. Next, the balloons were filled and tied. The fingers of the rubber gloves, except the thumb, were tied to prepare them for filling with gel beads. Then, the 'swim bladders' were put inside the gloves. The gel beads were then placed inside the rubber glove to fill the space between the glove and the bladder. Pictures were taken of the beads prior to being put into the gloves. Fish models that had small 'swim bladders' contained 100mL of gel beads and those that had large 'swim bladders' contained 50mL of gel beads. Finally, the opening of the glove was zip tied to close it and the balloons were zip tied to a rope. There were three 'fish models' of each of the four types on all three strands.

Three strands of 'fish models' were deployed in the river for the experiment: two replicate strands were placed by the pile being driven at the New NY Bridge to be exposed to the underwater noise, and one strand, which represented the control, was placed in the water at the end of Piermont Pier approximately 1.8 miles from the New NY Bridge (See Figure 5). The strings of balloons representing each of the four experimental treatments were attached to a cleat on the barge and put in the water adjacent to one of the steel piles just prior to pile driving. Each strand had a 25 pound weight attached to the bottom of the line to keep the line vertical in the water column. The weight was used as an anchor with a weight range from 10-30 pounds depending on the depth and tidal conditions of the water.

Figure 6

This map shows the distance, ~1.8 miles, between the bridge and the control line.

Measurement of the Sound Levels

While each strand of 'fish models' was in the water, underwater sound levels were measured to quantify the sound pressure levels that the 'fish models' were being exposed to. A Larson Davis model 831 integrated sound level meter and Reson model TC 4033 hydrophone were used to measure sound levels. A range finder was used to place the hydrophone at a distance of 10 meters from the noise source, which in this case was the pile being driven.

Analysis of the 'Fish Models'

After exposing 'fish models' to pile-driving noise, each 'fish' was carefully dissected to reveal any damage that may have occurred to the beads and the inner balloon, or 'swim bladder'. Pictures were again taken of the gel beads and 'swim bladder'. Data were analyzed by comparison of pictures taken before and after the experiment. Each swim bladder was inspected to determine if it had remained intact or if it had ruptured. Damage to the gel beads was assessed based on the relative number of beads that had burst using a scale with values ranging from 0-3. Each number represented a certain amount of gel beads that were damaged after the exposure to pile driving which were 0 (none damaged), 1 (few damaged), 2 (many damaged), and 3 (most damaged). As each 'fish model' was cut open, the gel beads were inspected and then given a rating from this scale.

Statistical Analysis

Both a chi squared analysis and an odds ratio were calculate based on the results of the experiment.

The chi squared analysis was performed using excel. The expected values were calculated by multiplying the total number of 'fish models' with or without damage by the total number of 'fish models' in the exposed or control group respectively. This value was then divided by the total number of 'fish models' in the experiment. The expected and observed values from the results were then subjected to a chi squared test.

The odds ratio was calculated using a statistical software from *MedCalc*. Using the odds ratio a 95% Confidence interval and a p value were also calculated using the same software.

Results

Measurement of the Sound Levels

While the three lines were in the water, the sound levels at the piles where Line 1 and Line 2 were placed were recorded. The two lines were put in the water at separate times and each were put in the water when different piles were being driven. The sound levels for Line 3, which was the control, were not recorded but because of its distance from the pile driving it was most likely exposed to quieter sound levels than the lines that were placed directly near the pile driving. Line 1 was in the water first for 22 minutes and was 10 meters away from the pile being driven. At this pile the maximum Peak Sound Pressure Level (SPL) recorded, which is the loudest sound level over a period of time, was 197.3 dB. Line 2 was in the water at a different pile for 19 minutes and was 16 meters from the pile driving. At this pile the maximum Peak SPL recorded was 194.0 dB.

Analysis of the 'Fish Models

After they were exposed to the pile driving, the three lines with 'fish models' were each put into a labeled bucket and kept separate. The next day the 'fish models' on the three lines were analyzed.

The first line that was analyzed was Line 1, which was directly next to the pile driving (See Data Table 1). The 'fish models' were first cut off the line and then each dissected separately. In Line 1 five 'fish models' were found to have a damage level of one, while the others had a damage level of zero. The 'fish models' found to have damage levels of one were two with small water swim bladders, two with large air swim bladders, and one with a large water swim bladder. On this line, one 'fish model' with a large water swim bladder burst.

Overall, on this line the 'fish models' with water swim bladders experienced the most damage, as well as that 'fish models' with larger swim bladders experienced more damage than those with smaller swim bladders. However, the most significant data found in Line 1 is that two 'fish models' with large air bladders had some damage to the gel beads.

Table 1- Line 1

	Damage to Beads				Damage to "Bladder"	
Type	0	1	2	3	Ruptured	Not Ruptured
SA1	0					NR
SA2	0					NR
SA3	0					NR
SW1		1				NR
SW2		1				NR
SW3	0					NR
LA1		1				NR
LA2		1				NR
LA3	0					NR
LW1	0				R	
LW2	0					NR
LW3		1				NR

The same process was done for line 2, which was also directly next to the pile driving (See Data Table 2). After the 'fish models' were cut off the line they were each dissected separately as well. On Line 2 three 'fish models' were found to have a damage level of one, while the rest all had damage levels of zero. The 'fish models' with a damage level of one were two with small air swim bladders and one with a large air swim bladder. Two 'fish models' on the line also had ruptured swim bladders; both had large water swim bladders. On this line 'fish models' with air swim bladders showed the most damage to the gel beads than water swim bladders.

Table 2- Line 2

	Damage to Beads				Damage to "Bladder"	
Type	0	1	2	3	Ruptured	Not Ruptured
SA1		1				NR
SA2		1				NR
SA3	0					NR
SW1	0					NR
SW2	0					NR
SW3	0					NR
LA1		1				NR
LA2	0					NR
LA3	0					NR
LW1	0				R	
LW2	0					NR
LW3	0				R	

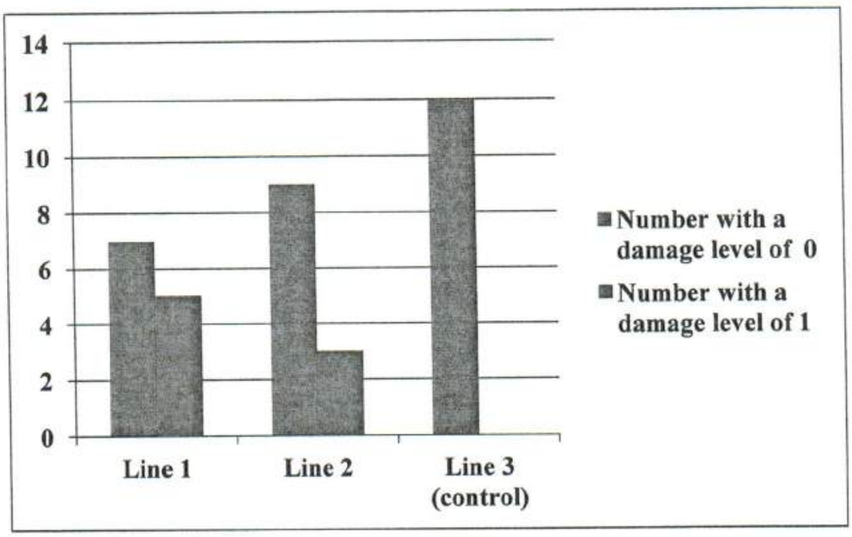
The same process of removing and analyzing the 'fish models' was repeated on line 3 which was the control line (See Data Table 3). This line was not directly near the pile driving while it occurred, but instead was dropped into the water of a separate pier that was 1.8 miles away from where the pile driving was occurring. For the control line all the 'fish models' had a damage level of zero, as well as that none of the swim bladders for any of the 'fish models' were ruptured.

Table 3- Line 3

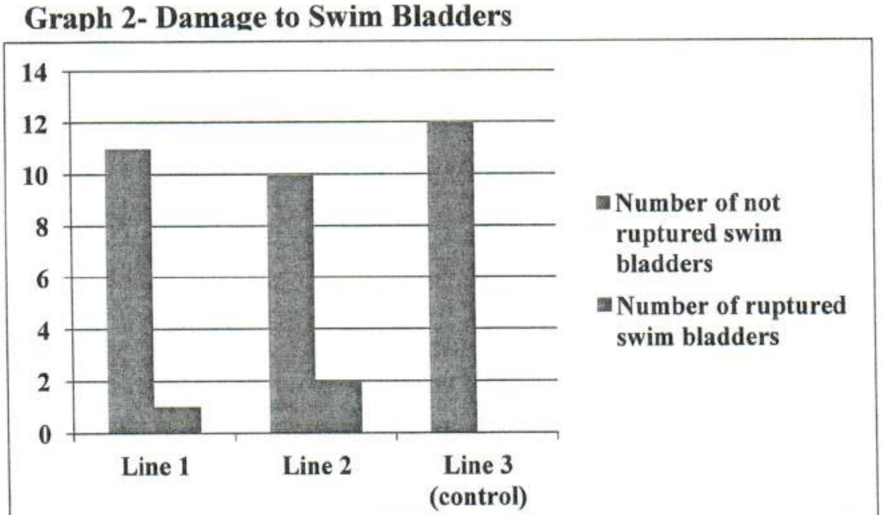
	Damage to Beads				Damage to "Bladder"	
Type		1	2	3	Ruptured	Not Ruptured
SA1	0					NR
SA2	0					NR
SA3	0					NR
SW1	0					NR
SW2	0					NR
SW3	0					NR
LA1	0					NR
LA2	0					NR
LA3	0					NR
LW1	0					NR
LW2	0					NR
LW3	0					NR

The results of the experiment showed that Line 1 experienced more damage to the gel beads than Line 2. On Line 1 there were five 'fish models' with damage levels of 1 compared to Line 2 which only had three 'fish models' with a damage level of 1. This finding is consistent with the noise data because Line 1 was exposed to higher sound levels than Line 2. Line 1 was exposed to sound levels up to 197.3 dB, whereas Line 2 was only exposed to sound levels up to 194.0 dB (See Graphs 1 and 2).

Graph 1- Damage to Gel Beads



Graph 2- Damage to Swim Bladders



Statistical Analysis

A chi squared analysis was performed comparing the expected values for the data results to the observed outcome (See Table 4). The result was a statistically significant p value of *0.0233,* showing that there was a significant difference between the expected values and the observed values. This negates the chance that the data results are randomly achieved, showing that the variable tested had a significant impact on the results, which supports the hypothesis of the experiment.

Table 4

	Expected		**Observed**	
Row Labels	**Damage**	**No Damage**	**Damage**	**No Damage**
Exposed	5.333333333	18.66666667	8	16
Control	2.666666667	9.333333333	0	12
***P Value**	*0.023342202*			

**The p value is statistically significant*

An odds ratio was also calculated for the results, which is a relative measure of effect, comparing the experimental group to the control group (See Table 5). The results had an odds ratio of *12.988* and because it is greater than 1, exposure to the pile driving can be said to be associated with higher odds of an outcome with damage. Based on the odds ratio a 95% confidence interval was also calculated, which defines a range of values that you can be 95% certain contains the population mean. This studies confidence interval was 0*.678 to 244.929.* A p value was also calculated based on the odds ratio, which was *0.089.* Although the value was greater than 0.05, and therefore not significant, it was approaching significance. The large range of the confidence interval indicates that there is a low level of precision in the odds ratio, which was most likely due to the small sample size of the experiment.

Table 5

Odds Ratio	*12.98788*
P Value	*0.089*
95% CI	*.67772 to 244.9291*

Conclusion

This experiment tested two variables, how size and presence of a swim bladder would affect the damage that occurred to fish during pile driving activities. To do this, a 'fish model' was developed to standardize the process so that the swim bladder size and amount of 'fish' that were tested throughout the experiment could be controlled. In order to be able to assess the damage that the 'fish models' experienced, gel beads, which would burst if damaged, were used. Balloons were also used to represent the swim bladders in order to see whether they would rupture after exposure to the pile driving, which is known to happen to the swim bladders of fish when exposed to high sound levels. It was hypothesized that the 'fish models' with large air swim bladders would have the most gel beads damaged, as well as that their swim bladders would be the most likely to burst. The results from lines 1 and 2 found that air swim bladders had more damage to the gel beads, but that size had no effect on these. It was also found that the large swim bladders ruptured more than small swim bladders, but water swim bladders ruptured more than air swim bladders which had not been expected.

Discussion

The most notable difference in this experiment was between the experimental and control groups regarding the damage to the gel beads and the balloons. The control experienced no damage which was expected whereas the experimental groups together had eight 'fish models' with a damage level of 1 and three 'fish models' with ruptured balloons. The control line was placed ~1.8 miles away from the pile driving as it was occurring and due to this it was likely that it would be exposed to significantly lower noise levels than the experimental group, which were directly near the piles as they were being driven. All other possible variables, such as water temperature and river current, were constant because the models were deployed on the same day in similar locations.

One surprising result of the data was that only 'fish models' with water swim bladders, which were meant to represent fish without swim bladders, ruptured. An explanation for this could be that when the lines were put in the water, if they hit the water too hard, the pressure could have caused them to burst. The large water balloons were filled quite full and were more likely to pop than the other balloons if handled too roughly.

This study originated as a novel way of using rubber gloves to represent fish, gel beads to represent the tissue in the fish, and water balloons to represent the swim bladder in order to attempt to analyze the impacts of the pile driving noise as best as possible without harming actual wildlife. It is important to develop a more standardized way of studying the impacts of anthropogenic noise on fish. Future studies should definitely focus on ways of improving these 'fish models' so that they can more accurately represent fish. One way this can be done is by possibly changing the composition of the solutions used to make the gel beads in order to decrease their hardness, as well as to make them better at expressing the damage to the 'fish models' from the pile driving. The other is to look at other possible materials that could be used to make the 'fish models' in order to make them better and more accurately represent fish so that they can become a viable way of studying the impact of high noise levels on fish.

Pile-driving has recently become a major topic of discussion especially regarding its effects on the marine organisms and their habitats. There continues to be more aquatic construction throughout the world as countries develop and improve their methods of transportation, as well as searching underwater for drilling fossil fuels in places like the Arctic Circle. There are many endangered species, like the sturgeon in the Hudson River, which are at risk if exposed to such high sound levels as created by pile driving. Some studies have been conducted examining the damage experienced by fish exposed to high sound levels, but in order for these studies to perform an extensive analysis such as a histology in order to see the internal effects, the fish used in many of these studies were euthanized. This methodology attempts to change this way of studying the fish by instead using models of fish in order to assess the possible damage. By gaining a better understanding of the injuries that pile driving can cause, they can be better prevented and new technologies like bubble curtains can be developed and improved in order to limit the impacts of the high sound levels caused by pile driving.

Chloe Hutchins

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