SELECTION CRITERIA FOR LARGE CAISSONS

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Abstract:

Caissons are necessary for the construction of structures in complicated deep foundation conditions. Construction of caissons involves unique construction methods due to various characteristics like cost, constructability, resources and time. This paper covers different methods of construction of caissons and provides a comparative analysis to show when to use every method of construction according to the conditions available. Two projects in which caissons were constructed with different sizes, from two different construction eras and project conditions were studied and examined against the developed selection criteria in order to evaluate the validity of the applied construction methods in each case.

Keywords: Caissons; Construction Engineering; Deep Foundations.

1 INTRODUCTION.

Deep foundations are used when there is a massive load coming from the building and the nearby soil is not strong enough to carry the load of the building. In such a case deep foundations will transfer the loads to deeper soils either using piles or caissons. The word caisson is originally French as it roots to the word "caissee" which means a chest or case. A caisson is used as a retaining watertight space which keeps out water, and it can be used in permanent purposes. Its main use is when a high ground water table is encountered and dewatering become costly and also when shoring is very difficult to be done or when the construction area is confined and the water is present. Also, caissons can be considered as a second deep foundation alternative instead of having a large number of piles due to heavy loads (Murthy, 2007) (Isaacson, 2001).

Caissons vary in size, smaller caissons are either socketed, suction or bell shaped. The bell-shaped type (which is the most ancient) is constructed by drilling or hand-digging using large auger drills. This type is mainly used in cases of cohesive soils where the soil can maintain the bell shape until the concrete is poured. Hand excavation is used only when the soil is too full of boulders for the drill. A temporary steel casing is usually lowered. A bell is created at the bottom of the shaft by hand excavation or a special belling bucket. On the other hand, the socketed and suction types are simply composed of hollow steel cylinders gradually immersed in the soil till reaching the supporting strata and imbedding into it for at least 2 m. In case of groundwater, the steel casing can prevent flooding during construction, but if water is able

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to penetrate from below, caisson construction may not be practical (Murthy, 2007). Accordingly, and as these smaller caissons (whether socketed, suction or bell-shaped) are limited in size when compared to the larger caissons they are not considered within the scope of this paper.

Caissons have been used since the era of the Roman Empire, in 250 years BC, in Alexandria; they have been used in constructing quarry walls. However, the modern shape and size of caissons started to emerge in the nineteenth century. In the twentieth century, it started to be used in different applications including (but not limited to), bridges, ports and harbors. Standard caissons were used for upgrading of old quarries. This is applied by installing them on the top of old piles. Afterwards reinforced concrete caissons were used as a permanent structure element by placing them directly on the sand bed. Caissons were used in the Second World War during the Allied invasion of Normandy, France. They were appropriate solution for the rapid assemblage of break waters as a part of temporary harbors (Gerwick, 2007).

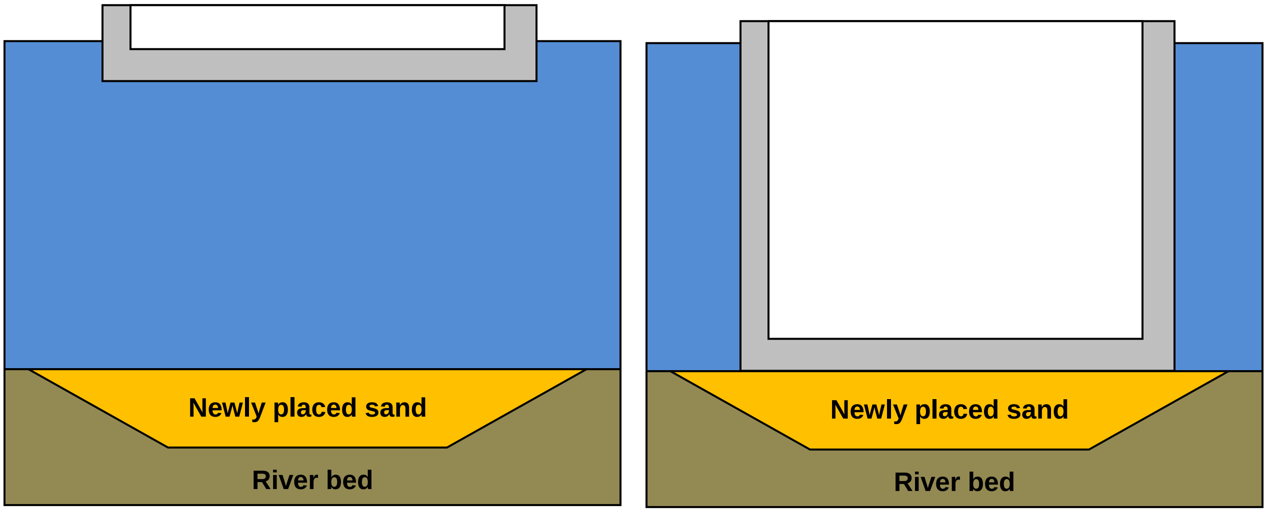
Caissons vary also in material type. The ancient Greek/Roman caissons were mainly made of rocks and/or blocks while the first caisson used to construct a bridge pier in North America in the second half of the nineteenth century was actually made out of timber (Prentzas, 2009). Modernly steel is typically used for socketed caissons while concrete is the most common material in modern caisson construction (Murthy, 2007). However, from a construction method perspective, the large sized caissons that could be used in land (in special cases) or under water are classified into opened caissons, boxed caissons and pneumatic caissons. Each of these three types will be discussed within the next section of this paper and the selection criteria governing the choice of each of them.

2 CONSTRUCTION METHODS.

2.1 Box Caissons

These caissons are opened from one side only as they are opened at the top and closed at the bottom. Usually constructed on land and so it is considered as a prefabricated concrete box. After that, they are floated to the required position as shown in Figure 1a. Then the caisson is lowered down by adding weights to it by either using slipform or climbing form technique to pour the upper segments of the concrete caisson hence adding weight to it and causing it to gradually sink down or by adding prefabricated concrete segments and connecting each segment to the segment beneath using wet joint connections and hence the caisson will gradually sink down, however the cast in place technology is more common because having joints is not preferred in the middle of a sea or a river. As the cross-section of most of caissons doesn’t significantly vary with the depth and due to the repetitive nature of the work, and because caissons are mostly constructed in batches, the concreting process is most commonly performed using the slipform construction technique. Generally, the concreting and slipforming process comprises three phases, the first is the assembling of slipforms, then the slipforming activity itself (involving pouring concrete followed by the form slipping upwards using a system of hydraulic jacks), and last is the slipform dismantling phase (Peurifoy & Oberlender, 2011). However, the slipforming activity could be changed in a more complex way if the floating dock cannot support the construction of the whole caisson in one stage due to limitations on its bearing capacity. This condition is frequently encountered in real-life construction projects because the existing floating dry docks in a given time period may not match the demands of the caissons’ design characteristics. Hence, and in most of cases, slipforming is conducted in two stages. The first stage takes place in the floating dock where concreting takes place and is terminated when slipforming is stopped after reaching at a certain height, which is specified so as not to exceed the dock’s bearing capacity. Then the caisson is floated to position where concreting begins again, and slipforming of the floating caisson continues while the caisson is sinking in position until reaching the sand layer it will rest on (Panas & Pantouvakis, 2014). However, if the depth is not significantly large the caisson could be floated in as one prefabricated box and then filled with concrete or sand, and immersed deep onto a previously prepared layer of soil, with its upper edge above water level as shown in Figure 1b.

This type of caissons serves as a suitable shell for a pier, or similar work. They remain permanently in place on the sea bottom. As this type of caissons is permanent and directly supported on the sea bed, it is not preferable for sites where high water currents can erode the foundation, it is only suitable when it can be set upon a soil having a sufficient bearing capacity. Because of that, in some cases in which the first 1 – 3 m of the sea bed have a low bearing capacity, this layer of weak soil is dredged (using dredgers or clamshells) and replaced by stronger soil on which the box caisson will rest. This bed preparation process is really sensitive as the preparation method can influence the behavior significantly as different methods (involving also different aggregate gradations) may produce the same vertical stress but different lateral stress levels in the sand (Leung, Lee, & Khoo, 1997). The other limitation of this technique is that because it is closed from the bottom it couldn't be used in cases in which the construction location itself is in the land as it couldn't cut through the soil like the opened caissons that could do so as described in the following subsection (Murthy, 2007) (Gerwick, 2007).



a. The floated box caisson before sinking.
b. The box caisson after sinking.

Figure 1: Locating and fully constructing a box caisson.

2.2 Opened Caissons

The open caisson is a reinforced concrete structure, having dimensions corresponding to the needed foundation area. As it is clear from the name, unlike the box caissons, these caissons are opened from both ends; from the top and the bottom. They have the ability to sink through soft material during excavation inside the caisson. This is because they are fitted with a cutting bottom edge usually strengthened with steel. This is why, unlike the box caissons, these caissons could be used for construction of foundations on the land or in the waters (Nonveiller, 1987) (Abdrabbo & Gaaver, 2012).
The first stage of the caisson walls is cast on the ground, if the location of the future foundation is in the sea/river as this first section is prefabricated on the land and then transported using barges to the location however if the foundation is in the middle of the land, then this first section is constructed at the same location as the future foundation. After curing, soil excavation begins inside the caisson until a state of plastic equilibrium is reached along the whole length of the cutting edge, and the first phase of the caisson is progressively sunk into the ground (Abdrabbo & Gaaver, 2012) (Nonveiller, 1987). This excavation phase should be done in a pattern that is constant all over the perimeter of the caisson as if one side of the caisson had more soil excavated near to it than the opposite side the caisson may tilt and solving such a problem could be really time-consuming and cost-consuming (Abdrabbo & Gaaver, 2012). In order to do that, an even number of radial trenches, always in opposite pairs, are successively excavated to the cutting edge. These trenches are widened (again in opposite pairs) as shown in the plan view and section shown in Figure 2. While each phase of excavation brings the caisson down by 0.5 – 1 m, a succeeding phase of the concrete wall is cast on the upper part of the sinking walls, and the process continues until the cutting edge penetrates the bearing layer to the targeted depth (Nonveiller, 1987). Again, this concrete pouring phase should be done in a rate that is constant all over the perimeter of the caisson as if one side of the caisson had more concrete poured above it than the opposite side, the caisson may tilt and solving such a problem could be really time-consuming and cost-consuming. Due to that, the use of slipforms in this application is recommended as on using these forms, the concrete will be poured at a constant rate and the probability of tilting due to difference in weight along the perimeter will

be very low (Panas & Pantouvakis, 2014) (Nonveiller, 1987). The caisson will go down into the soil as the soil inside is dug and as new parts add to the load until the desired depth is reached. When it reaches the required depth concrete is placed using tremie tubes through water to make a bottom sealing by applying a floor, usually of tremie concrete, that fulfills this purpose (Basha, Gab-Allah, & Amer, 1995). After that, water is pumped out after the hardening of the concrete. Finally, and depending on the design requirements, the caisson is partially or entirely filled with concrete (Nonveiller, 1987).

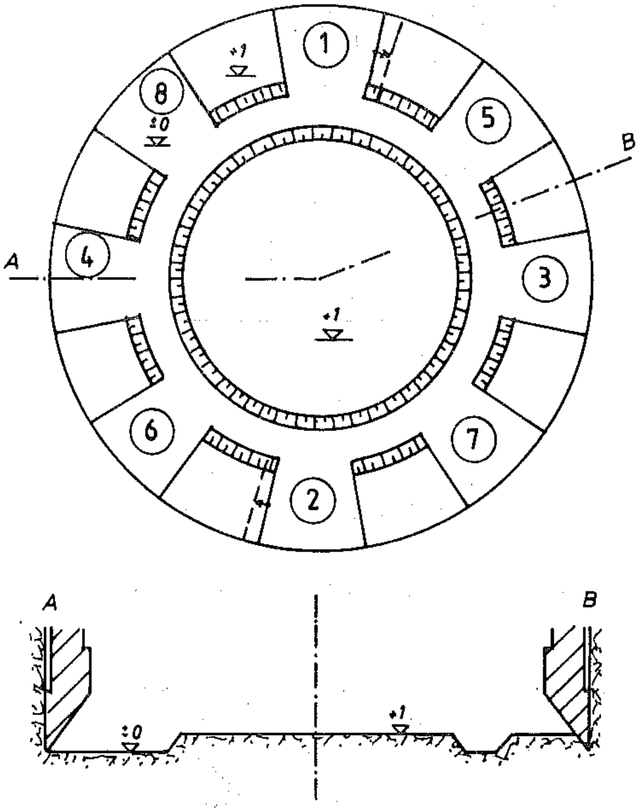


Figure 2: The process of gradual simultaneous excavation (Nonveiller, 1987).

This method is less risky than the box caisson in terms of not having to depend on replacing the first layer of the sea bed and depend on its bearing capacity and the bearing capacity of the soil beneath. However, the fact that the sequence of construction could carry high probabilities of tilting the opened caisson due to any mismanagement during excavation or wall concreting introduces another source of risk present when using this method and not present when using the box caisson method (Basha, Gab-Allah, & Amer, 1995) (Abdrabbo & Gaaver, 2012). However, the major advantage of this method is that it could be used in the middle of the water or on the land which makes it more flexible in application than the box caisson method. Finally, the fact that the cutting shoe is the main contact between the soil and the structure makes it a very sensitive component as it could be subject to structural failure in case of cutting into firm soils, hence it should be structurally and geotechnically analyzed and designed taking the soil properties into account (Nonveiller, 1987) (Abdrabbo & Gaaver, 2012).

2.3 Pneumatic Caissons

This type of caissons is similar to the open caissons except that they are provided with airtight bulkheads above the cutting edge. The space between the bulkhead and cutting edge, called the working chamber, is under pressure to the extent necessary to control the inflow of soil and water. Thus, the excavation can be performed by workmen operating in the working chamber at the bottom of the caisson (Murthy, 2007). The first pneumatic caisson was constructed to construct the Pedee Bridge pier in 1852 however the most famous of the earlier pneumatic caissons were the two caissons constructed to support the Brooklyn Bridge in New York few years after (Isaacson, 2001).

This type of caissons is placed directly on the surface (whether dry land or sea bed) and the excavation workspace a pressurized air-tight chamber as shown in Figure 3. The caisson goes downward as the excavation is performed within the workspace including the areas beneath the caisson walls. Due to that gradual increase in depth, the hydrostatic pressure outside the bottom of the caisson gradually increases. Hence, the chamber pressures are gradually increased as the caisson goes down in order to exceed (or at least match) the outside hydrostatic pressure outside the caisson. In order to maintain a constant high pressure within the chamber, workers and materials are moved in and out of the chamber through air locks as shown in Figure 3. As the excavation proceeds, the caisson walls slip against the excavation sides. Once the final grade of excavation is achieved, all or part of the chamber is filled with concrete, the structural design and the chamber dimensions shall determine whether this concrete should fill all or part of the chamber (Isaacson, 2001).

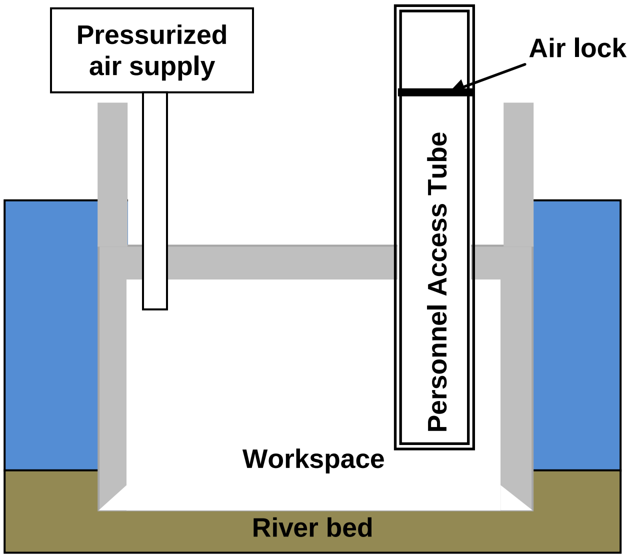


Figure 3: Schematic of a pneumatic caisson.

The major advantage of this technology is that all of the excavation work is done in the dry which gives a higher level of control on the quality of the work and the preparation of the foundation than the other types discussed previously. This in-the-dry working environment also facilitates the placement of the concrete seal after the excavation to be placed in a dry environment producing concrete of much higher quality than tremie concreting under water. Even the risk of facing dilemmas due to unexpected soils like boulders is reduced as it is much easier to remove such boulders in-the-dry than in wet conditions (Gerwick, 2007) (Isaacson, 2001). However, all of that is on the account of cost which is significantly high due to the high mechanization of the technique and the high level of skill and fitness required by workers working in the highly pressurized chamber which will reflect in high wages. Another limitation arises in the penetration depth which is limited by American laws to approximately 35 m below the water surface due to the fact that higher pressures below such depth are higher than what the human body could endure (Murthy, 2007). However, this issue has been subject to extensive research in order to develop technologies enabling automatic removal of excavated materials in the pneumatic caisson method with minimum human interference hence enabling deeper excavations, however due to its automation, the size of this application is still limited to few projects in Japan (Kodaki, Nakano, & Maeda, 1997) (Gerwick, 2007).

3 CONSTRUCTION METHODS SELECTION CRITERIA.

Based on the discussion of the different caisson construction methods presented in the previous section, a selection criteria could be developed to aid the decision making process concerning the caisson construction methods. The time frame, resources (especially labor or equipment), cost, level of risk, attainable depth, constructability, quality and soil type are the main factors governing the method choice.

From a project schedule perspective, due to its in-the-dry excavation, the pneumatic type is the fastest (especially if the excavation is automated) followed by the box caisson (its speed is also a function of its size and the amount of soil replacement) while the opened type is the slowest. However, this speed could be on the account of something else as the level of worker safety is lowest in the pneumatic type. The non-conventionality of the pneumatic caissons is also attributed to the non-conventionality of the equipment associated with this method in comparison with the relatively conventional equipment utilized in the other two methods. Hence, for most of cases, due to this capital intensiveness of pneumatic caissons, it is the most expensive type. Finally, the effect of the soil type comes into the picture due to its bearing capacity, stiffness and the load transfer mechanism associated with the caisson type as due to the fact that boxed caissons are directly supported on the soils, they need to rest on strong/stiff soil to carry the load. On the other hand, the situation is different for the opened type that depends mainly on the excavation and the increase in load to sink with the cutting edge directly cutting through the soil which makes its optimum performance (with least risk of cutting edge failure) is within cohesionless soils as there is a high risk of the cutting edge failure if it cuts in hard/stiff cohesive soils. On the other hand, the pneumatic type has a high flexibility from that perspective due to the dryness of its working chamber that enables the removal of any undesired layers of soil or even boulders in a much easier manner than in the case of opened caissons. A summary of the selection criteria could be found in Table 1.

Table 1: Selection criteria for caisson construction methods.

	Boxed	Opened	Pneumatic
Suitable Location	Only in the waters	In land or in water	In land or in water
Load Transfer Mechanism	Only end bearing	Skin friction and/or end bearing	Skin friction and/or end bearing
Suitable Soil Type	Dense soils	Sandy soils	Suitable for most soils
Cost	Medium	Lowest	Highest
Level of Mechanization	Moderately mechanized	Moderately mechanized	Highly mechanized
Needed Labor	Semi-skilled	Semi-skilled	Highly skilled and highly fit
Constructability	Easiest	Moderate	Demanding
Construction Speed	Medium	Slowest	Fastest
Attainable Depth	Lowest	Largest	Up to 35 m
Construction Risk	Medium	Highest	Lowest
Quality	Low – medium	Low – medium	Highest
Safety	Safest	Less safe	Hazardous

4 CASE STUDIES.

4.1 The Brooklyn Bridge Caisson, NY, USA

The construction of a bridge connecting Brooklyn and Manhattan so as to provide a more time and cost effective route rather than the ferry service aroused in the seventh decade of the nineteenth century. The Brooklyn Bridge became the first bridge incorporating suspension cables in its structural system. In 1869 the design of the bridge was accepted and construction of the bridge started in 1870. At that time, there were various challenges during construction as this bridge was the first of its kind, and the first to utilize huge pneumatic caissons (each weighing 3000 tons) were used to construct the foundations for the towers. Funded by the New York Bridge Company, Brooklyn Bridge was finished and opened in 1883 (McCullough, 1972) (Prentzas, 2009).

4.1.1 Applied Method

Two wooden yellow pine caissons where constructed within this project. The caisson near the New York side was 172 ft x 102 ft (52.4 m x 31 m) in cross section with a height of 14.5 ft (4.41 m) when launched and a height of 31.5 ft (9.6 m) on completion while the caisson on the Brooklyn side was 168 ft x 102 ft

(51.2 m x 31 m) in cross section with a height of 14.5 ft (4.41 m) when launched and a height of 21.5 ft (6.55 m) on completion. This difference in depth due to the variation in the soil profile caused the New York caisson to be more difficult to construct (McCullough, 1972). Figure 4 shows a vertical section in the New York caisson showing the two entrance shafts and the two water shafts and the working chamber at the bottom of the caisson where the excavation took place.

When these caissons were constructed in the shipyard, the upper ceiling of the chamber (the bottom of the caisson) was closed hence it had a boxed shape. Then the caissons where shipped to the site and lowered down the river by putting stones on top of them. After that, compressed air was pumped into the caissons allowing water to escape outside. Then workers started excavating the bedrock. As it was really difficult to guarantee water tightness by the technologies available at that era, water used to leak in the chamber during the excavation and pumps where pumping out any water reached during the excavation and transferring them out of the caisson through the water shafts shown in Figure 4. Due to the lack of suitable excavation equipment in that century, the excavation was performed manually and hence, extensive labor power was needed throughout the construction of Brooklyn Bridge (McCullough, 1972) (Prentzas, 2009). There was a total of 264 laborers in a crew in each caisson working underground (referred to as sandhogs), in addition to 100 laborers working above the ground. Working hours were three 8-hour shifts for six days per week. The site and working conditions were very harsh; it was reported that an average of 100 laborer per week leaving the site due to the unsafe and unhygienic working conditions. The use of candles, explosives within a pressurized air environment created frequent risk of fire and explosions in addition to the first records of the "Caisson disease" (Prentzas, 2009). This newly discovered disease had some symptoms like giddiness, ear pains and sometimes breaking of ear drums and/or bursting of blood vessels in the nose or ears of workers which could escalate to severe joint pains which can lead to bending.

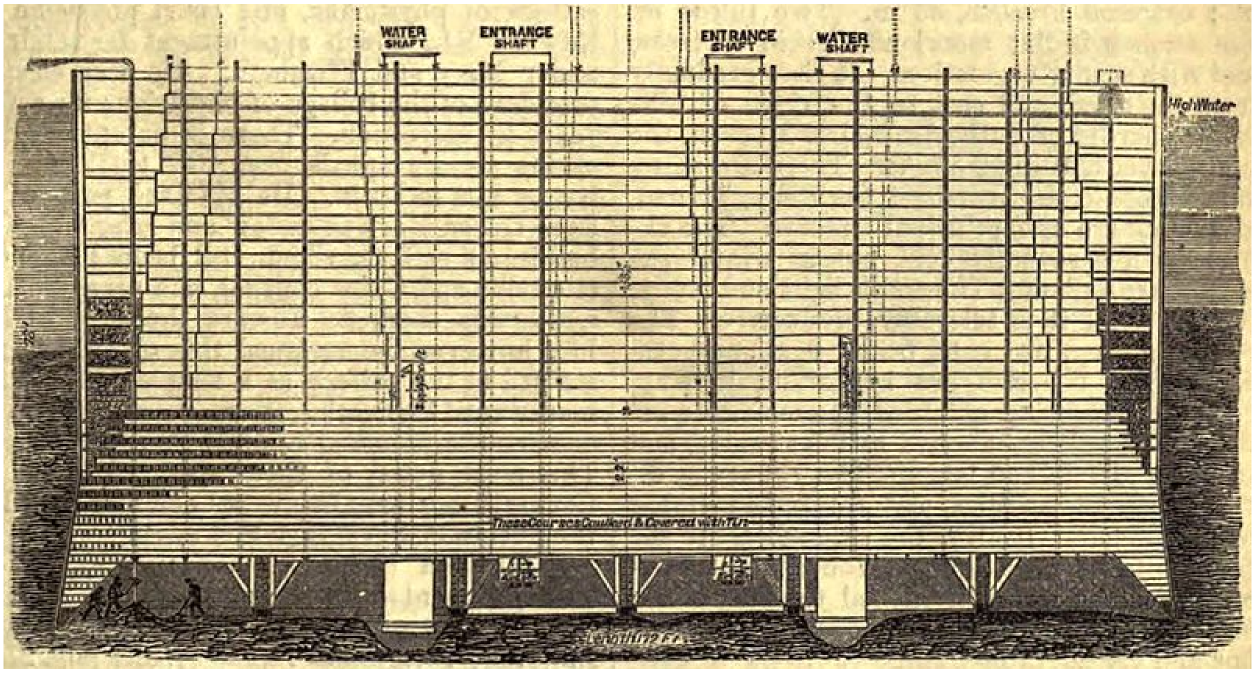


Figure 4: The New York caisson of the Brooklyn bridge foundation. (Wikimedia, 2014)

4.1.2 Construction Method Evaluation

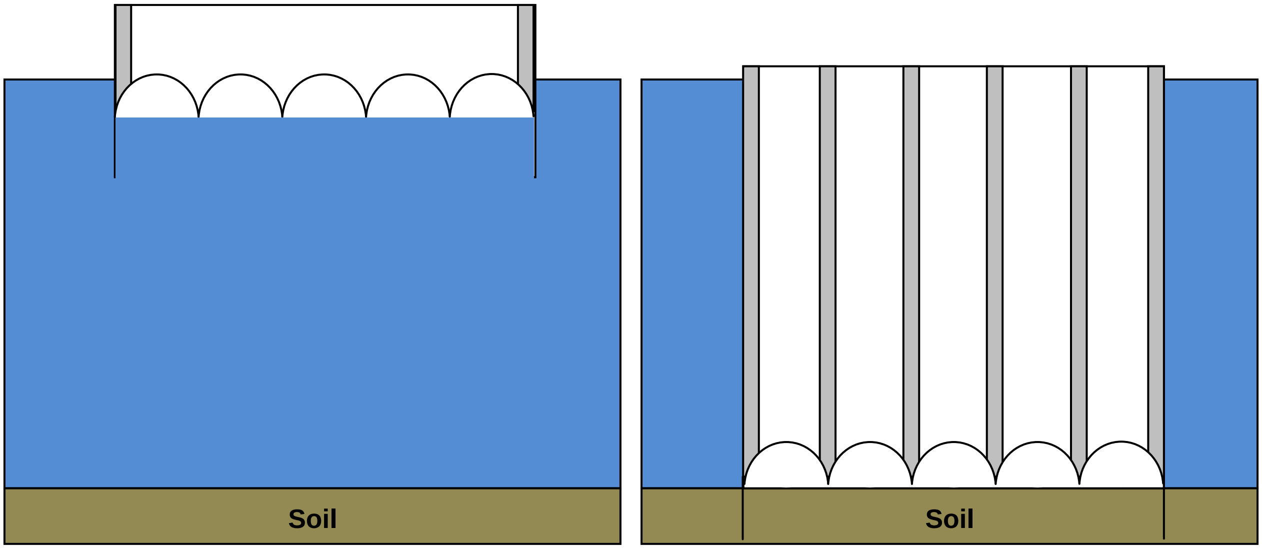
Concerning the engineer decision of using a pneumatic caisson in this project, it was a daring decision but a correct one. On referring to the selection criteria developed in section 3, using an opened caisson in such a project would have carried high risks of the cutting edge destruction during the process of cutting into the soil as it contained significant amount of boulders that could have broken the cutting edge and stopped the construction from its early stages. On the other hand, the use of a box caisson in such a case was nearly impossible by that era as it involves replacing the first layer of organic soil in the river bed by a layer of sand and the suitable dredgers or clamshells that could do such a job weren't readily available by that time. Hence, using box caissons instead of the pneumatic ones wasn't an option by that time. However, and due to the difference in technologies and know-how between the era of that first generation of pneumatic caissons and nowadays, if this project was done nowadays it would have been done with lower risks, higher safety standards, higher quality standards and higher level of mechanization which would have lead to less human losses and a faster construction process.

4.2 New Tacoma Narrows Bridge, Tacoma, USA

This project was initiated to make another bridge parallel to the old one that was initially built in the 1950s to satisfy more purposes for transportation crossing the Tacoma Narrows near Seattle. The new bridge has four 3.3 m wide lanes of eastbound traffic going towards Tacoma. The bridge has a 3 m right shoulder and a 3 m barrier-separated bicycle/pedestrian lane. The New Narrows Bridge opened to traffic on July 16, 2007, which was surprisingly ahead of schedule by four weeks and also under the previously estimated budget at the beginning of the project. The caissons in this project are ones of the largest caissons ever built in the world. They are equivalent to a 20-story building underwater that is carrying the 155 m high towers. The construction was performed under extreme environmental conditions as the water depth ranged between 39 m and 45 m, currents up to 7 knots, 50 ^{o}F waters and 50-mph winds (Krishna, Chakrabarti, Chakrabati, Mukkamala, & Anavekar, 2004).

4.2.1 Applied Method

Each of the two bridge pier caissons was about 24.4 m wide and 39.6 m long in plan. The bridge caissons were cast in vertical layers starting with a 5.5 m deep cutting edge, followed by a 3.7 m deep layer of reinforced concrete (with 16.7 m high exterior steel skin) and then followed by several more layers of reinforced concrete each of which was 3 m deep. The cutting edge at the bottom was used to facilitate initial penetration of the caisson once touchdown occurred. At the top of the cutting edge section, 5 transverse inverted steel half cylinders were welded to the cutting edge as shown in Figure 5. The bottom of the caisson was sealed by these five inverted half-cylinders (called domes) creating a false bottom running in the transverse direction. These cylinders trapped air underneath, which could be controlled to guarantee caisson stability. The caissons were towed to the site from the harbor after the assembly of the steel cutting edge, and casting of the first full lift, and the second and third exterior lifts. After that the transportation process took place in which the caisson was towed to the site (Chakrabarti, Chakrabarti, & Krishna, 2006).



a. A schematic section (not to scale) within the caisson before sinking.

b. A schematic section (not to scale) within the caisson just after sinking (before cap construction).

Figure 5: The sinking process of the caisson.

Once the caisson is held in place using barges with the aid of pretensioned cables (mooring lines), the caisson construction began. Installation of reinforcements was followed by slip forming and concreting. Due to the use of slip forms, the concreting process had to be continuous. Hence, the concrete was made on the Narrows bank and pumped through a piping system to a placing barge. On pouring, the concrete placing barge was aligned next to the caisson and concrete pumps were used to pump concrete. Here emerges the main benefit of the inverted half-cylinders as after each pour the air pressure under the half-cylinders was adjusted to control the desired draft and any minor inclination of the caisson. As construction progressed, the depth of the caisson increased continuously until the cutting edge cuts through the soil as shown in Figure 5. As the caisson reached each of the main drafts, the main barge was used to tension up the mooring lines to obtain the targeted pretension at that draft (Chakrabarti, Chakrabarti, & Krishna, 2006). The pretensions had to be maintained close to the set values, to guarantee safety of the mooring system and the caisson. The pretensions were monitored using installed load cells in each line. After the desired depth was reached the concrete cap was constructed after the removal of the half-cylinders (Gerwick, 2007).

4.2.2 Construction Method Evaluation

These two caissons were very unique, not only due to their size but also due to their unique construction method. The uniqueness of the construction method is apparent in the fact that in terms of the mechanism of its cutting edge penetration into the soil it is considered as an opened caisson however the presence of the half-cylinders at the transition between the caisson and its cutting edge makes it transported and sunk as a floating box caisson. Hence, these caissons had the merits of both types avoiding the drawbacks of each of them. If the selection criteria developed in section 3 was to be used to choose the type of caissons to be used it would have been a tough decision as the sandy soil had a high bearing capacity however it was not high enough to carry this gigantic weight while using an opened caisson and depending totally on the skin friction of the portion in contact with the soil would have also been insufficient. However, combining both systems was the best option in order to have several load transfer mechanisms and also facilitates floating the first sections of the caisson to the site.

5 CONCLUSIONS AND RECOMMENDATIONS.

When examining the methods applied in the two cases discussed in section 4 of this paper against the selection criteria developed in section 3, the selection criteria proved that it covered the different aspects governing the selection of the most suitable methods for different caisson construction cases. The most governing factor of choice is the soil conditions and following that comes the safety, level of risk, constructability, speed and cost. Hence, it is highly recommended when using the selection criteria matrix to take all the factors governing the method selection into account as neglecting some of them could cause serious problems that are difficult in fixing.

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