Design and Testing of an In-Water Nursery for Orphaned Corals on O’ahu’s South Shore

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Senior Design Project (Mechanical Engineering)
Mentor: Dr. Bardia Konh

In-situ coral nurseries have been implemented around the world and play a critical role in resource management and conservation. However, with Hawai‘i’s strong currents, a coral nursery presents a new challenge for such a dynamic ocean landscape. In this work, an in situ marine structure was designed and tested towards deployment off the southern coast of O‘ahu, Hawai‘i. This structure is designed specifically for the rehabilitation of orphaned corals of opportunity, i.e. non-fragmented coral colonies. It is safe, practical, and cost-efficient. In addition, it has been designed towards minimizing its potential environmental impact, meeting United States Army Corps of Engineers (USACE) regulations for permitting, and performing its desired functions under the unique conditions present in Hawaiian waters. Considering these design parameters, modeling software was used to draft a 3D design of the structure, which was then analyzed using finite element analysis software. This unique structure is suitable for mass husbandry and transplantation of coral colonies, using economies of scale to achieve impactful and systematic restoration. This type of in-water nursery will be the first of its kind in Hawai‘i, and the world.

Background

For many years, in-water coral nurseries across the globe have been built successfully and researched extensively, but never before in Hawai‘i. With Hawai‘i’s often turbulent waters and strong currents, a coral nursery is a new challenge for such a dynamic ocean landscape. The focus of previous research endeavors was to test different methodologies in farming fragments of coral sampled from donor coral colonies, and reintroducing them to denuded reefs after reaching a desired healthy size. Previous nurseries...
ery designs were analyzed and determined to fail were they subjected to the combined forces present in Hawai‘i’s waters, and the weight of large coral specimens. The project requires that the structure be able to hold large pieces of coral ranging from 20 to 60 centimeters, an undertaking not previously attempted. There is currently no formal effort to gather and re-attach these corals. Therefore, NOAA has identified a need for an in-water nursery where detached corals can be revived and stored for mass transplantation, using the advantage of economies of scale to achieve impactful and systematic restoration.

**Objectives**

The objective of this project is to design, test, and manufacture an in-water marine structure for the rehabilitation of orphaned corals that have been damaged due to manmade or natural events. This type of in-water nursery will be the first of its kind in Hawai‘i, and the world. The design must be safe, practical, and cost-efficient. In addition, it must minimize its environmental impacts, meet all United States Army Corps of Engineers (US-ACE) regulations for permitting, and perform its desired functions under the unique conditions present in Hawai‘ian waters. To objectively determine the functionality of any possible designs, a list of specifications was generated. These specifications deal with all aspects of the structure and are listed in Table 1.

**Design**

_Preliminary Concepts_. The overall shape of the structure has changed over the course of the project. It began as a buoy-suspended platform, as seen in Figure A-1, to a dome structure, Figure A-2, which was initially chosen for the benthic design. It was decided that the multi-tiered platforms in Figure A-1 would have a high risk of failure, as the horizontal dynamic forces from an oscillating current would cause the structure to tip and act as a sail. As a result, the design of the structure as a whole was modified to a spherical shape, Figure A-3, to allow a more hydrodynamic design. The spherical design was carried over to the benthic structure in order to have one shape to design for both types of structure. After several iterations depicted in Figure A-4, a final analysis and consultation with NOAA, the shape of the structure was adjusted to a single-tiered hexagonal one, seen in Figures A-5 through A-7.

| Specifications |  
|----------------|----------|
| 1 Factor of Safety (FoS) > 2 for peak dynamic loading (e.g. waves, currents) |  
| 2 FoS > 2 for static loading (e.g. coral, divers, equipment) |  
| 3 House coral at depth of 40–70 ft, at minimum 5 ft over the ocean floor |  
| 4 Must be submerged at least 40 ft |  
| 5 Fixed in space; will not detach from substrate |  
| 6 Low environmental impact of materials |  
| 7 Materials and joining perform at range of approx 75–85 °F |  
| 8 Materials and structure perform under 3x atmospheric pressure |  
| 9 Materials chemically durable for nursery lifetime of 5 years |  
| 10 Materials mechanically durable for nursery lifetime of 5 years |  
| 11 Product life of 3–4 years |  
| 12 Life in Service > 5 years |  
| 13 Minimal maintenance |  
| 14 Provide each coral sample access to light |  
| 15 Provide each coral sample access to water motion |  
| 16 Allow divers to easily add/remove coral of varying sizes and shapes |  
| 17 Allow divers to easily view/monitor coral |  
| 18 Product size no greater than 25’ x 25’ x 40’ ft (width, length, height) |  

This maintained most of the hydrodynamic capabilities, while still maintaining ease of manufacturing.

_Final Design_. Based on the previous mentioned conditions and requirements, the best design was determined to be a single-tier, hexagonally-shaped, benthic structure, fabricated with a composite of fiber-reinforced plastic (FRP). This simplistic design, seen in Figure 1 below, was
determined to be the best structure to resist the potential static and dynamic load requirements. It also provides a structure that is relatively easy to assemble, requires little to no maintenance, and will have a more than adequate service life.

The determination of the structure shape was heavily influenced by the impacts that dynamic forces would have on the structure. The direction and magnitude of the dynamic forces would change with seasons, tides, and weather systems throughout the year. Therefore, the shape necessitated a nearly symmetrical design to provide for an evenly distributed support system in all directions. The ideal shape for an even distribution of forces would have been a circle, but due to the difficulty of implementing curved structural members, straight members were chosen, giving the structure a hexagonal shape. As seen in Figure 1, the single-tier platform is supported by eighteen horizontal beams that are supported at their ends. The platform is also supported vertically by twelve upright beams. The member sizes and shapes were chosen to provide adequate strength to resist the load while maintaining a profile that will reduce the drag caused by potential dynamic forces. The final design with the grating removed for support beam visual can be seen in Figure A-8.

Due to the potential of assembling the nursery on-site at a depth of 70–90 feet of water, it was important to include within the design, a simplistic method to connect the structural members. To accommodate this necessity, the design also included custom-designed joints to connect the members. As seen in Figure A-9 and Figure A-10, the joints will provide a way to easily assemble the structure with predetermined angles, and provide ample rigidity to support alignment and loading requirements. The location of the structure will be a sandy bottom, since the structure will be resting on this surface, it was imperative to design the base against potential sinking effects. This solid base is established with a custom-designed footing attached at the bottom of all vertical supporting beams. This footing is seen in Figure A-11. This will allow for the structure to rest on the surface of installation with little potential for major sinking effects of a soft bottom. The horizontal platform of the of the final design consists of permeable grating for the purpose of providing a surface for coral attachment. This grating, as well as the rest of the structure, was chosen to be of a size and shape that will be sufficient to attach the coral to, while not creating a biological hazard to the environment or marine life. Lastly, the final design was selected on a basis of cost and performance. The FRP material is not only significantly strong enough to handle the potential load, it’s also light enough to be handled without large machinery. It’s also non-corrosive in salt water, which will negate the need to implement preventive or corrective corrosion control maintenance. These characteristics will significantly reduce the cost of the overall project, and will offset the initial high cost of the base material and custom manufacturing of the joints and footing.

Analysis

The performance of the structure was determined through three different methods: analytical, numerical, and experimental. Analytical methods included calculations of static and dynamic forces on the structure. Finite element analysis was used to analyze the stress and displacement of critical subsystems. Experimental methods were employed to compare with analytical and numerical results. A visualization of the forces considered are found in Figure 2 below, and are explained in the following sections.

**Calculation of Pressure Forces.** Underwater structures are subject to increased ambient pressure as compared with those on land. A simple calculation of the force exerted by the pressure of the ocean was undertaken, and compared with literature values for FRP’s compressive strength rating. The ultimate compressive strength of solid FRP is 30,000 pounds per square inch (psi) longitudinally and 15,000 psi transversely. At a depth of 64
ft (assuming the benthos is 70 ft and vertical leg lengths are 6 ft), the structure experiences 28.1 psi over all surfaces. This is well below the compressive strength of FRP. However, the pressure on these types of elements becomes increasingly important in the case that the members are thin and hollow. Therefore, any hollow elements will be allowed to fill with water, which will equalize the pressure on the inside of the element.

Calculation of Hydrostatic Forces. The hydrostatic forces that will affect the structure include both the weight of the coral, and the weight of the structure itself. The Archimedes principle states that any object(s) submerged in a fluid experiences a buoyant force equal to the weight of the fluid it displaces. The volume of the displaced fluid is equivalent to the volume of the object that is submerged. This principle was applied to the raw weight and volume of these elements, as seen in equation (1) and (2) below.

\[
F_{total} = F_{object} - F_{buoyancy} \\
\left[ (\rho_{object} \cdot V_{object} \cdot g) - (\rho_{water} \cdot V_{water} \cdot g) \right] = F_{total}
\]

For a realistic estimation of the weight of coral on the structure at full capacity, the platform area was considered with a superimposed grid of square divisions at width 20 inches, or the diameter of a typical coral piece to be attached to the structure. To account for spacing between pieces, half of the divisions were calculated to contain coral. For a hexagonal face of radius 10 ft., it was estimated that 42 coral pieces could be placed on the structure with adequate spacing. Coral pieces were estimated to be solid half-domes 20” in diameter. Theoretical coral pieces contained a volume of 0.0343 m³, and at a density of 2290 kg/m³, were calculated to be 769.76 N each, with a combined dry weight of 32.3 kN. Accounting for the buoyant force acting on the coral, the net loading due to coral was calculated to be 17.9 kN. The summation of hydrostatic forces is listed in Table 2 for an estimated mass of structure and coral.

Calculation of Dynamic Forces. There are several sources of dynamic forces in the ocean, including waves, currents, and tides. Wave oscillation velocity at depths of 60–70 ft on the south shore of Oahu can be estimated to be roughly 0.5 m/s in average conditions, between 1–2 m/s during a swell event, and up to approximately 2.5 m/s in the case of a tsunami. This data has been provided by NOAA for the purpose of fluid-structure interaction calculations (G. Fryer, personal communication. October 20, 2016), and by request, the structure was designed to withstand wave oscillation velocities of up to 1 m/s. Current velocities, according to the Pacific Oceans Ocean Observing System (Flament 1996), may reach up to 0.25 m/s near Hawaiian shorelines. For safety, the structure was considered under currents of 1 m/s for analytical calculations. Considering wave oscillations with directionality normal to the seafloor, and with an orthogonal incidence to the structure’s coral attachment mechanism (shelving, basket, etc), drag force was considered to be the main factor in dynamic force loading. In order to analytically solve for the drag force produced in wave-structure interaction, several simplifications and assumptions were made. First, a fully loaded coral shelf was simplified as a thin, annular disc (Figure 3). Secondly, given the non-time dependent data points supplied, steady state analysis was used. Thirdly, the temperature of the seawater and associated parameters.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Total estimated hydrostatic forces of infrastructure and max coral</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Density [kg/m³]</strong></td>
<td><strong>Volume [m³]</strong></td>
</tr>
<tr>
<td><strong>Low Packing Volume</strong></td>
<td></td>
</tr>
<tr>
<td>Coral</td>
<td>2290</td>
</tr>
<tr>
<td>Water Displaced</td>
<td>1024</td>
</tr>
<tr>
<td><strong>High Packing Volume</strong></td>
<td></td>
</tr>
<tr>
<td>Coral</td>
<td>2290</td>
</tr>
<tr>
<td>Water Displaced</td>
<td>1024</td>
</tr>
<tr>
<td>Structure</td>
<td>1815.85</td>
</tr>
<tr>
<td>Water Displaced</td>
<td>1024</td>
</tr>
<tr>
<td><strong>Total Low</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Total High</strong></td>
<td></td>
</tr>
</tbody>
</table>
(density, viscosity) were considered to be constant. Water
temperature was assumed to be 25 °C, which represents
a conservative (cooler, therefore more dense) estimate
based on literature surface temperature data for the
south shore of Oahu (noaa.gov 2016).

The coral platform was modeled as an annular ring,
since the coefficient of drag for this geometry is known,
whereas the coefficient of drag for an annular hexagonal
disc was not found in the literature. First, using the en
vironmental parameters and the geometry of the annu-
lar ring, the Reynolds number was found. For all given
wave velocities, representing normal, swell, and tsunami
conditions, the order of magnitude of the Reynolds num-
ber (Re) was $10^6$. This allowed for determination of the
drag coefficient ($C_D$), as this is dependent on both the
geometry and the Reynolds number regime (Subrama-
nian, n.d.). The legs and holding platform the structure
were calculated to have Re numbers on the order of $10^6$.
Estimated as a thin annular disc, the hexagonal platform
was calculated to have a drag coefficient of $C_D = 1.17$, and
the rectangular cross-sectional legs for $C_D = 1.5$. The drag
force was then calculated according to:

$$F_D = 0.5C_D \rho AV^2$$

with seawater density , annular ring surface area A, and
wave velocity V. The results, summarized in Table 3,
show that a platform with a diameter of 6 m will be sub-
ject to up to 4.1 kN of dynamic force load under normal
wave conditions, 16.4 kN under swell conditions of 1 m/s,
and 65.5 kN in the event of a tsunami. When multiplied
by a permeability factor to account for a more permis-
sive grated platform surface with adequate coral spacing,
these forces could be reduced by half, as shown in Table
3. The structural support members found on Figure A-12,
would be subjected to a horizontal load of just over 200
N per supporting member in currents reaching 1 m/s.
Under these conditions, the structure would experience a
combined horizontal load of about 5 kN.

**Calculation of Anchoring and Sand Bearing Forces.**
The stability of the structure, which refers to vertical
motion due to settling and uprooting, as well as lateral
motion due to currents, is dependent on properties of
sand because of the integration of footings into struc-
tural anchoring. The safety of systems pertinent to these
considerations were designed to satisfy building code
standards and calculated according to Equation (1). A
footing height of 1.25 ft. was determined, for a minimum
anchoring force of over 13,000 lbf vertically (FoS = 1.8)
and nearly 6,500 lbf horizontally (FoS = 2.2). However,
the variability of angle and elevation introduced in bury-
ing individual footings presented an issue in orientation
and assembly of the structural members. By mounting
the six inner footings of the structure to a frame, guid-
ance for subsequent adjoining members will be provided
to ensure sound assembly of the structure.

**Finite Element Analysis.** To validate the structural de-
sign (a benthic one tiered structure) with FRP members, a
finite element analysis (FEA) simulation tool was utilized
using a 3D design program called Solidworks. This tool
allows the user to design the structure as it will be built,
then run simulations of varying forces and in various di-
rections onto the structure. The tool realizes the strength
of the material and shows the user where the weak points
are and at what point the structure will fail. Applied to the
structure is total downward force of 20,000 pounds in

### Table 3: Dynamic Forces at Various Flow Velocities

<table>
<thead>
<tr>
<th>Permeability Factor</th>
<th>0</th>
<th>0.5</th>
<th>Drag Force Per Leg (V = 1 m/s)</th>
</tr>
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<tr>
<td><strong>Drag Force</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal Conditions</td>
<td>N</td>
<td>4,094.85</td>
<td>2,047.43</td>
</tr>
<tr>
<td>(V = 0.5 m/s)</td>
<td>lb</td>
<td>20.19</td>
<td>460.10</td>
</tr>
<tr>
<td>Moderate Swell</td>
<td>N</td>
<td>16,379.42</td>
<td>8,189.71</td>
</tr>
<tr>
<td>(V = 1 m/s)</td>
<td>lb</td>
<td>3,680.77</td>
<td>1,840.38</td>
</tr>
<tr>
<td>Tsunami</td>
<td>N</td>
<td>65,517.66</td>
<td>32,758.83</td>
</tr>
<tr>
<td>(V = 2.5 m/s)</td>
<td>lb</td>
<td>14,723.07</td>
<td>3,308.54</td>
</tr>
</tbody>
</table>
the vertical direction, 30 pounds of drag force in the horizontal direction across the surface area of the structural legs as well as supporting cross beams, and a horizontal 444 pounds of drag force across the surface area of the basket at the top of the structure. These specific forces represent a worst-case scenario, a large swell event of 2.0 m/s velocity of water that the structure may endure. Results for critical sections of the structure using a custom FRP programmed material in Solidworks are as follows: a single 72” and hollow 4” x 4” x ¼” supporting leg (12 in total) would experience roughly 1,667 pounds of downward force creating a max displacement of 1.3 inches and maintaining a minimum FoS of 6.4; a single coral basket, walls made from 6.5” x ½” x 2” x ¼” (6 in total) and lined with a 1.5” thick FRP plate (simulates worst-case scenario of a mesh fully covered) will experience a downward force of 3,333.33 pounds with a maximum displacement of 0.28 inches and has a minimum FoS of 11.2. These results reflect the structural design a very viable option, which considers its strength and cost effectiveness. Several simulations had been done on varying member dimensions in an effort to minimize their size and overall cost. Initially we thought to use 6.5” x ¼” x 2” x ½” sized members for all horizontal and vertical beams. The 6.5” x ¼” x 2” x ½” member under specified loads showed a FoS of 5 and a displacement of 2.4”. The 4” x 4” x ¼” member has a FoS of 6.4 and a displacement of 1.3” showing that changing to cheaper dimensioned member was not only successful but also superior. In running an even smaller available member size, the 2” x 2” x ¼”, the member fails under same conditions showing a FoS of 1.4 with a displacement of 12.7”. This series of simulations solidified the 4” x 4” x ¼” member size for the support legs. Further solidifying the selection of member sizes for the horizontal supports, additional analysis was done on single “pie” pieces of the structure. This simple single pie piece is simply an independent ⅙ of the structure of which simulations will be ran in order to investigate weak points. The varying dimensions of members are the walls that make up the inner hexagon, the connecting beam to the outer hexagon and the outer hexagon itself. The simulations are ran for a basket made of 6.5” x ¼” x 2” x ½” and a basket made of 4” x 4” x ¼” beams, both using a 1.5” thick FRP solid plate simulating the mesh and both are situated over 72”—4” x 4” x ¼” support beams. The basket made of 6.5” x ¼” x 2” x ½” resulted in a minimum FoS of 11.5 as seen in Figure A-13 and a max displacement of 0.22 inches. The simulations were then applied to a pie piece with the basket made of 4” x 4” x ¼” resulted in a minimum FoS of 11.2 as seen in Figure A-14 and a max displacement of 0.28”. It was determined that the 4” x 4” x ¼” members perform just as well as the more costly 6.5” x ¼” x 2” x ½” members and thus solidifies our member dimension choice in the final design.

Scale Model. A scaled down prototype of the structure was 3D printed into individual pieces so that a handheld model can be assembled essentially like a toy model set seen in Figure A-15 and A-16. The purpose is to practice and understand the building process. This will aid exponentially in the staging and building process NOAA divers will encounter underwater. Having this handy will allow others to see the ease of build and deployment.

Conclusions

Summary of Initial Objectives. In summary, the main objectives of the structure were structural and environmental safety, ease of accessibility, and longevity, with a goal capacity of 170 ft3 of coral at maximum capacity. It was also designed to stay within a $25,000 budget, be easily cleaned, and easy to manufacture and deploy. It was found that the safest and most stable structure type was a stationary benthic design. To maximize lifespan, FRP was determined to be the choice material for its strength and resistance to corrosion.

Original Contributions. Multiple designs and considerations were discussed and explored including: spherical shapes, hexagonal shapes, single tiered or multi-tiered, floating or benthic type structures as well as how coral should be attached, how the structure should be anchored and how robust it needs to be to carry the coral load and survive environmental impacts. Figures A-17 through A-26 show many other variations of the structure. Unlike past coral reef nurseries, the proposed structure will be housing large, damaged coral up to 20,000 lbs. For ease of assembly, custom designed joints with sleeves for inserting structural beams were fabricated by Plas-Tech. Depending on the site location, the ocean floor may be very sandy. Thus, footing for the support legs were designed to have a wide base to prevent the structure from sinking and moving laterally.

Potential Design Improvements. The structure design could be improved to be more aesthetically pleasing. Considering the prospect of submarine tourism, the structure could afford more visual appeal. In addition, the design could be adapted for non-substrate and/or in-
clined areas. To achieve this, the footing would need to be redesigned to prevent lateral movements if drilling is not feasible.

**Overall Conclusion.** In conclusion, structure design and analysis has been completed. The FRP material has been ordered through Plas-Tech and the structure will be built in May 2017 to June 2017. Rather than a budget of $700,000 for the whole project, NOAA has approved a float of $25,000 to build one structure. A miniature model of the structure was 3D-printed to provide a visual for the NOAA client. Overall, manufacturing the structure will require a total of 100 man-hours of work for completion. A safe and easily accessible coral nursery will soon be used to revitalize large corals of opportunity.

**Acknowledgements**

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**References**


Appendices

Decision Making Matrices and Risk Assessment

Table A-1  Pairwise Comparison Chart: Design Parameters

<table>
<thead>
<tr>
<th>Criteria</th>
<th>A. Safety</th>
<th>B. Function</th>
<th>C. Coral Husbandry</th>
<th>D. Durability</th>
<th>E. Ease of Manufacture/Repair</th>
<th>F. Cost</th>
<th>Totals</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Safety</td>
<td>A 2</td>
<td>A 1</td>
<td>A 3</td>
<td>A 2</td>
<td>A 1</td>
<td>A 9</td>
<td></td>
<td>0.375</td>
</tr>
<tr>
<td>B. Function</td>
<td>B 1</td>
<td>B 3</td>
<td>E 1</td>
<td>F 1</td>
<td>B 4</td>
<td></td>
<td></td>
<td>0.167</td>
</tr>
<tr>
<td>C. Coral Husbandry</td>
<td></td>
<td></td>
<td>E 1</td>
<td>C 3</td>
<td>C 3</td>
<td></td>
<td></td>
<td>0.125</td>
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<tr>
<td>D. Durability</td>
<td>D 2</td>
<td>D 1</td>
<td>D 1</td>
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<td></td>
<td></td>
<td></td>
<td>0.167</td>
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<tr>
<td>E. Ease of Manufacture/Repair</td>
<td></td>
<td></td>
<td></td>
<td>E 3</td>
<td>E 3</td>
<td></td>
<td></td>
<td>0.125</td>
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<tr>
<td>F. Cost</td>
<td></td>
<td></td>
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<td>F 1</td>
<td></td>
<td></td>
<td></td>
<td>0.042</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>/24</td>
</tr>
</tbody>
</table>

Rating | Multiplier
---|---
Slightely More Important | 1
More Important | 2
Much More Important | 3

Table A-2  DMM: Benthic vs Floating Structure

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weight</th>
<th>Magnitude</th>
<th>Rating</th>
<th>Score</th>
<th>Magnitude</th>
<th>Rating</th>
<th>Score</th>
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<tbody>
<tr>
<td>Safety</td>
<td>0.375</td>
<td>Exceeds Expectations</td>
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<td>1.125</td>
<td>Adequate</td>
<td>2</td>
<td>0.75</td>
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<tr>
<td>Function</td>
<td>0.167</td>
<td>Exceeds Expectations</td>
<td>3</td>
<td>0.501</td>
<td>Adequate</td>
<td>2</td>
<td>0.334</td>
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<td>Coral Husbandry</td>
<td>0.125</td>
<td>Adequate</td>
<td>2</td>
<td>0.25</td>
<td>Exceeds Expectations</td>
<td>3</td>
<td>0.375</td>
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<tr>
<td>Durability</td>
<td>0.167</td>
<td>Exceeds Expectations</td>
<td>3</td>
<td>0.501</td>
<td>Poor</td>
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<td>Poor</td>
<td>1</td>
<td>0.125</td>
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<td>Poor</td>
<td>1</td>
<td>0.042</td>
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<td>2</td>
<td>0.084</td>
</tr>
</tbody>
</table>

Sum 1.001 0.77 2.669 0.61 1.835 16%

Rating  
Troll 0
Poor 1
Adequate 2
Exceeds Expectations 3

Table A-3  DMM: Structure Shape

<table>
<thead>
<tr>
<th>Structure</th>
<th>Cube (Cd = 1.05)</th>
<th>Sphere (Cd = 0.5)</th>
<th>Cylinder (Cd = 0.6 : 1.2)</th>
<th>Disk (Cd = 0.7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criteria</td>
<td>Rating</td>
<td>Score</td>
<td>Rating</td>
<td>Score</td>
</tr>
<tr>
<td>Safety</td>
<td>0.375</td>
<td>2</td>
<td>0.75</td>
<td>3</td>
</tr>
<tr>
<td>Function</td>
<td>0.167</td>
<td>1</td>
<td>0.167</td>
<td>3</td>
</tr>
<tr>
<td>Coral Husbandry</td>
<td>0.125</td>
<td>2</td>
<td>0.25</td>
<td>2</td>
</tr>
<tr>
<td>Durability</td>
<td>0.167</td>
<td>1</td>
<td>0.167</td>
<td>3</td>
</tr>
<tr>
<td>Ease of Manufacture &amp; Repair</td>
<td>0.125</td>
<td>3</td>
<td>0.375</td>
<td>1</td>
</tr>
<tr>
<td>Cost</td>
<td>0.042</td>
<td>3</td>
<td>0.126</td>
<td>1</td>
</tr>
</tbody>
</table>

Sum 1.001 1.835 2.544 1.160 2.21

Compared to Sphere (% off) 28% 54% 13%

Rating  
Troll 0
Poor 1
Adequate 2
Exceeds Expectations 3
Drag force calculation. Towards calculation of drag force on a thin annular disc, first let the temperature of seawater be 25 °C, then seawater viscosity \( \mu = 0.00096 \text{ kg/ms} \) and seawater density \( \rho = 1029 \text{ kg/m}^3 \). Subsequently, the Reynolds number Re can be calculated as:

\[
Re = \left( \frac{\rho V D_e}{\mu} \right)
\]

where \( h = 0.6 \text{ m} \) is the height of the disc when covered with coral specimens, \( r = 5 \text{ ft} = 1.5 \text{ m} \) and outer radius \( r_0 = 20 \text{ ft} = 6.1 \text{ m} \). Then the at \( V = 1 \text{ m/s} \) for normal conditions, then \( Re \approx 5,000,000 \) and at \( V = 2.5 \text{ m/s} \) for tsunami conditions, then \( Re \approx 13,000,000 \). These Re numbers gives a coefficient of drag of \( CD = 1.17 \) (Subramanian n.d.). Having determined this, the drag force \( F_D \) can be calculated as:

\[
F_D = 0.5 C_D \rho A V^2
\]

with surface area \( A \) for a thin annular ring with diameter \( D \) and outer diameter \( D_o \) defined as:

\[
A = \pi / 4 (D_o^2 - D^2)
\]

The resulting values are given in Table A-7:
Table A-7 Drag forces on holding platform.

<table>
<thead>
<tr>
<th>Drag Force</th>
<th>PERMEABILITY FACTOR</th>
<th>N</th>
<th>lb</th>
<th>N</th>
<th>lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Conditions (V = 0.5 m/s)</td>
<td>N</td>
<td>4,094.85</td>
<td>920.19</td>
<td>2,047.43</td>
<td>460.10</td>
</tr>
<tr>
<td></td>
<td>lb</td>
<td>4,094.85</td>
<td>920.19</td>
<td>2,047.43</td>
<td>460.10</td>
</tr>
<tr>
<td>Moderate Swell (V = 1 m/s)</td>
<td>N</td>
<td>16,379.42</td>
<td>3,680.77</td>
<td>8,189.71</td>
<td>1,840.38</td>
</tr>
<tr>
<td></td>
<td>lb</td>
<td>16,379.42</td>
<td>3,680.77</td>
<td>8,189.71</td>
<td>1,840.38</td>
</tr>
<tr>
<td>Tsunami (V = 2.5 m/s)</td>
<td>N</td>
<td>65,517.66</td>
<td>14,723.07</td>
<td>32,758.83</td>
<td>3,308.54</td>
</tr>
<tr>
<td></td>
<td>lb</td>
<td>65,517.66</td>
<td>14,723.07</td>
<td>32,758.83</td>
<td>3,308.54</td>
</tr>
</tbody>
</table>

**Assembly Drawings**

Figure A-1 First floating disk table design with estimated parameters.

Figure A-2 First benthic structure design.

Figure A-3 Spherical structure design.

Figure A-4 4 iterations of hexagonal design.

Figure A-5 Simple hexagonal truss structure.

Figure A-6 Simple hexagonal flat top design.
Figure A-7  Simple hexagonal build using available dimensions of FRP material.

Figure A-8  Final design—Top view, grating removed for support beam visual.

Figure A-9  Inner Joint.

Figure A-10  Outer Joint equipped with pad eye.

Figure A-11  Plate footing.

Figure A-12  Analysis of custom plate footing and support beam. Min FoS of 5.5.

Figure A-13  6.5 x 2 hollow beams—basket, min. FoS 11.5 at joining area.
Figure A-14  4” x 4” hollow beams—basket, min. FoS 11.2 at joining area.

Figure A-15  3D printed structure without grating and L-bars.

Figure A-16  3D printed structure in full.

Figure A-17  Benthic concept design with support columns.

Figure A-18  Benthic structure design with support tube.

Figure A-19  Floating structure design with ring buoy.
Figure A-20  Floating structure design with single buoy.

Figure A-21  Trimetric view of moored benthic structure with loaded coral trays.

Figure A-22  Top view of moored benthic structure design with loaded coral trays.

Figure A-23  Close up of idea for coral loading trays.

Figure A-24  Benthic robust truss build—pylons.

Figure A-25  Benthic robust truss build—mooring block.
**Figure A-26**  Floating robust truss build.

**Figure A-27**  Technical drawing of Inner custom joint for fabrication.

**Figure A-28**  Technical drawing of Outer custom joint for fabrication.

**Figure A-29**  Technical drawing of subsurface footing for fabrication.