MATERIALS AND SHAPE OF UNDERWATER STRUCTURES

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Abstract

Scuba divers risk decompression sickness everytime the ascend to the surface. An underwater habitat reduces the need for a diver to surface to once per mission. This report is focused around the question: *What factors determine the shape of an underwater structure?*
This research paper is part of my graduation project. The aim of my graduation project is to design an underwater habitat for long term research of marine life in the Great Barrier Reef. It is therefore relevant to have an understanding of the most suitable materials and construction methods for my design. To answer the research question relevant literature is studied to illustrate the development over time of three underwater structures: aquarium tunnels, military submarines and immersed tunnels.
The aquaria started of as simple boxes, but new materials and techniques allowed them to develop into more complex aquarium tunnels. Military submarines developed from a sphere like vessel towards a cigar shaped body with the invention of the pressure hull. The pressure hull allowed the military submarine to be developed from a hydrodynamic point of view. The immersed tunnels started of as a cylinder, but new techniques were developed to change the shape of the tunnel to a rectangle. This rectangle better matched the profile of the transportation tunnel. The answer to the research question is very versatile, because multiple factors have influenced the shape of underwater structures over time. For example construction techniques, new materials and economic factors all influenced the design of underwater structures.

Keywords: Underwater, Water pressure, Aquarium Tunnels, Submarines, Immersed Tunnels, Optimal Shape, Concrete, Steel, Glass, Acrylic Glass

Table of Contents

Introduction

Background

This research paper is part of the graduation project in Architectural Engineering. The aim of the paper is to research an underlying theme, which sprouts from a personal fascination and has a certain relevance to the graduation project and final design. I started my study of architecture in 2009 at the University of Technology in Delft and finished my bachelor in 2012. After my bachelor I followed the Msc3 and Msc4 master tracks of RMIT. After my time at two different RMIT studios I decided to join the Architectural Engineering studio in 2014. While this is a research paper for the Architectural Engineering studio I also apply the skills I learned at RMIT by analysing the history of the subject.

In this paper the research question, relevance of the topic, fascination and problem statement will be explained first. Second, the chosen research methods will be justified and clarified. Then the results of the thematic research will be laid out and evaluated, main results will be highlighted and addressed in order of relevance. Last, the final conclusions will be drawn from the gathered data and the research question(s) will be answered. Unanswered questions will also be addressed and the work accomplished will be evaluated, followed by recommendations for further research.

Research question

The theme of this paper is underwater construction an will focus on the question:

What factors determine the shape of an underwater structure?

Sub-questions:

How does pressure work on underwater objects?

What kind of materials are common when designing structures which have to deal with large pressures?

Why are these materials chosen and what are their properties?

What kind of structures or objects are constructed out of these materials?

How did the design of these structures or objects develop over time?

Relevance

This research paper is part of my graduation project. The aim of my graduation project is to design an underwater habitat for long term research of marine life in the Great Barrier Reef. It is therefore relevant to have an understanding of the most suitable materials and construction methods for my design.

Fascination

In 1963 Jacques Cousteau spent a record setting thirty days in an underwater habitat beneath the surface of the Red Sea. Now, fifty years later, his grandson Fabien Cousteau set a new record by spending thirty-one days in Aquarius, an underwater research habitat off the coast of Florida. For a long time society has been fascinated about living and working underwater whether it is in a yellow submarine (The Beatles - Yellow Submarine 1966) or an underwater castle (The little mermaid 1989). I share this fascination of living in a different world under the waves. I want to combine this fascination with my interest in architecture and engineering in order to explore the possibilities of underwater construction.

Problem

Humans have invented a multitude of ways to explore the ocean. We started of with ships to explore the surface of the ocean, but we needed diving equipment to start exploring what's below the surface. However, humans can only stay under water for a limited amount of time. The limiting factors here are the supply of oxygen, but more importantly, the high pressure under water. Water is much more dense than air and is incompressible. This means that while air, when put under pressure, will increase it's weight and decrease its volume, water will retain its volume and weight.

The pressure at the surface is one atmosphere (atm). At a depth of ten metres beneath the surface the pressure is two atm, at a depth of 20 meters it is three atm and so on. To be able to breath under water your lungs need to push all the weight of the water outwards to make room for the air. If you try to breath air from the surface with a pressure of one atm at a depth of twenty metres, where the pressure on your body is three atm, it is impossible to breath, because the pressure on your lungs is three times bigger then the air you are trying to inhale. Scuba diving has allowed us to breath pressurized air, which has the same atmosphere as the water around us. The air you breath in pushes out just as hard as the water is pushing in.

Scuba divers risk decompression sickness (DCS; also known as divers' disease, the bends or caisson disease) when they ascend to the surface. DCS occurs when dissolved gases come out of solution and form bubbles. Because this can happen in any part of the body the symptoms range from joint pain and rashes to paralysis and death.

The risk of DCS increases when diving at a greater depth and/or for extended periods of time without giving the body time to process the accumulated gases safely out of the body trough the lungs, to prevent the formation of bubbles. In order to prevent DCS scuba divers have to take breaks during their ascend at the end of the dive at regular intervals. Because of this, dives from the surface take a long time and get less efficient with increasing depth.
A decompression chamber can artificially decrease and increase the pressure inside the chamber to allow the gases in the divers body time to return to 1 atm. Combined with an underwater habitat at the same pressure as the surrounding water, divers can stay under water for an extended period of time. Undertaking multiple dives from the habitat, the need to resurface between the dives is eliminated, thus reducing the risk of DCS and time lost to controlled ascension.

Method

The research report is based on literature studies and case studies. The report first focusses on explaining how pressure works with basic principles, literature examples and diagrams. The next step is to explain how certain materials behave under pressure and what their advantages and disadvantages are for underwater construction.

Finally, an investigation of three different underwater structures, aquarium tunnels, military submarines, and immersed tunnels is done. This research is done by taking a close look at the development over time of each structure. To understand the timeline of a structure, three questions are asked when the structure changes in a mayor way: What changes? Why does it change? How does it change?

Results

Shape related to Pressure

The biggest challenge for an underwater structure is withstanding the constant water pressure. To understand how these structures solve this problem we have to have a better understanding of the forces at play.

Pressure is a force divided by the area the force is acting on. The force of this pressure is exerted perpendicular to the surface on the object. The illustrations on the right are based on a gas pressure from inside the object, but the principles work the same with water pressure from the outside. Gas pressure is easier to work with because you can assume the gas exerts equal pressure to all sides, while water will exert more pressure on the bottom of the object than on the top, because the pressure is depended on the height of the water column above the object. Forces acting on the outside of the object will cause compression stresses in the material and forces acting on the inside will cause tensile stresses.

The amount of water above the object and the resulting pressure on the object have a linear relationship, where each 10 meters of depth correspond with 1 atmosphere of pressure.

Pressure exerted on a object results in tension in the casing material, to counteract the forces acting on the material. This principle is simplified in the diagrams on the right. For a given vessel radius and internal pressure, a spherical vessel will have half the wall tension of a cylindrical vessel.[1] Therefore the most efficient shape to withstand equal pressure from all sides is a sphere.

The wall tension is dependent on the pressure and the radius of the sphere. With an equal pressure the wall tension will increase when the radius is increased. This principle is explained in the diagrams on the right, where the pressure force P remains equal, but the tension T has to increase with the increasing radius to counteract this force.

Buildings only have to withstand forces that

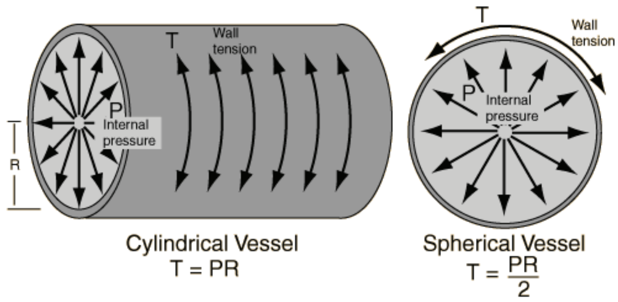

Fig. 01: Pressure principles

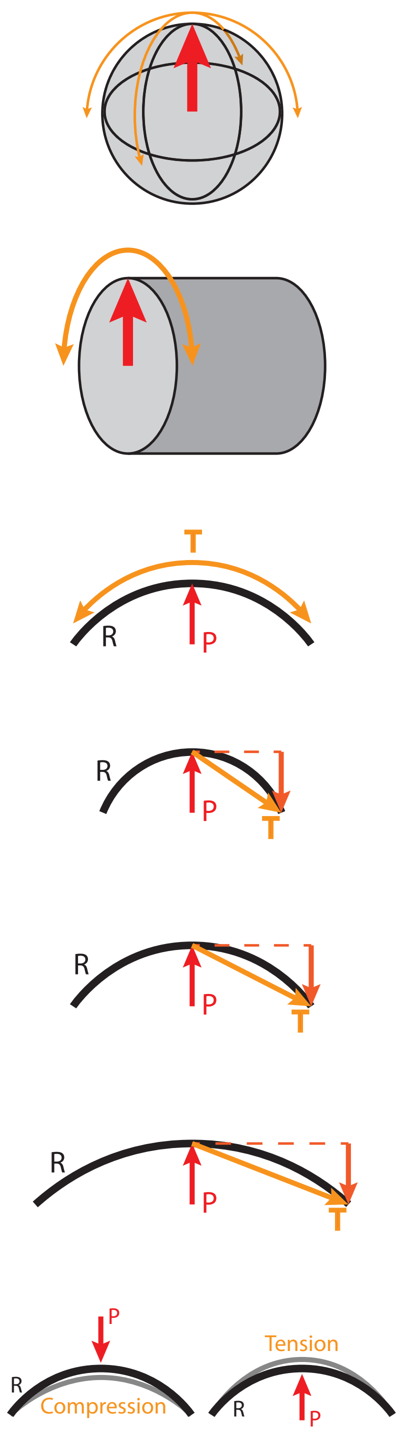

Fig. 02: Tension principles (own image)

1 Nave C. R. (2012)


Fig. 03: Aquabulle (1978)


Fig. 04: Galathee (1977)


Fig. 05: Petroleum refinery, Karlsruhe

either go down or horizontally, because these are the only ones that occur. Domes and arches are derived from a spherical shape and are therefore used in architecture when dealing with large spans or high carry loads.

A common example of spherical structures are large pressure vessels such as the ones in the petroleum refinery in Karlsruhe (Fig. 05). Another advantage of this shape versus another shape is the optimized volume circumference ratio, this means that the heat exchange between the contents of the pressure vessel and the surrounding area is limited to a minimum. This means less energy is needed to keep the contents on a constant temperature, which is often very important for various dangerous gases and liquids.

Shape related to Material

We have concluded that a sphere is the optimal form to withstand outside or inside pressure, it uses the least material with a minimum surface area to encompass a certain volume. Most of the time however, another shape is chosen over a sphere for various reasons. This chapter will discuss the influence of different materials on the shape of the object by looking at its properties and production processes.
Pressure vessels use the spherical shape to withstand large pressure loads coming from inside the tank, instead of pressure from the outside. While the shape is the same, the forces that work on the object are very different. Pressure from the outside compresses the material while pressure from inside of the object stretches the material. This difference is very important, because materials have different compressive and tensile strengths. The construction of underwater structures is almost always done with steel, concrete or acrylic glass. These materials have become the pillars of three underwater industries; aquarium tunnels, submarine design and immersed tunnels. These industries will be discussed in the next chapter.

Steel

Since the industrial revolution steel has become one of main construction materials. Steel has both high compressive and tensile strength and can be produced as strips, plates, wires, profiles, beams and columns in various shapes. These properties make it an ideal construction material for a lot of applications. Steel can also be produced as a sphere, but this is very difficult and not commonly done, which makes it expensive.

Pressure vessels are often cylindrical because of the high expenses involved with the construction of a sphere. These cylinders are capped of with a dish or dome to form a pill or can shape. A lot of studies have gone into optimizing these shapes with the least thickness and best cap shape.

The wall tension in a cylindrical pressure vessel is twice as big as in a spherical vessel. Therefore the larger the pressure vessel, or the higher the pressure gets, it becomes more and more beneficial to invest in the more expensive dome shape. Another way of reducing the costs of the dome shape is to divide it into segments. But this is only profitable if the sphere is large enough, because more segments means the dome takes a longer time to construct.

Steel can be welted, bolted or riveted. Welding creates a continues connection between two steel components. This gives steel great flexibility when it comes to combining different elements to create a certain shape. Welding can also happen under water, but the best quality is achieved in a factory, where the elements are pre-constructed. This method is called hyperbaric welding and is normally only used to make repairs to objects, which can not be done dry, such as offshore rigs and pipelines. Bolts are often used to connect steel to other materials, such as wood, but can also be a sustainable choice to allow the structure to be disassembled.

Concrete

Concrete is a mixture of water, cement and an aggregate. This aggregate can be almost any type of sand, gravel, slag or natural stone. A concrete mixture hardens over-time into a durable stone-like material, but the exact properties depend on the mixture used. The type and amount of cement, aggregates and water all influence the finished product. A famous example is the Pantheon in Rome which, with a diameter of 43,4 meters, is still the largest unreinforced solid concrete dome in the world. The Romans constructed the dome with different types of concrete using lighter aggregates in the top of the dome and heavier ones at the bottom. If modern concrete of around 2200 kg/m^3 would have been used, the stresses in the structure would be eighty percent higher than they are now.[2]

The Romans also already used concrete for underwater construction around the middle of the first century. This special type of concrete was able to harden under water using an hydraulic cement, but after the fall of the Roman empire the knowledge to do so was lost. It is not until 1756 that hydraulic cement is rediscovered by British Engineer, John Smeaton.[3]

In the modern era some of the worlds most iconic architecture has been constructed using concrete. Buildings such as Burj Khalifa (the tallest man-made structure), the Sydney Opera House (probably one of the most recognizable buildings around the world) and countless others were all made with concrete. It has also been used in great works of civil engineering, for example the Hoover dam and the Panama Canal.

Reinforced concrete is used in almost each new structure, be it as foundation, prefabricated walls and floors or monolithic skin. However, the possibilities of concrete are fairly limited. Concrete has a high compressive strength, but needs to be combined with steel for a high tensile strength. While beams, walls, floors and roofs can be easily constructed, complex shapes require customized moulds. Concrete can take almost any shape if it is poured into such a mould and left to harden. While most of the time easily fabricated out of wood, these moulds are expensive, which makes complex concrete shapes rare. Complex shapes can also cause stresses in the material, for which the concrete would need reinforcement (in the same complex shape).

Concrete can be combined by pouring new concrete on an already existing element. It is common to pour the walls on a floor element after the floor has already set. The next floor will only be poured after the walls have set and so on. Special care is often taken to make sure the elements bond sufficiently, because influences like the temperature of the concrete can create an interface between the two elements.

Reinforced concrete is often connected by connecting the reinforcement of the concrete. This connection can also happen by creating an overlay between the reinforcement of two different elements and join them by pouring concrete on the overlay.

When large concrete elements need to be connected under water the joints are kept simple to prevent construction problems. The ends are temporary sealed, while the connections are prepared from inside the element. An example of a simple joint is the match cast half-joint. A hydrophilic seal and a flexible rubber seal prevent water from leaking into the structure. A cement mixture is injected around the continues water stop to fill any pores in the concrete. Another seal is the omega seal which can withstand large water pressure and allows the elements to move in any direction as a result of temperature effects or settlement.[4]

2 Moore D. (1995)

3 Gromicko N. & Shepard K. (2006)

4 Trelleborg Bakker B.V (2011) p.04

Glass & Acrylic glass

Acrylic glass, also known as Polymethyl methacrylate or PMMA, while technically not a type of glass, is often used as an alternative for glass. The material was first made available for commercial use under the name Plexiglas by Rohm and Haas Company in 1936, but has had many adaptations with different names such as Acrylite, Lucite and Perspex.

Just after the invention of acrylic glass it was used during the Second World War by both Allied and Axis forces in submarine periscopes, aircraft windshields and the iconic translucent gun turret enclosures on bombers.[5]

Acrylic glass and conventional glass look very similar because they are both transparent, but behave very differently. Conventional glass is brittle while acrylic glass will crack and dent before breaking into shards. While it is more vulnerable to scratching than glass, acrylic glass can be enhanced with a coating or film to prevent scratching. It has less than half the density of conventional and tempered glass and has a higher impact strength than both glass types when compared by weight. When comparing sheets of the same thickness, tempered glass and acrylic glass are more or less equal in strength. The tensile strength of acrylic glass, however, is lower than that of tempered glass.[6]

Acrylic glass has a higher transparency than conventional glass which bends the light and can have a green appearance, especially when used as thick windows for a pool or aquarium. Basically, the thicker the glass pane the more light is absorbed, while acrylic glass doesn't absorb any light. Acrylic glass has a warm touch because of its higher insulating value. However, tempered glass can withstand much higher temperatures without melting or otherwise deforming. This makes tempered glass the preferred choice when fire safety measures prevent the use of acrylic glass.

When comparing the design flexibilities of tempered glass to acrylic glass the latter jumps ahead in every category. Acrylic glass can be processed in a similar way as wood, making it easy to cut in different shapes. It can also be thermoformed into almost any three dimensional shape. Tempered glass can't be cut after it has been processed and has limited capabilities when thermoformed. When installed the acrylic glass will expand and contract far more than glass.

Tempered glass and acrylic glass each have their own advantages and disadvantages. Because acrylic glass has higher transparency, higher impact strength and is light weight it is the most suited for underwater applications. Because of fire regulations acrylic glass is almost never used in buildings. While fire is a serious threat for an underwater structure, it mainly is because fire is very dangerous in close quarters such as a submarine. By the time the acrylic glass fails it is already too late and the crew should have abandoned ship or extinguished the fire.

Glass is often connected using a frame of either wood or aluminium, but other materials are possible as well. Another common connection method is using steel nodes which grab onto, often four, corners of a glass plate. Acrylic glass can be mounted in a similar matter as glass, but can often do with smaller fasteners because of its light weight.

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5 *Schwarcz J. (2012)*

6 *Evonik Cyro LLC (2009)*

Shape related to Function

We've seen how new materials can inspire a new design, such as the transparent nose of the Boeing B-17 Flying Fortress and other bombers. The function of a building or object, however, is even more determining for its shape than the material it is made of. When approaching a new assignment, most designers will determine what the design needs to accomplish and then search for materials with the fitting properties and capabilities. Analysis of the design of different objects that deal with high pressure environments show us multiple reasons to revise the 'ideal' sphere shape. These reasons will be explained on the basis of three examples: aquarium tunnels, submarine design and immersed tunnels. Each of these types of structures get the most out of one of the previously discussed materials steel, concrete or acrylic glass.

Aquarium Tunnels

While the first fish were kept in marble tanks with one glass pane in the year 50 AD by the Romans, aquariums really started to develop in the nineteenth century. After centuries of fear for the ocean, fed by fisherman stories, scientific interest in the ocean started to peak for the first time. First only concentrated on the physiological properties of the ocean such as temperature, salt content and density and later also in marine life, especially creatures such as crabs, jellyfish, sponges and corals. While interest in marine life was awoken, the general assumption was that no creature could live beneath a depth of 1000 fathoms because the pressure would crush any living organism. Edward Forbes's theory was that the ocean had a layered system with different organisms at each depth. After a communication line was dug up for repair in 1860, Forbes's theory would be proven right as the cable brought numerous creatures to the surface from below 1000 fathoms.[7]

With the growing interest in marine life came a way to observe the organisms from up close. Named an aquarium for the first time, in 1854 by Philip Henry Gosse the

Fig. 08: Boeing B-17 Flying Fortress

Fig. 06: L'aquarium; vue intèrieure, the interior of the Jardin zoologique at Bois de Boulogne

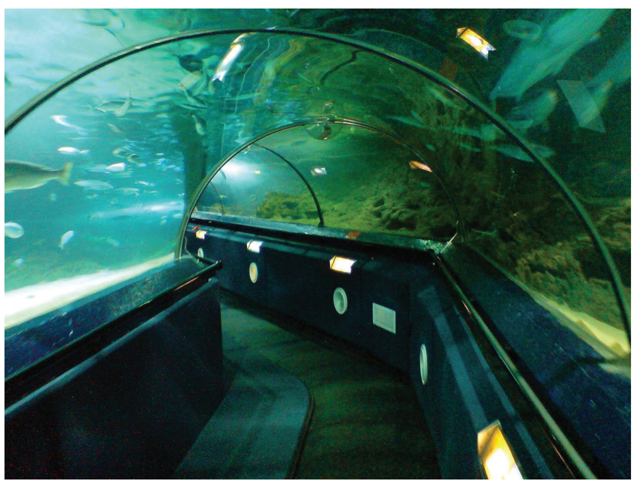

Fig. 07: Kelly Tarlton's Underwater World

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7 Brunner B. (2005) p.10-12

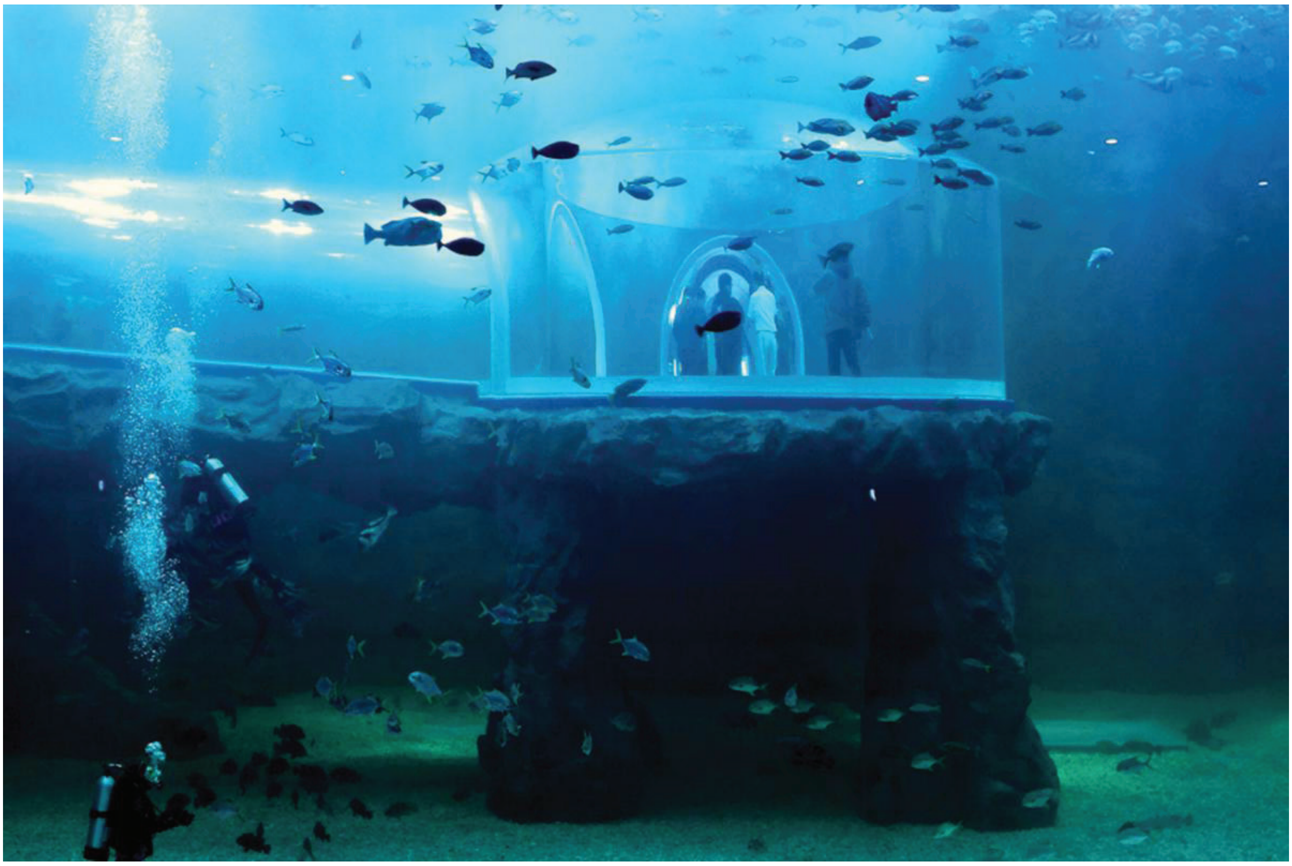

Fig. 09: Aqua Planet Yeosu

aquaria resembled the collection cabinets of the time. The aquarium developed from a wooden box with one viewing panel to an all glass box with a metal frame. The first large public aquarium, called the Fish House, was opened in the London Zoo in 1853. This building resembled an greenhouse and housed a collection of aquaria made from wood and glass which where placed on tables for better viewing.[8]

Other public aquaria quickly followed the Fish House in America and Europe. In 1860 Jardin zoologique at Bois de Boulogne displayed fish in both fresh and salt water aquaria. This was done in a way which is still common for zoo's to use by integrating the aquaria in the wall. In 1869 a large public aquarium of multiple stories was opened in Berlin.

The first aquarium to have a transparent tunnel was built in 1985, Kelly Tarlton's Underwater World in Auckland, New Zealand. To construct the 110 metre long tunnel, slabs of sheet plastic were imported from Germany. These slaps, weighing over a tonne, were shaped on site in an oven. For the first time, this new technique made curved panels of such a large size possible. The panels are cylinders with a diameter of 2,4 metres and a 180 degree angle. A moving walkway guides the visitors slowly trough the tunnel where, for the first time, the general public could gaze around under water.

The construction technique of acrylic glass has improved over the decades and possibilities now include larger and more complex shapes, up to 360 degree transparent tubes and complete transparent rooms.

8 CBC (2014)

Military Submarine Design

The first submarine designs were tools for exploring under water; however, the modern submarine was developed by the military. The first military submarine was the Turtle, built in 1775 to attach explosives to the hulls of British warships in the New York Harbour. The design was a clam like shape which could only accommodate the captain and no passengers. The design focussed the basic requirements; being able to submerge, have enough air, being able to manoeuvre underwater.

The submarine could be submerged by letting water into a tank beneath the captain which could be pumped out with a hand pump to resurface. In case of emergency a load of lead could be released to resurface quickly. The turtle had enough air to stay submerged for about twenty-five minutes and could manoeuvre with a rudder at the back and a paddle propeller blade at the front. While the Turtle only had a speed of 5 km/h and never managed to sink a ship it was the first step towards a military submarine.[9]

The next step was the HL Hunley. This 13 meter long cigar shaped submarine was able to manoeuvre with great accuracy with the use of fins at the side. Modern submarines use these same principle to steer the vessel in a similar way to a plane. The fins can be adjusted to send water flowing over or under them. This creates more pressure on the top or bottom of the fins, sending the submarine up or down.[10]

The HL Hunley was armed with a spare torpedo and became the first submarine to sink a ship in 1864, after which The HL Hunley vanished. The spar torpedo it was armed with is nothing more than an explosive attached to a harpoon. The harpoon is driven into the hull of the enemy ship, after which the attacker distances himself and the explosive is detonated. This required the attacker to get close to the enemy without being spotted and make a safe retreat after ramming the target.[11]

The Germans already started to develop their submarine design, the unterseeboot or U-boot, during the First World War. The design started of as a patrol boat capable of making a naval blockade and cutting of enemy supply lines. With enhanced detection methods of the enemy the desire for a fully submerged boat increased. This explains why the first German U-boot designs resembled a normal naval war ship.

During the Second World War the Germans equipped their submarines, a 77 meter long design named the U-66, with a new weapon: the torpedo. These self propelled explosives were able to hit the target from a far, but the compressed air, which was used as propulsion, left a tell tale of bubbles at the surface. The torpedo could only travel in a straight line, thus the bubbles sent a warning to the enemy giving them time to evade the explosive.[12]

A new propulsion system was invented using an electric battery, but this made the torpedo 7 meters long. The U-66 was 77 meters long to be able to carry 22 torpedoes. The Axis sank 33 ships with their U-66 design. The only flaw in the design was that the U-Boot had to refuel frequently.[13]

With the invention of nuclear power the refuelling problems of the U-boot was solved. Modern nuclear submarines get their air from the water around them by electrolysis. This method requires a lot of energy, something a nuclear submarine has an abundance of. With this method the submarine has an unlimited supply of oxygen. The only reason the submarine has to resurface is to restock on food for the crew.
While the submarine is designed to withstand the pressure of the water it also needs to be able to navigate trough the water both submerged and above water. To withstand the pressure the submarine has

9 *National Geographic (2014)*
10 *National Geographic (2014)*
11 *National Geographic (2014)*
12 *National Geographic (2014)*
13 *National Geographic (2014)*

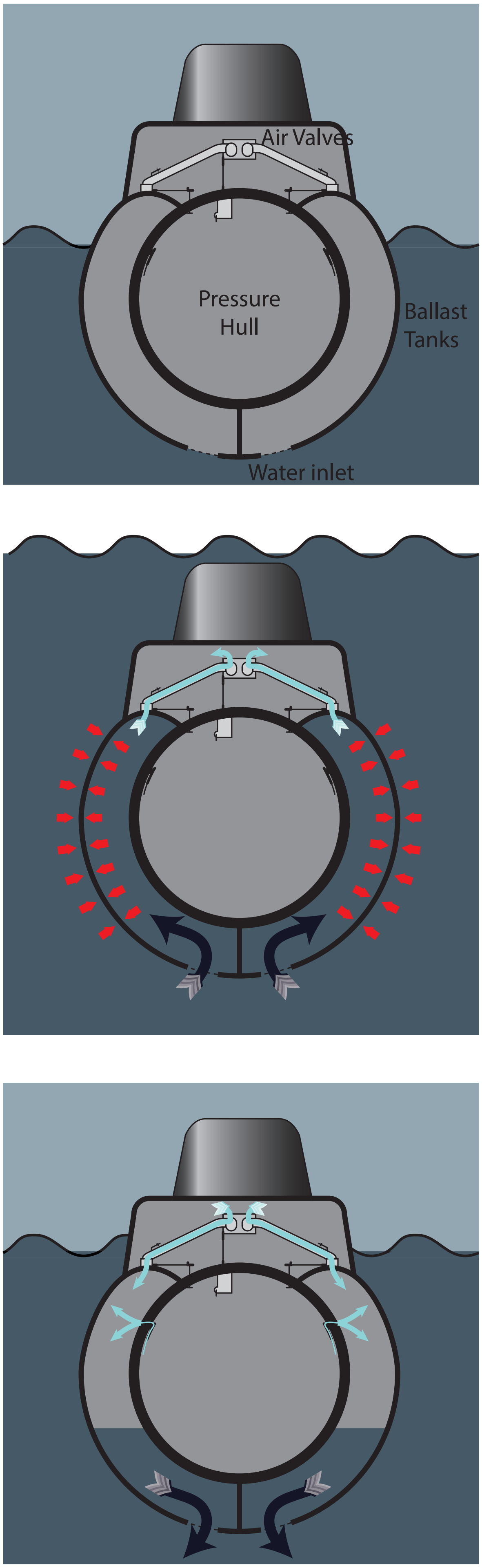

Fig. 10: Submarine submerging principle (own image)

a structure called the pressure hull. The pressure hull is watertight and airtight and contains all spaces and equipment needed by the crew to operate the submarine. The pressure hull is often a long cylinder shape reinforced with steel bands. The pressure hull is divided into different compartments by airtight doors to be able to contain a leak in case of emergency.

Around the pressure hull are the ballast tanks, which can be filled with water to submerge the submarine. The superstructure that surrounds the ballast tanks and pressure hull is not designed to withstand the enormous water pressure, but instead to reduce the amount of drag from the water when the submarine is moving to make it go as fast as possible with as little energy as possible. The superstructure does not have to be as strong as the pressure hull because the ballast tanks, the space between the pressure hull and the superstructure, fill up with seawater when the submarine is submerged. Therefore the pressure at both sides of the superstructure is the same and thus does not create any stresses in the material. When the water is let out again the space is filled with pressurized air to maintain the equal pressure while the submarine ascends to the surface. During the ascend the pressure of the air is adjusted down accordingly.[14]

We have already concluded that the tension in a material increases when the radius of the sphere or cylinder is increased. Because of this reason the pressure hull is kept as small as possible. The smart integration of pressure hull, ballast tanks and superstructure make the submarine such an interesting underwater structure.

Once the basic cigar shape of the submarine was developed it was maintained throughout its development. A nice example is the submarine used by James Cameron. As part of the Deepsea Challenge of the National Geographic the submarine dove to the bottom of the Mariana Trench in 2012. This submarine uses the hydrodynamic

14 *National Geographic (2014)*

cigar shape to make a vertical dive instead of the mostly horizontal movement required by the military.

Fig. 12: Deepsea Challenge Submarine

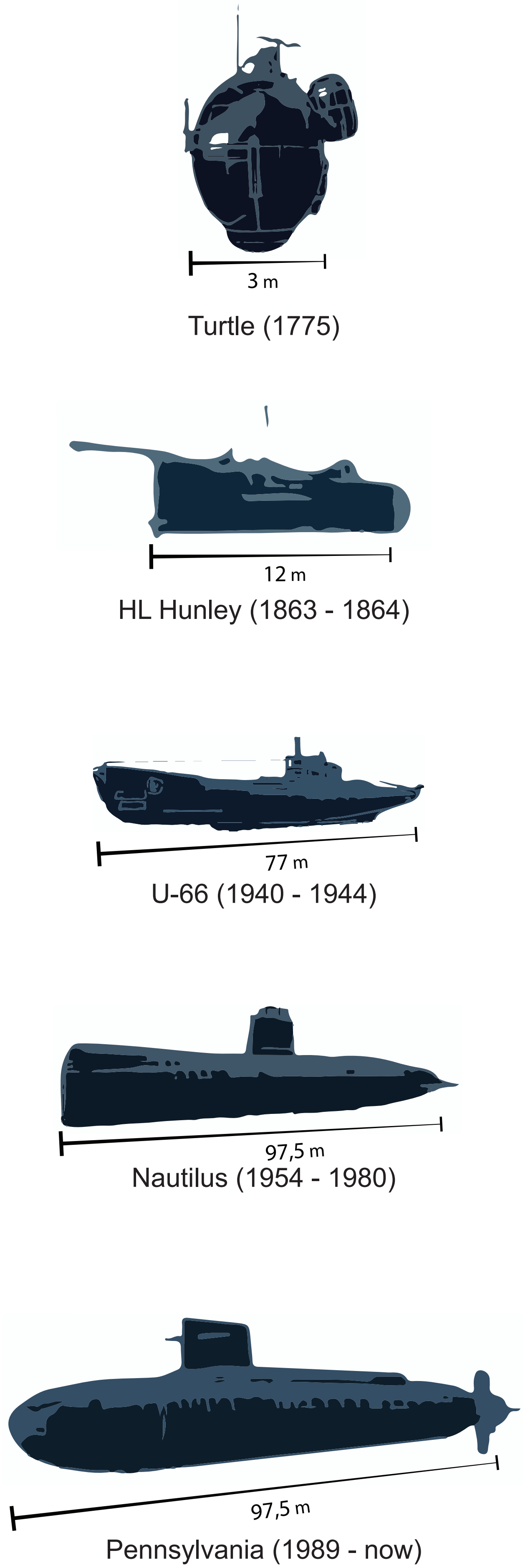

Fig. 11: Submarine Development Timeline (own image)

Immersed Tunnels

Civil engineering has developed multiple ways of crossing water with infrastructure. The most common being bridges, the other being tunnels either drilled or immersed. While immersed tunnels are relatively young, since the first one was built in 1893, the techniques behind immersed tunnels stem from many different established disciplines.

An immersed tunnel relies on water for the transport and placement of its segments. A trench is dredged at the bottom of the waterway. The segments, usually between 100 to 200 meter long, are lowered into the trench and joined. The trench is backfilled and the finishes in the tunnel are completed. This is a general description of how an immersed tunnel is constructed, but each project has its own problems and solutions.[15]

In order for the tunnel segments to be placed, they need to be able to perform the same actions as a submarine: they need to manoeuvre over water to a certain location and then dive to a precise depth. Of course the segments do not have to propel themselves and once they are at the right location they stay their during their entire lifespan.

In 1810 experiments with immersed tunnels were conducted by Charles Wyatt for a tunnel under the Thames in London. Wyatts trials used 7 meter long brick cylinders with an inside diameter of 2,75 meter. While technically feasible, the trials were abandoned in 1811, when it became clear that joining the brick cylinders with puddled clay was too problematic.[16]

After the experiments in 1811 many other plans were made, mostly in England and the United States, to construct an immersed tunnel. None would be realised until the completion of a sewer line in 1883, beneath a sixty meter wide tidal sea inlet called Shirley Gut in the United States. The tunnel

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15 Lunniss, R. & Baber, J. (2013) p.01
16 Lunniss, R. & Baber, J. (2013) p.06

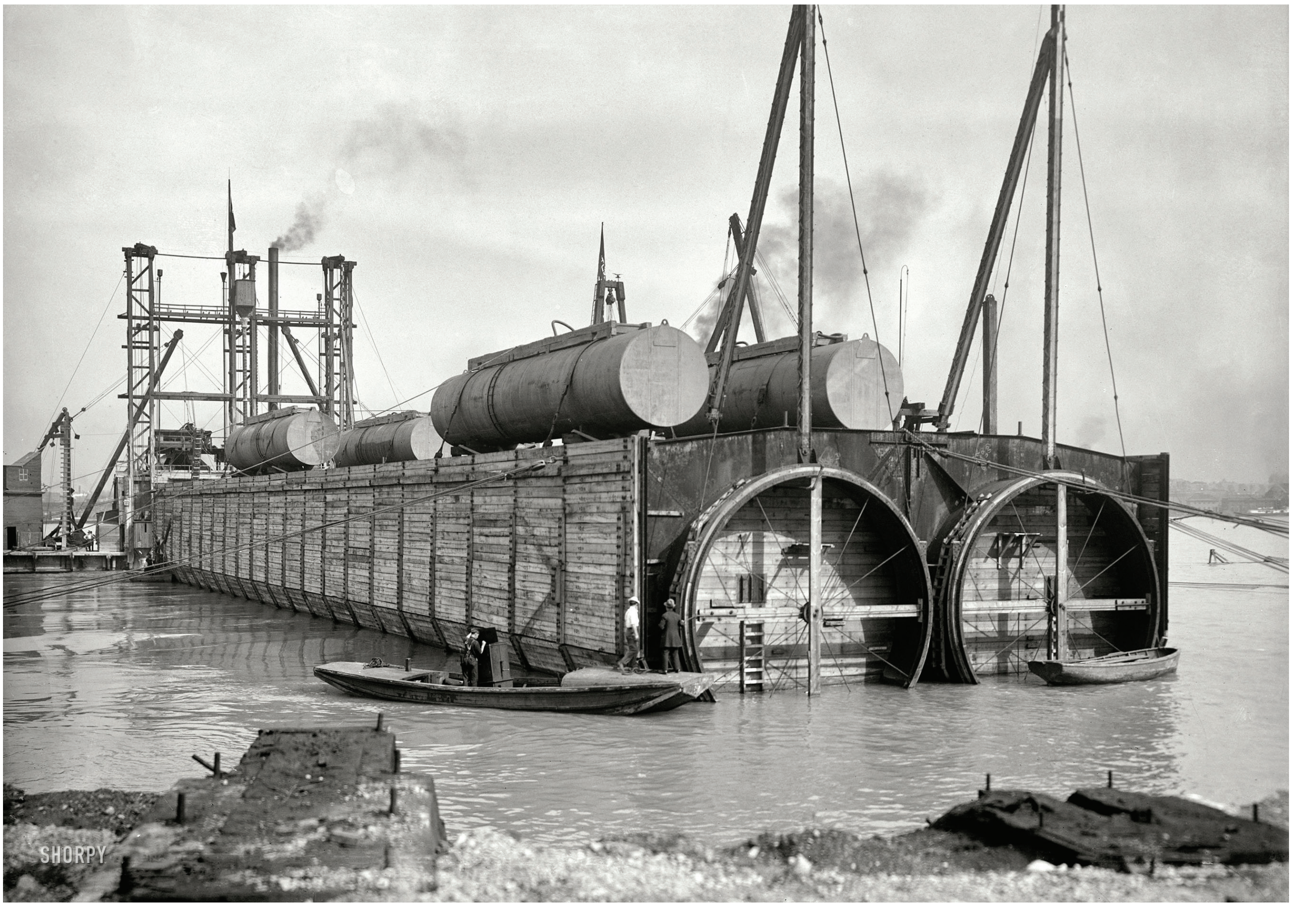

Fig. 13: Section of the Detroit River tunnel in 1910

elements were made of brick and concrete and joined at the outside with steel flanges. With the same technique other sewage projects in France and Denmark followed quickly and paved the way for the first transportation tunnel in 1910 called the Detroit River Tunnel.[17]

This railway tunnel utilized the expertise from the shipbuilding industry in Detroit. Eighty metre long tubes were prefabricated in pairs out of 9,5 millimetre thick steel plates. Ten pairs were lowered into the trench, each pair was surrounded by a U-shaped box which was filled with concrete as ballast. Underwater concrete was still in its early stages so it took several tries to get the mixture right. Divers guided the concrete pouring process and joined the elements with steel flanges, made watertight with rubber gaskets.[18]

Two types of steel shell tunnels sprouted from the Detroit River Tunnel: the single and double variant. The Detroit River Tunnel mostly resembles the double steel shell, with the only difference being the U-shaped box. The simple U-shape developed into a hexagonal and steel plates were used instead of wood. The single steel shell tunnel does not use concrete as ballast, but has a box on top of the tunnel which is filled with stone. Because the steel shell is not surrounded by concrete, the single variation needs an alternative as corrosion protection.

Because of the relative light weight, the elements have a shallow draught of sixty millimetres. This allows them to be transported over almost any waterway and theoretically over any distance.[19]

In 1942 the first large scale transport tunnel outside of the United States was completed, the Maastunnel in the Netherlands. Because of relatively lower steel prices in the United States than in Europe the Dutch evolved the steel shell tunnel into one made out of reinforced concrete. Danish contractor Christiani & Nielsen developed

17 Lunniss, R. & Baber, J. (2013) p.08
18 Lunniss, R. & Baber, J. (2013) p.10
19 Lunniss, R. & Baber, J. (2013) p.13

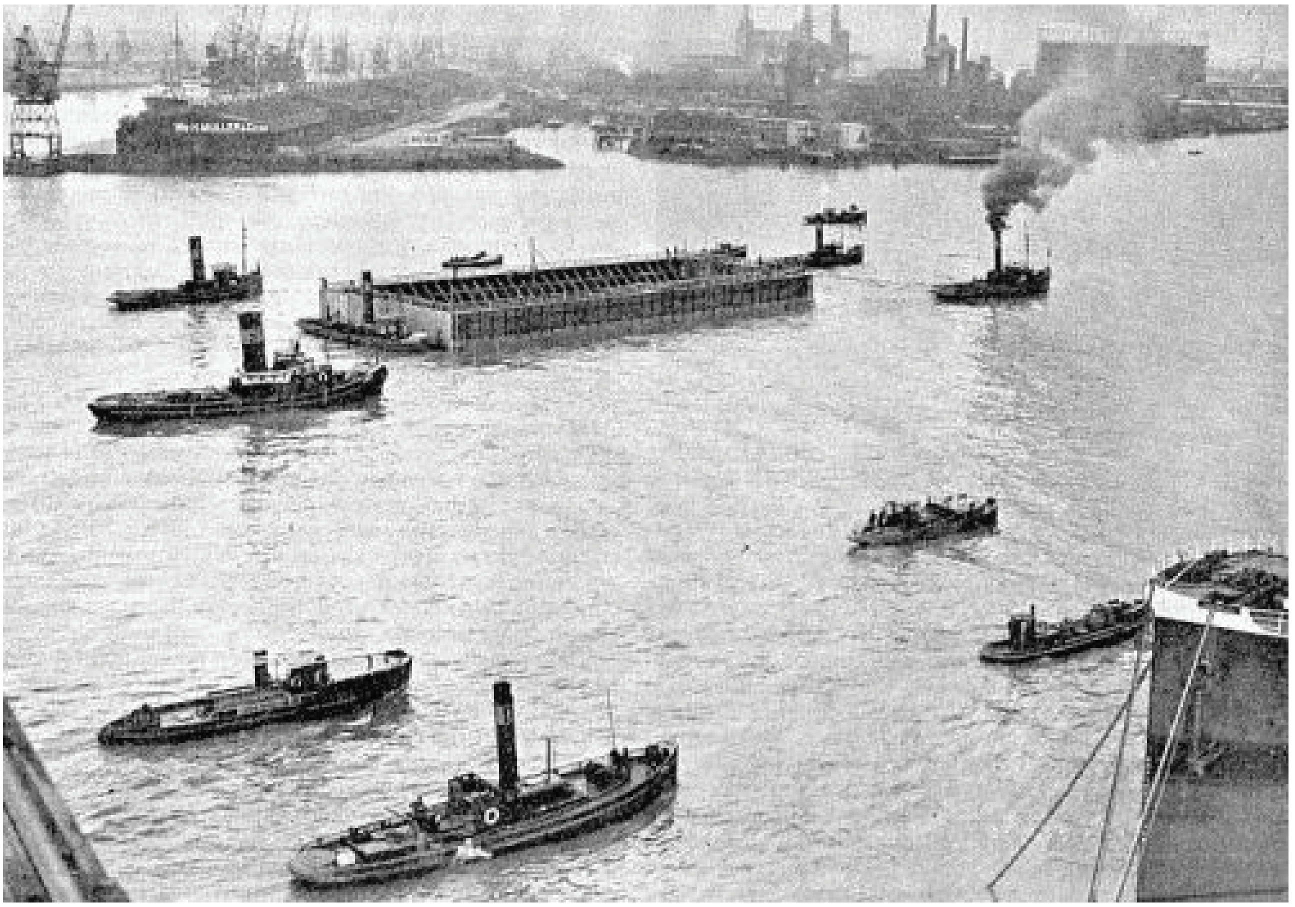

Fig. 14: Maastunnel 1941 construction

a new foundation method by injecting sand beneath a tunnel element. An external rig moved along the tunnel and jetted the sand beneath the tunnel element. Because this method was far more precise it made it possible for the tunnel to have a flat bottom. Discrepancies in the height of the gravel foundation layer made this previously impossible because of the stresses it would cause in the concrete floor.[20]

Until now, the cross section of the immersed tunnels had always been a circle or else an approximation of a circle like the hexagon. Because the Dutch waterways are not very deep, the roof of the tunnel could also be flat. All these factors together meant the tunnel could have a rectangular shape. This shape was also more preferable because it matched the requirements of the traffic road in the tunnel.

The reinforced concrete immersed tunnel became the favoured option for tunnel construction in Europe. The technique was developed and improved over time. The new foundation method was improved by jetting the sand trough ports in the floor of the concrete segment. By removing the rig that jetted the sand under the tunnel and moved along the outside of the tunnel the waterway was no longer obstructed during construction.

The next improvement came by dividing the tunnel element, which can be 100 to 200 metres long, into segments. The first reinforced concrete tunnels needed an external waterproofing membrane to prevent water from leaking in trough thermal shrinkage cracks. These cracks arose because the large elements were cast in one go, and run across the entire depth of the wall. By dividing the elements into segments of 25 metres the cracking due to thermal shrinkage can be controlled and prevented. While extra effort is put into making and placing of the concrete a waterproofing membrane can be omitted, saving a lot of money. This technique was fully adopted in the Netherlands during the eighties and is still used for a lot of tunnel projects.[21]

20 *Lunniss, R. & Baber, J. (2013) p.16*

21 *Lunniss, R. & Baber, J. (2013) p.18*

Conclusion & Reflection

Conclusion

The aim of this research report was to answer the research question; *What factors determine the shape of an underwater structure?* As could be expected at the start of this report the answer is very versatile. First was concluded that the water pressure is the primal factor in determining the shape of an underwater structure. Only taking into account this factor, every underwater structure would have a sphere shape, but this sphere shape is often overturned by a combination of other factors.

To identify these factors three materials often used for underwater structures; steel, concrete and glass/acrylic glass were analysed. The fabrication processes, construction methods and material properties all influence the design possibilities of each material. While theoretically each material can take any shape, some shapes proved easier to construct and thus are cheaper.

The analysis of the development over time of the design of aquarium tunnels, military submarines and immersed tunnels uncovered more factors that influence the shape of the design. Aquariums developed alongside the invention of new materials and techniques to use these materials. From early stone basins to complex shaped acrylic tunnels the aquarium shape became more complex because new materials and techniques allowed it.

The military realised the potential of the submarine for warfare early on. The development of the submarine was realised in steps with each step solving the next problem. The first was to be able to breath and have basic movements under water. This design closely resembled a sphere, the Turtle. After this first design, new factors start to morph the sphere into a long cigar body. A new design, the HL Hunley, needed to be faster and manoeuvre precisely. Fins, rudders and ballast tanks made this possible.

The basic cigar shape of the submarine could be optimized with hydrodynamics because of the smart combination between the pressure hull and the ballast tanks. Diesel engines, electro motors and nuclear reactors made the submarine more powerful, but basic cigar shape is maintained through all the advances made in power technology.

Immersed tunnels started out with a cylinder shape. This shape made sense as it is the ideal shape for a tunnel to withstand the water pressure and it was used to transport sewage water. Because a rectangular shape is more efficient fro most transportation tunnels a compromise was made and the shape became hexagonal. The first rectangular tunnel was made possible because of a combination of factors. Technique improved with a new foundation method, the context of the Netherlands with its shallow waterways and the cheaper price of concrete in the European economy.

Personal Reflection

For this research report I had to dive into a lot of different disciplines. It was very interesting to dissect each design to find out how they work. The most interesting design was the submarine because I can use a lot of its principles in the rest of the graduation track. Studying and understanding the physics of water pressure was also very interesting. During the design process for an architectural assignment you naturally apply the basic laws of physics such as gravity. It is your job as an architect to find a way to deal with these laws. These laws work slightly different under water and it was fun to return to these roots of physics to understand their basic principle.

The research was limited to only a few materials and industries. To expand on the research other industries and materials could be investigated as well as marine life. I think especially marine life could inspire a new approach to design underwater structures. Less than two centuries ago, society could not believe anything could live in the dark depth of the ocean that could resist the immense water pressure. Therefore I think there is still a lot to learn from these creatures from the deep.

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Figures