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Design and Fabrication of a Semi-Submersible Fish Cage for Inland Water and Offshore Applications

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Abstract

This study presents a simplified and efficient design of a submersible cage for offshore fish production for inland and offshore waters. The study utilized a Critical Path Analysis to outline the construction processes. The structure was designed to be fully semi-submersible with 4 buoys providing the supporting force for the entire structure. The offshore fish farm has key dimensions of 4200 x 3000 x 1800 (mm) and a total displacement of approximately 0.8 tons. The frame was constructed using ASTM-36 (low carbon steel), L-angled bars with individual dimensions of 25 x 25 x 4 (mm) joined with heavy-duty steel bolts for easy disassembling. Four ballast tanks made out of 2mm thick ASTM-A36 low carbon steel were integrated into the structure and have dimensions of 700 x 520 x 1250 (mm). Suitable paint application and zinc anode was designed and installed to reduce effect of corrosion. The study offers valuable insights, based on actual data, into the design and fabrication process of the structure, and its potential scalability. Further works may be performed on the economic feasibility and also the integration of advanced technologies such as feeding automation and remote monitoring systems to enhance the efficiency and productivity.

Keywords: *Buoyancy, Semi-submersible, Offshore, Structure, Ballast tank*

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1. Introduction

Offshore aquaculture involves locating fish farms in deep, less sheltered waters away from the coast, where fish stocks are exposed to more natural conditions with wider range of nutrient flow (Naylor and Burke, 2005). With recent technological advancements, offshore aquaculture, particularly offshore fish farming, presents a sustainable and intelligent way for countries to utilize their coastlines. For example, China's fishing sector has grown considerably over the last three decades due to government policies and the country's increasing demand for fishery products, making it the largest producer of fishing goods worldwide (Zang, 2015).

Offshore fish farming is a relatively new concept for aquatic food production, especially in Africa. Some of the methods for offshore fish farming are the open net pen method and the submersible cage method. The Open net pen method has been successfully applied in mass fish production in fishing countries like Norway, South Korea and Greece. This method is known for being energy and cost efficient because it is usually low technology. However, it is associated with a number of problems such as not being strong enough to withstand high sea waves, and also the pollution of the marine environment because the wasted nutrients from the unconsumed feeds and fish faeces can accumulate inside the netting, leading to increased algae growth and hence the pollution of the benthic region of the water floor. The Submersible cage method combines knowledge from the oil exploration world as well as that of aquaculture to design high technology semi-submersible cages with autonomous operating features carrying out operations such as cleaning, feeding, fish monitoring and also hydrological parameter monitoring.

Studies have been done on various offshore fish farm constructions as evidenced in Chu et al. (2020), in which the authors reviewed different fish cage designs for offshore fish farming and compared their advantages and disadvantages. In a prior study performed by Li et al. (2018), an innovative fish farm design resembling a vessel was investigated for potential implementation in open sea environments. Chu et al. (2023) reviewed design guidelines for offshore fish farms, while Wang et al. (2022) conducted a study on the hydrodynamics and nonlinear interplay between regular waves and a submersible steel-frame offshore fish farm called "ShenLan 1". Pang et al. (2023) introduced an innovative fish farm platform in the form of a semi-submersible vessel-shaped truss. The researchers also investigated the platform's dynamic behaviour in varying wave environments, while incorporating a single-point mooring system. Huang et al. (2020) tested a physical model of a semi-submersible offshore fish farm and determined a safe and reliable mooring system. Lindeboom et al. (2019) performed wave basin tests on an innovative fish farm concept and found favourable hydrodynamic behaviour. Chu et al. (2022) developed a method to analyse wind and wave coupling effects on a structure called COSPAR, which integrates an offshore fish cage and wind turbine. They used a frequency domain analysis and validated their method with published results. Riyanlol et al. (2020) designed a steel structure offshore fish cage for both fish farming and ecotourism. Drach et al. (2013) introduced the use of copper alloy nets in open ocean aquaculture as a new technology for reducing biofouling and improving cage stability and structural strength.

This study seeks to address the lack of detailed analysis in the design and fabrication processes of offshore fish farms in previous studies by providing insight into the construction of a functional semi-submersible cage type prototype that could be adapted for both small- and large-scale offshore fish farming purposes.

2. Materials and methods

The Critical Path Method was employed in order to identify the sequence of activities that are critical to completing the construction of an offshore fish farm on time and to determine the minimum time needed for the project completion. Computer Aided Design software was also employed in this study for the design analysis of the offshore fish farm. The materials employed were low carbon steel and polyester mooring lines.

2.1 Critical path and duration analysis

The critical path method is a widely utilized scheduling technique employed to determine the critical path and establish the interdependencies among various activities when carrying out a project (Ba'Its et al., 2020). Employing critical path analysis helped to streamline the design and fabrication process by identifying the sequence of activities that are crucial for timely completion and highlighting potential bottlenecks or delays. The activities involve in the design, fabrication and installation processes are highlighted in Table 1. The critical path analysis was conducted with the aid of the activities presented in Table 1, as shown in Fig. 1.

Table 1: Construction activities

Activity Codes	Activities	Duration in days
A	Feasibility Study	30
B	Model the structure using CAD	14
C	Analysis of hydrostatic properties	2
D	Analysis of the dynamic response	3
E	Determination of the structural loads	1
F	Optimization of the design	1
G	Columns Preparation	2
H	Bracing Preparation	3
I	Wire gauge preparation	7
J	Buoyancy tanks fabrication	4
K	Assembling the components	6
L	Cathodic protection and Mooring systems preparation	3
M	Mooring systems & Anchor installation	1

The critical path for the offshore fish farm project is displayed in the flowchart below, comprising activities A, B, C, D, E, F, I, L, and M, with a total duration of 62 days. Each activity box in the flowchart contains the Early Start (ES) on the top left, the activity name on the top centre, the Early Finish (EF) on the top right, the duration at the bottom centre, and the Late Finish (LF) and Late Start (LS) at the bottom right and left sides, respectively. Additionally, the Total Float is the difference between the Late Finish and Early Finish or the Late Start and Early Start of an activity. Furthermore, the Free Float of an activity is the difference between the minimum Early Start of successor activity, minus the activity's Early Start, minus the duration of the activity. The Total Float and Free Float of each activity are displayed above and below the activity box, respectively.

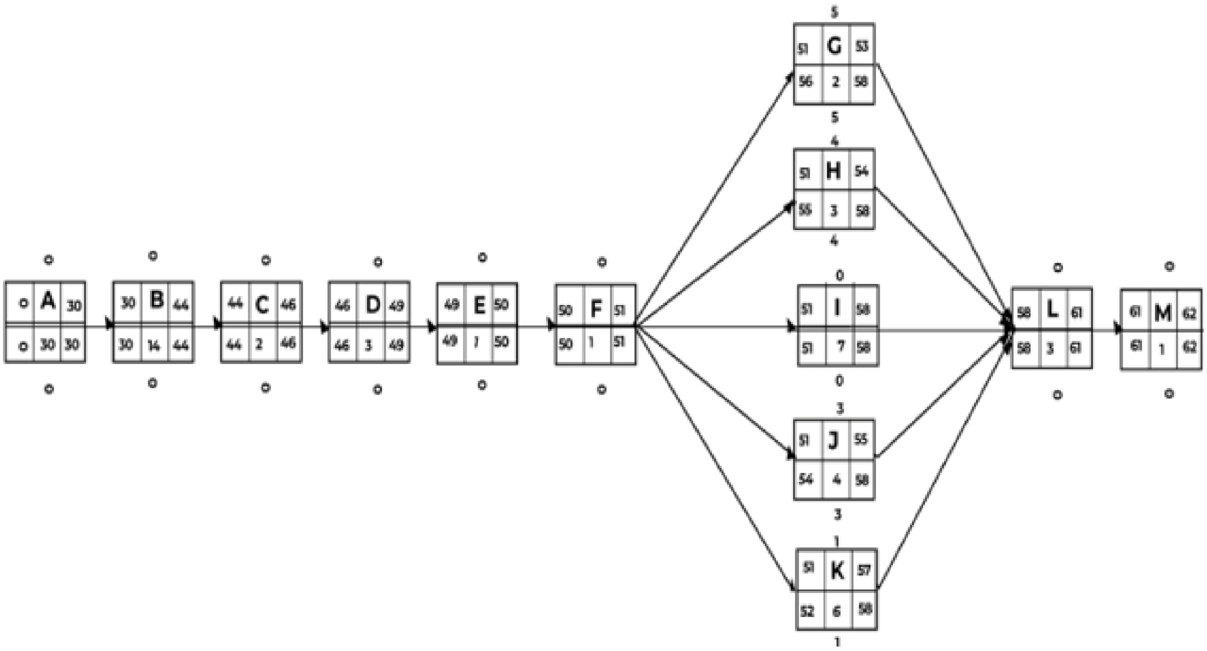


Fig. 1: Critical path analysis flowchart

3. Design analysis

The structure was designed to hold more than 3000 fishes, producing about 12 tons of catfish per year. The structure was designed to be fully semi-submersible using 4 buoys which were attached to the frame by heavy duty bolts to provide the supporting force for the entire structure. The key dimensions of the offshore fish farm were 4200 x 3000 x 1800 (mm) and the entire structure has a total displacement of approximately 0.8tonnes. A clear picture of the full assembly is shown in Fig. 2.

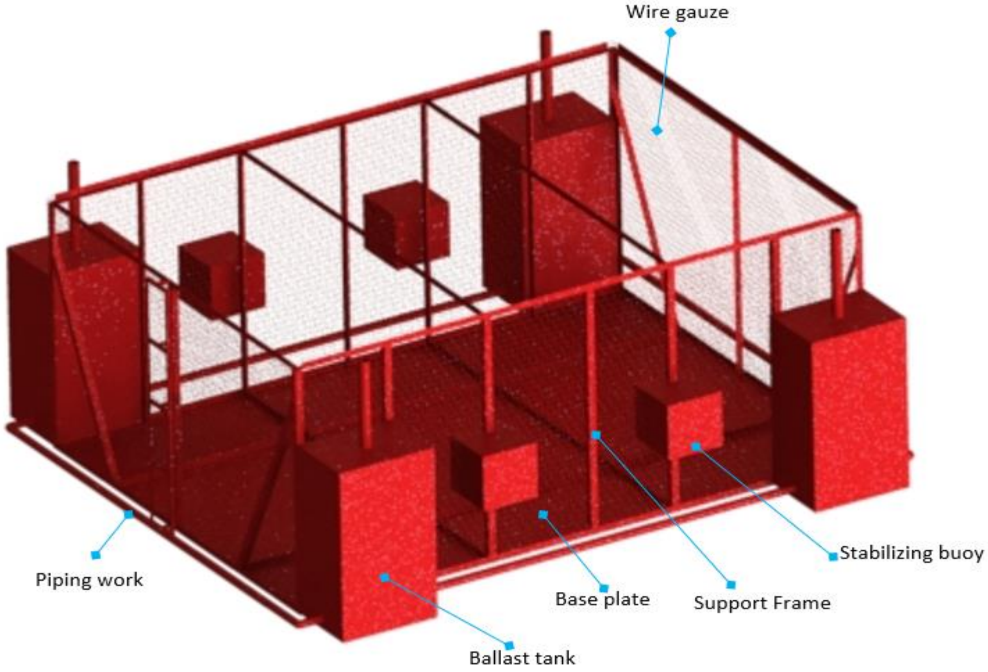


Fig 2: Full assembly of the offshore fish farm system

The key dimensions and details of the individual components of the fish cage are of paramount importance as they lay the foundation for the successful operation of the offshore fish farm. The key dimensions are detailed below:

i. The Support frame: The frame has dimensions 4200 x 3000 x 1800 (mm) and was made with ASTM- 36 (low carbon steel) L-angled bars with individual dimensions 25 x 25 x 4 (mm) joined with heavy duty steel bolts for easy disassembling. The type of metal used was chosen for its low cost and high availability. The dimensions of the support frame are shown in Fig. 3.

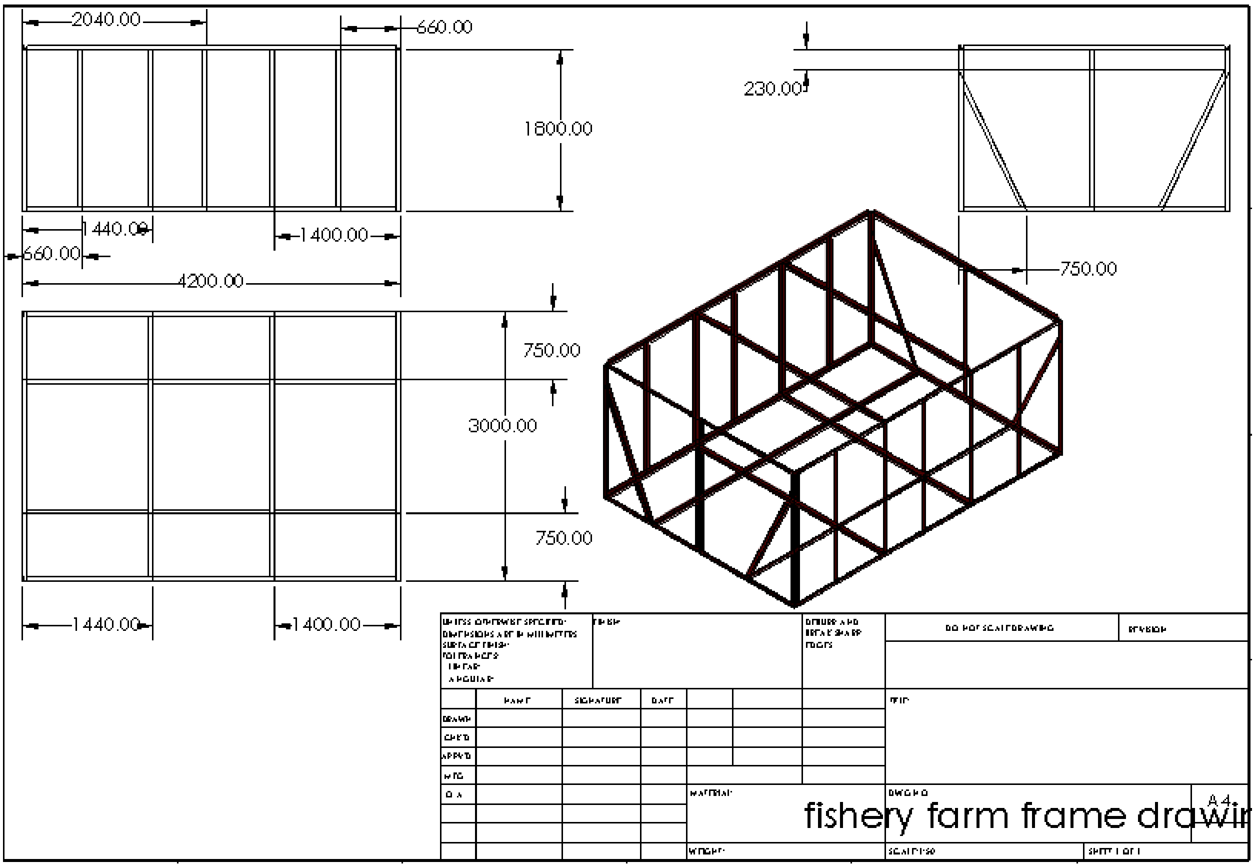


Fig 3: Support frame

ii. Ballast tank: The four ballast tanks have dimensions 700 x 520 x 1250(mm) and are made out of 2mm thick ASTM- A36 low carbon steel. The material was selected because of their high strength against buckling forces. ASTM- A36 is used in general construction for this very reason. Their lower cost and availability were also considered. The function of the ballast tanks is to provide enough supporting force to the entire structure. Each of the ballast tanks weigh about 60kg but supply a buoyancy of around 450kg to the structure, since each tank can hold up to 450 litres of water. Three of the four ballast tanks are fitted with 2 inch- diameter PVC pipes to serve as vents for the air contained inside the tank to escape as water fills the tanks, the last ballast tank known as the ‘Master Ballast’ is fitted with a galvanized pipe on the top which serves as the inlet for pumping water. The master ballast also features two outlets that connect to the outlets of the other ballasts through 2 inches galvanized steel pipes so that water being pumped into the master ballast is channelled equally to all the other ballasts to achieve equal weight distribution. The dimensions of the ballast tank are shown in Fig. 4.

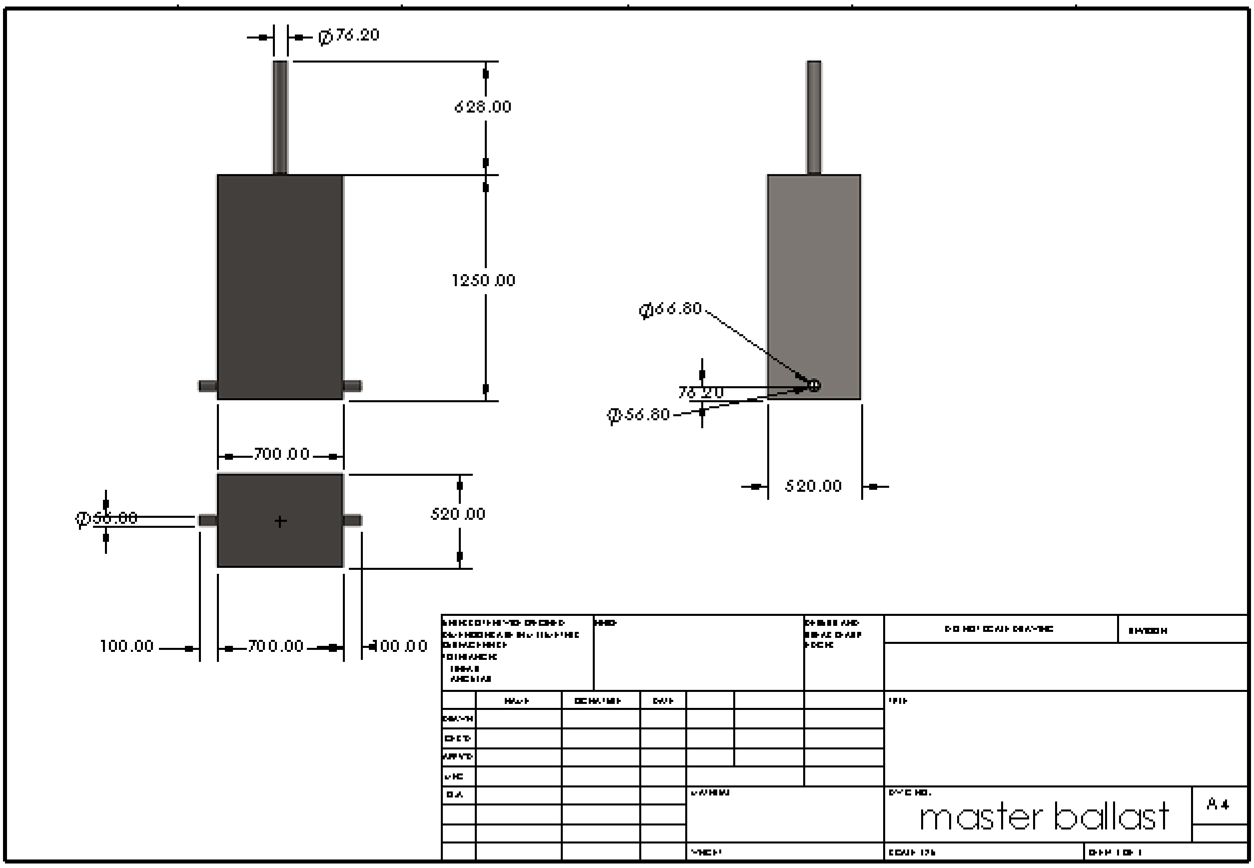


Fig 4: Ballast tank

- **iii. Stabilizing buoy:** These are 2mm thick ASTM-A36 steel 400 x 400 x 400 (mm) boxes attached to the longer sides of the structure. There are exactly 4 of them and their major function is to provide stability, even weight distribution, and reserve buoyancy to counter unusually stronger waves than is common in Nigerian and most African waters. The dimensions of the stabilizing buoy are shown in Fig. 5.
- **iv. Wire gauze:** The wire gauze is used to keep the enclosure secure to prevent escape of the fish from the enclosure. They are made small enough to prevent escape of the fish from the enclosure. The wire gauze was designed to fit both sides of the structure (the longer and shorter side) tightly enough to close up all loopholes. The gauze was made out of galvanized steel due to its corrosion resistant properties. The dimensions of the long side wire gauge and the short side wire gauge is shown in Fig. 6 and Fig. 7 respectively.
- **v. Piping:** All the piping connections (including the bushings, elbow joints and valves) were made out of galvanized steel for their corrosion resistant properties. The dimensions of the long side piping and the short side piping are shown in Fig. 8 and Fig. 9, respectively.
- **vi. Base plate:** This is where sediments such as feed and other particulate matter which the fish feeds on are expected to settle. It is made out of the same 2mm low carbon steel plate 4200 x 3000 and is welded to the bottom of the structure. The dimensions of the base plate are shown in Fig. 10.

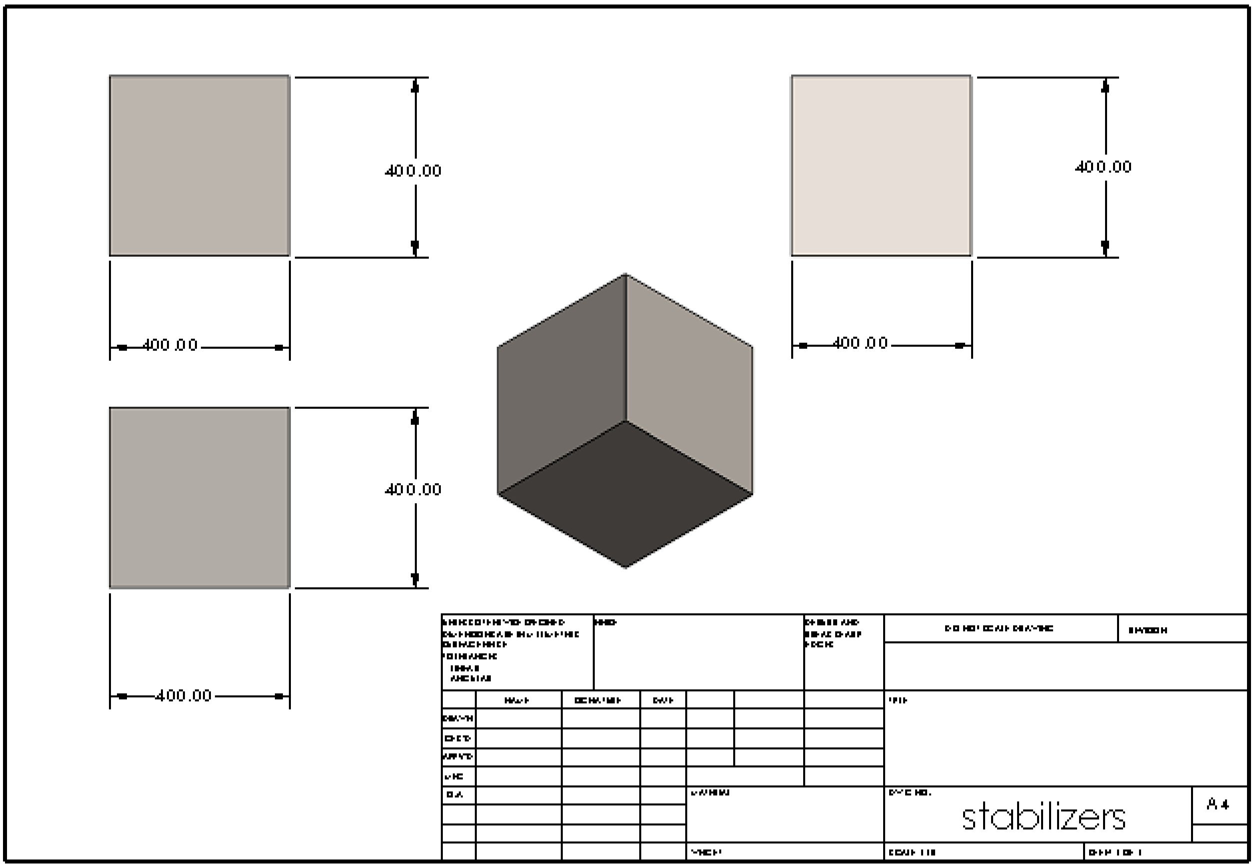


Fig 5: Stabilizing buoy

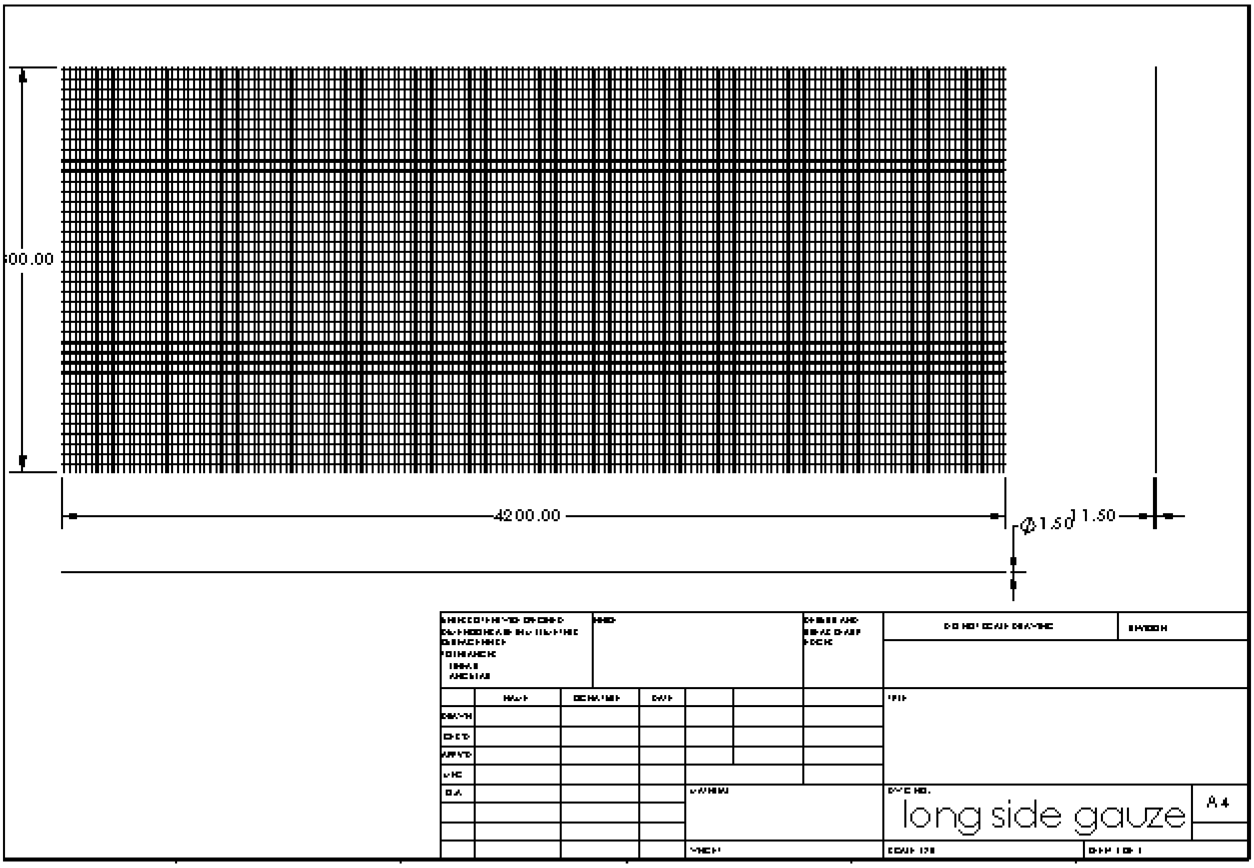


Fig 6: Long side wire gauze

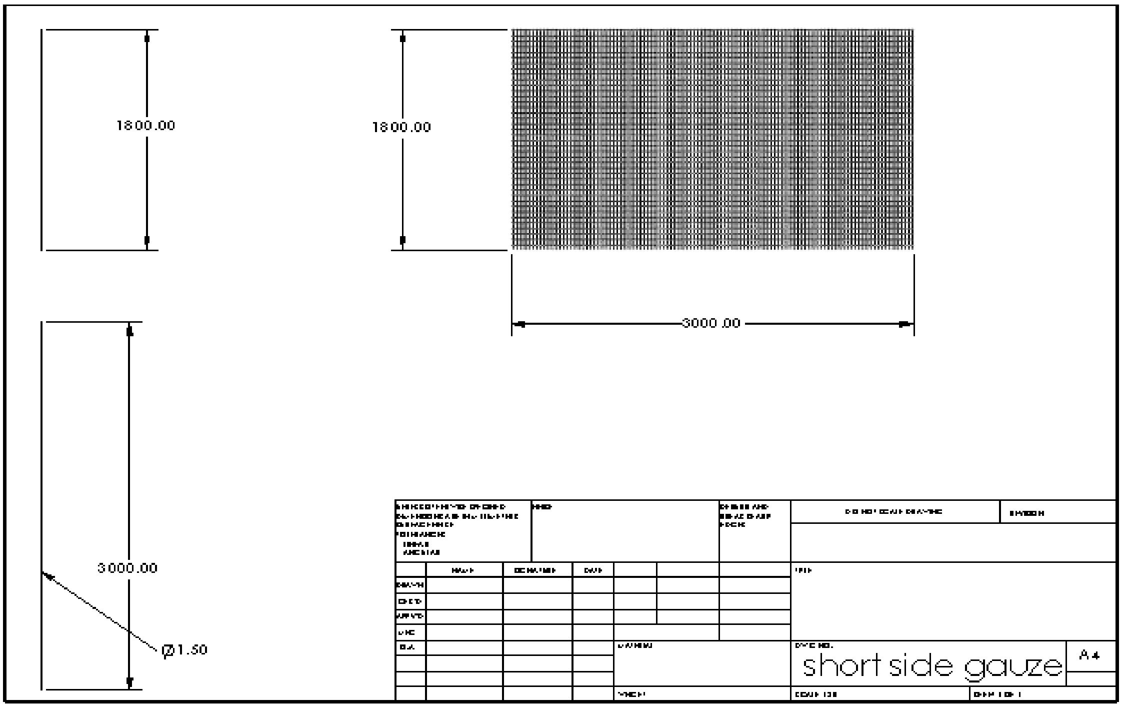


Fig 7: Short side wire gauze

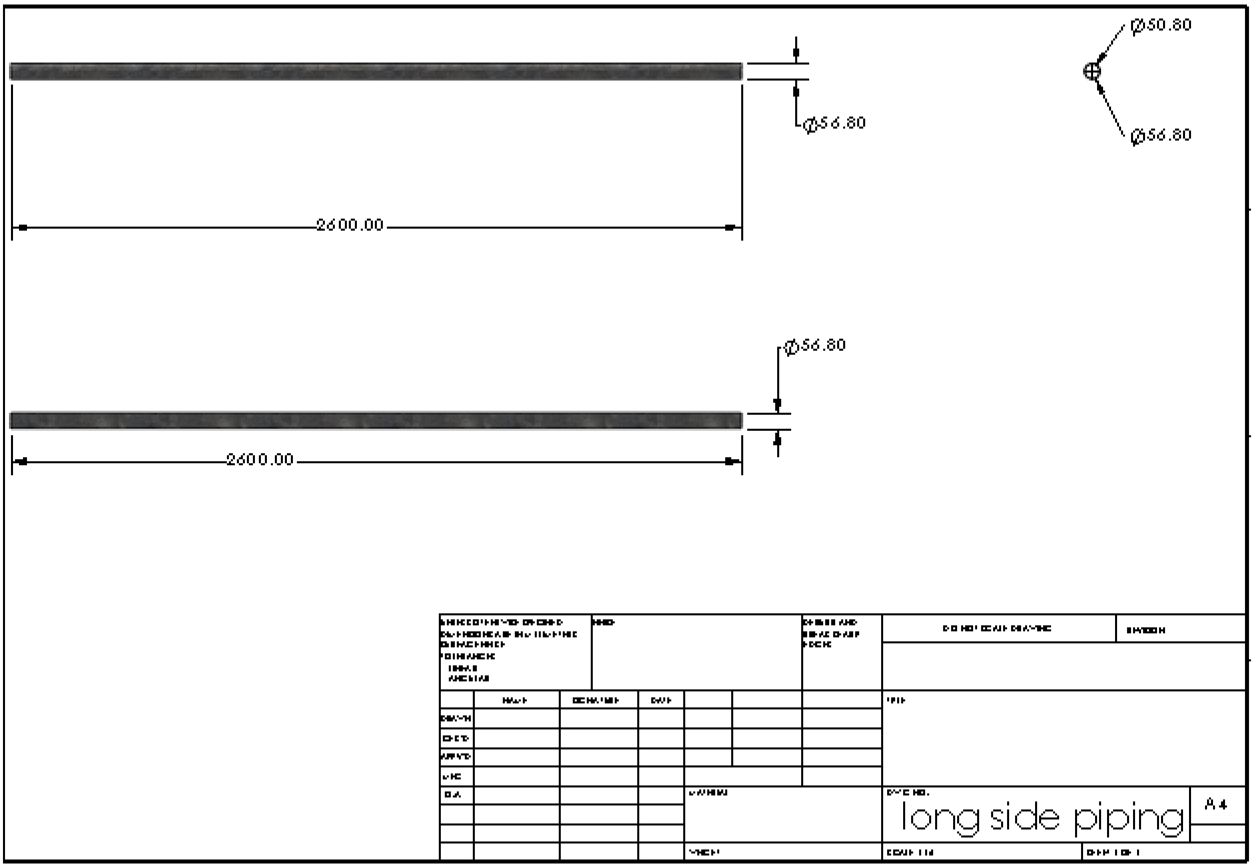


Fig 8: Long side piping

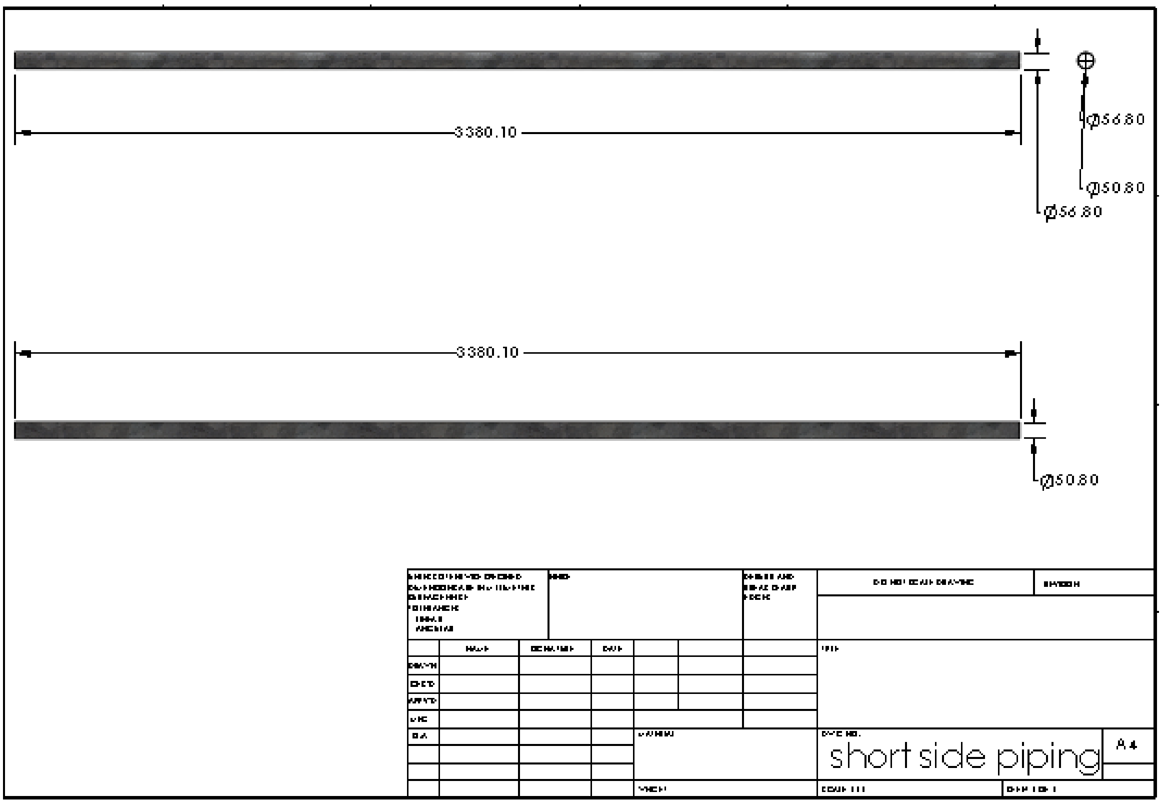


Fig 9: Short side piping

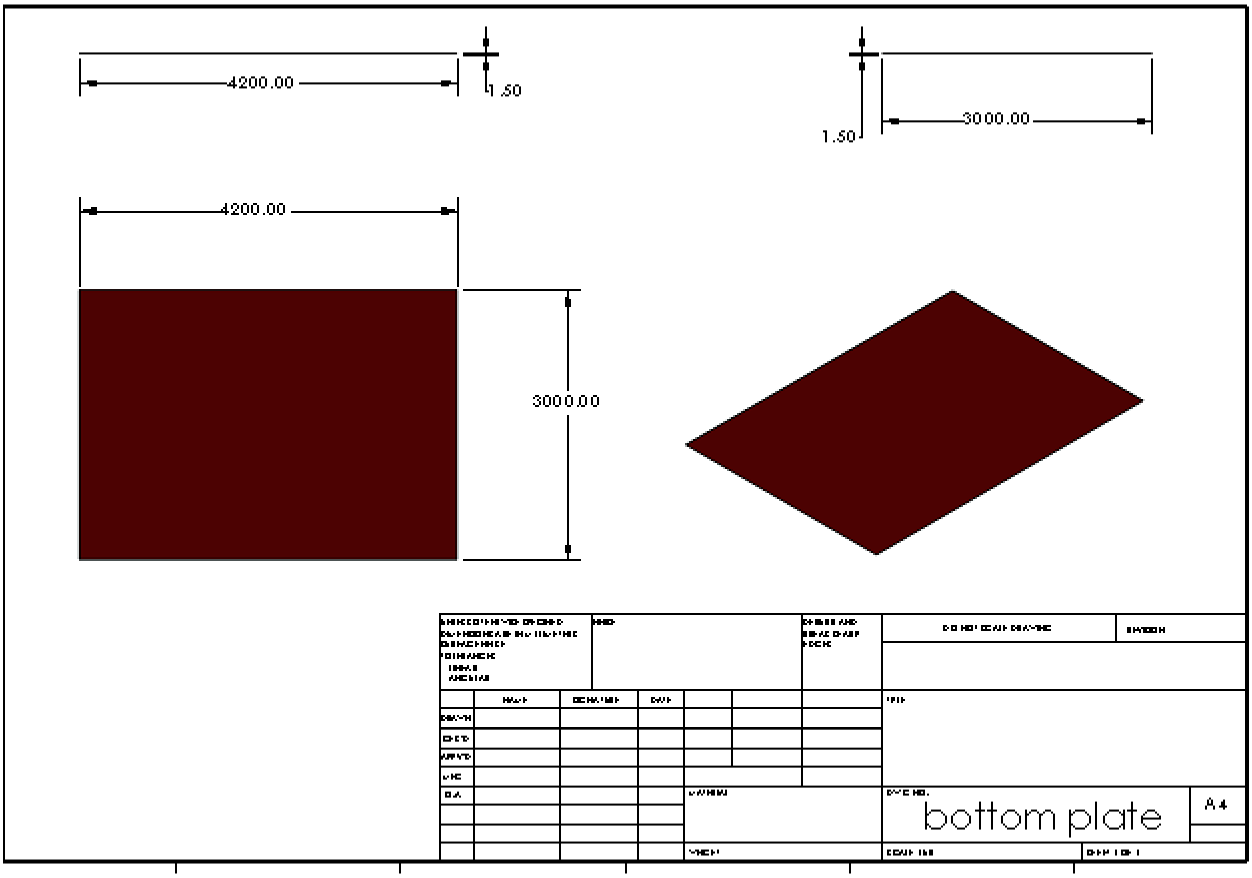
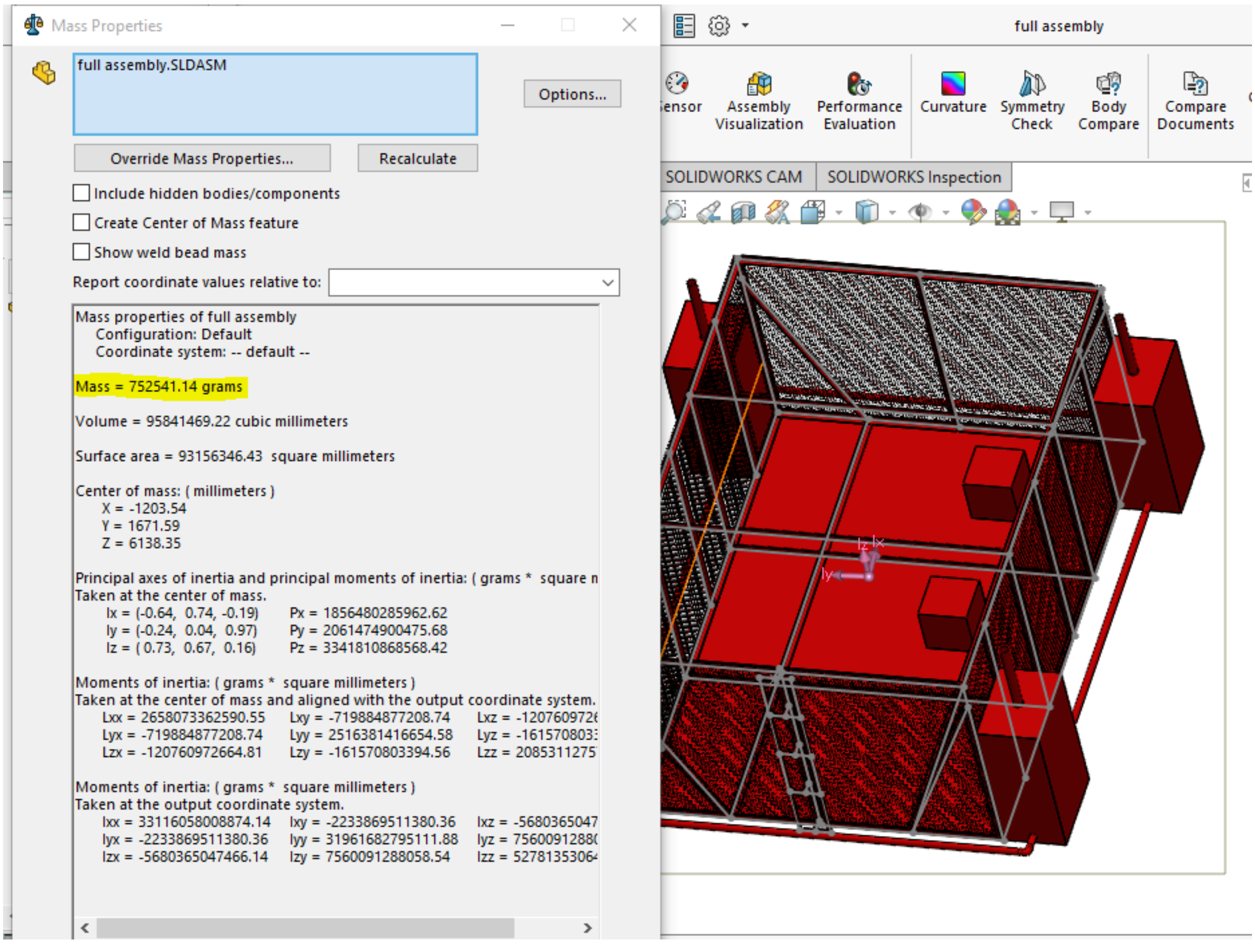


Fig 10: Base plate

3.1 Design calculations

The most important requirement for this design is to ensure that it has sufficient buoyancy and stability to perform all its normal functions. The ballast tanks and the stabilizing buoys are designed to ensure that the buoyancy and stability requirements are met. Fig. 11 shows the mass properties of the fully assembled structure, obtained from the 3D Computer Aided Design software. The overall mass of the structure is obtained from Fig. 11 as 752541 grams or 752. 541kg. This means that the buoyant force required to keep the structure afloat is at least 7382N. In order to evaluate and possibly validate the design of the ballast tanks, the buoyant forces provided by all the ballast tanks together in both freshwater and saltwater media were calculated.



```
Mass properties of full assembly
    Configuration: Default
    Coordinate system: -- default --

Mass = 752541.14 grams

Volume = 95841469.22 cubic millimeters

Surface area = 93156346.43  square millimeters

Center of mass: ( millimeters )
     X = -1203.54
     Y = 1671.59
     Z = 6138.35

Principal axes of inertia and principal moments of inertia: ( grams *  square
Taken at the center of mass.
      Ix = (-0.64,  0.74, -0.19)      Px = 1856480285962.62
      Iy = (-0.24,  0.04,  0.97)      Py = 2061474900475.68
      Iz = ( 0.73,  0.67,  0.16)      Pz = 3341810868568.42

Moments of inertia: ( grams *  square millimeters )
Taken at the center of mass and aligned with the output coordinate system.
     Lxx = 2658073362590.55     Lxy = -719884877208.74     Lxz = -120760972
     Lyx = -719884877208.74     Lyy = 2516381416654.58     Lyz = -161570803
     Lzx = -120760972664.81     Lzy = -161570803394.56     Lzz = 208531127

Moments of inertia: ( grams *  square millimeters )
Taken at the output coordinate system.
     Ixx = 33116058008874.14    Ixy = -2233869511380.36    Ixz = -5680365047
     Iyx = -2233869511380.36    Iyy = 31961682795111.88    Iyz = 756009128
     Izx = -5680365047466.14    Izy = 7560091288058.54     Izz = 527813530
```

Fig 11: Mass properties of the fully assembled structure

3.1.1 Design calculations for freshwater application

The data required for this calculation include:

Ballast tank overall dimensions = 700 x 520 x 1250 (mm)

Density of fresh water = 1000 kg/m^3

The total volume displacement of each ballast tank was obtained as 700 mm x 520 mm x 1250 mm, which equals to 455000000 mm^3 or 0.455m^3

Employing Archimedes principle, buoyant force is directly proportional to displacement volume:

$$F_b = V_d \times \rho \times g \qquad (1)$$

where F_b is the buoyant force, V_d is the displacement volume, ρ is the density of fluid (freshwater), and g is the acceleration due to gravity. The total buoyant force possible for each ballast tank is obtained as:

Total buoyant force for each ballast = 0.455m^3 x 1000 kg/ m^3 x 9.81 m/s^2= 4464N

Total buoyant force for all 4 ballast tanks together = 4464 N x 4 = 17854N

Equation (2) was used to determine the factor of safety of the structure with regards to buoyancy.

$$\text{Factor of safety} = \frac{total\ buoyancy}{total\ weight\ of\ the\ structure} \qquad (2)$$

Factor of safety = $\frac{17854}{7382}$ = 2.4

The computed value for factor of safety falls within the range of acceptable industry standards (1.8 to 2.5) and thus, indicates that the design meets buoyancy requirements satisfactorily.

The draft that the structure is expected to rest is calculated as follows:

With no extra weight considered, the weight of the offshore fish farm is given as 752.5kg.

In order to provide 752.5kg of total buoyancy, each ballast tank must provide a buoyancy of 200kg at the minimum.

The volume displacement at draft D becomes = 4 ballast tank x (700 x 520 x D mm^3) = 1,456,000D mm^3 or 1.46D m^3

The draft can then be calculated using the equation for buoyant force,

$$W_C = V_{d(draft)} \times \rho \times g \quad (3)$$

where W_C is the Weight of the cage, $V_{d(draft)}$ is the displacement volume (at draft D), ρ is the density of freshwater, and g is the acceleration due to gravity.

7382N =1000kg/m^3 x 9.81m/s^2 x 1.46 x D

D = 0.51m

Without any extra weight (i.e. without water in the tanks), the structure will float with a 0.51m draft.

The operating draft of the fish farm is at 1m, hence we must estimate the exact amount of water required inside the tank to provide an operating draft of 1m.

The data required for this calculation is the volume displacement at 1m draft (1000mm)

At light-weight, draft of the semi- submersible system is 0.51 m.

New draft of 1.0m will require increased draft of 0.49m

Volume for increased displacement = 4 ballast tank x (700 x 520 x 490 mm^3) = 713,440,000mm^3 or 0.713m^3

For an operating draft of 1m,

Water required to be pumped into the ballast tank is 0.713 m^3 or 713 litters.

The salt water situation is computed by substituting water density by 1025 kg/m^3

Saltwater provides good buoyancy compared to freshwater. However, salt water comes with its own problems. Saltwater is more corrosive than freshwater and will likely cause the ballast tanks to lose its function fast. It is more logical to explore other means of corrosion prevention other than painting such as installation of cathodic protection on the submerged structure if the fish farm is used in offshore environment.

3.1.2 Design calculation for cathodic protection

The design calculation for cathodic protection involves determining the required current density, surface area, and materials to be used in order to minimize corrosion of a structure. Zinc anode was employed in this project in line with DNV-RP-B401. The design parameters are:

Operating draft = 1m

Light-weight draft = 0.51m

Total height = 1.8m

Total metal surface area = 93.16m^2

Surface area of the submerged part of the barge under normal operation:

Area of submerged part = 0.51 x total surface area = 0.51 x 93.16m^2 = 47.5m^2

To determine the Current demand for the Offshore Fish Farm system, a coating break down factor (F_c) of 20% was assumed.

Coating breakdown factor (F_c) = 20% = 0.2

The current density (I_c) of the ASTM material used= 0.070 A/m^2

The current demand by the steel material (I_d) = A_C x I_c x F_c = 47.5m^2 x 0.070 A/m^2 x 0.2 = 0.665 A

Determining the resistivity of the sacrificial anode (R_a) for a long flush mounted anode:

Therefore, $$R_a = \frac{\rho}{2S} \quad (4)$$

Resistivity of the environment, ρ = 25Ωcm = 25 x 10^{-2} Ωm

Also, $$S = \frac{L+B}{2\pi} \quad (5)$$

where the L and B are the length and breadth of the anode, respectively.

We found anode of ; Length of the anode (L) = 0.2m, Breath of the anode (B) = 0.2m

Therefore, S = $\frac{0.2 + 0.2}{2\pi}$ = 0.064m

Resistivity of the anode is obtained as;

$$R_a = \frac{0.25}{0.064} = 3.9\Omega$$

The current output of the anode can be obtained using:

$$I_a = \frac{V}{R} = \frac{E_\alpha - E_0}{R_a} \tag{6}$$

Where; Design Voltage, $E\alpha = -900mV = -0.9V$

The anode employed is a zinc base, $E_0 = -1.00V$

The Current output is determined as:

$$I_a = \frac{-0.9-(-1.0)}{3.9} = 0.026A$$

The total number of sacrificial anode needed is obtained as:

$$N_a = \frac{I_d}{I_a} \tag{7}$$

$I_a = \frac{0.665}{0.026}$ = 26pieces of the anode is sufficient

To determine the expected service year(s) of the Offshore fish farm with this configuration,

$$M_a N_a E_c U_f \geq 8760 * T_d I_c \tag{8}$$

where M_a is the Mass of each anode (1.2kg), N_a is the Number of anodes (26), E_c is the 780Ah/kg, U_f is the Utilization factor for long flushed mounted anodes (0.85), T_d is the Service lifespan in years, and I_c is the Current density, obtained from table as $0.070A/m^2$. From the equation, T_d is obtained as 34 years.This implies that the structure can remain in service for 34 years. The current generation of the anode system will also assist to check concerns of biofouling in the system.

3.2 Fabrication and installation

The fabrication process of the semi-submersible offshore fish farm involved cutting and welding steel plates to form the structure's base, columns, and braces. The fabrication and installations of the buoyancy tanks and other necessary components were also made. After fabrication was completed, the structure was coated with a protective layer to prevent corrosion. The coating process deployed was a two-coat system where the base primer is topped with a suitable marine top coat. Once the coating was complete, the semi-submersible offshore fish farm was transported to the installation site (Fig. 12). The installation phase involved lowering the semi-submersible offshore fish farm into the water and securing it in place. This was done using 4-point anchor systems and mooring lines to prevent the structure from drifting away. After installation, the semi-submersible offshore fish farm was tested to ensure that it is fully operational, this involved checking the integrity of the structure and monitoring for leaks for 7-days against an established draft mark on the structure.

Fig. 12: The developed semi-submersible offshore fish farm moored in a Nigerian inland water.

3.3 Discussion

The existing fish farm projects mentioned in the cited literature focus on various design concepts, such as vessel-shaped farms, semi-submersible platforms, wind and wave coupling effects, and copper alloy nets, while the newly designed and fabricated fish farm incorporated the reviewed advantages and disadvantages to optimize efficiency, hydrodynamic behaviour, mooring system reliability, biofouling reduction, and structural strength for improved offshore fish farming operations. In order to guarantee adequate buoyancy, meticulous attention was given to the design of the ballast tanks and stabilizing buoys. These components were carefully engineered to meet the specific requirements for buoyancy and stability. To assess and potentially confirm the efficacy of the ballast tank design, calculations were performed to determine the combined buoyant forces exerted by all the ballast tanks in freshwater and saltwater environments. The fish farm can be deployed in any of the offshore environment, provided that it is cathodically protected. The design calculation for cathodic protection was made, and the current demand for the offshore fish farm structure was obtained as 0.665A, while the expected service years was obtained as 33.7 years for this given design.

4. Conclusion

The design and fabrication of a semi-submersible offshore fish farm for inland water and offshore applications has been successfully accomplished. The prototype demonstrated excellent buoyancy and stability in water, while also providing an efficient environment for fish farming. The use of low-cost materials in the construction process makes it affordable and accessible to fish farmers. The study provides valuable insights into the design and fabrication process of offshore fish farms, which could be adopted for both small and large-scale applications. Further research could explore the economic feasibility and also the integration of advanced technologies such as automation and remote monitoring systems to enhance the efficiency and productivity of the fish farming process.

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