Highwave Off-Shore Energy

HOSE 2

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***Abstract*— An artificial reef of floating HPDE pipe can be built in a harbor then towed and installed just offshore in the near shore of a sandy beach area. Position accurate installation is achieved using GPS-guided anchors. Precisely focusing wave energy on the reef has led to consideration of harvesting this focused energy. Structural reef pipes not only provide a secure platform for the wave energy collectors (WEC), but are also used as plumbing to push pressurized seawater to shore. Installed on the ocean bottom, porosity in the wave shoaling structure causes the reef to act like a snow fence to trap sand. Reduced energy on the inshore also encourages sand accretion on the beach inshore of the reef. This design has been refined over 20 years. The goal is to find a simple solution for a shore management device as a shoaling reef and to consider the harvesting of wave energy.**

I. Introduction

HOSE 1 was published and presented at the Oceans 11 conference in Kona, Hawaii, November 2011. In the previous IEEE paper we introduce efforts in the discovery and development of two corresponding technologies: an artificial reef design and a wave energy collector (WEC) design fitting this artificial reef. Our presentation also highlights findings on the environmental aspects of the technology.

Projects worldwide are currently being developed focusing on harvesting wave energy with the promise of electricity production. However, some ventures are occurring in countries displaying a lack of consideration for environmental and stakeholder interest. Conversely, we understand and implement the importance of clean energy, which produces minimal side effect while holding high environmental protection standards. Visual appeal, environmental protection and stakeholder interests are vital to consider for any wave energy design. Our guideline is as follows.

1. Nothing seen or floating on the surface of the ocean.

2. No materials that will degrade in the ocean when exposed over long periods of time for risk of failure, with environmental consequences if abandoned.

3. Compatible, safe and can co-exist with swimmers, divers, surfers, marine life and fisherman.

4. No noise or structuring that will affect marine mammals adversely.

HOSE 1 reported the work of G. Crapper in 1984 which educates wave energy is so efficient that a 9 second wave can travel around world 3 times if unobstructed and would only loose 10% of its amplitude on this voyage [1]. Can we conclude that offshore buoy collectors with offshore power grids are attempting to harvest just a very small fraction while most of the energy is still landing on the beach? Harvesting of wave energy has not been perfected and debate is still active on the best place in the ocean to harvest it. Unique approaches and perspectives should still be considered, investigated, and explored.

Wave energy becomes more compressed moving to the inshore. Layers of energy produced by storms from different directions are forced to exist together when the depth no longer supports the open transmission of these independent energy sources [2]. When the depth decreases further, it forces the wave refraction process. Greater energy events occur further offshore while lesser events transpire closer to shore. The area encompassed of breaking waves is a highly energetic region for any beach.

Wave refraction only occurs when the water column is too small to allow free transmission of the energy [3]. Refraction bends all differing wave sources inwards to orient perpendicular to the shore, and waves are slowed because of ocean bottom resistance, which takes away from the incoming energy [2]. The surface will rise as a result in the formation of swells as a part of this process. This is also referred to as amplification of the energy. Observed in first hand testing is the osculating wave motion where the motion under water not only goes towards shore but also back out to sea.

The Wave Roller technology from Finland [4] is one of the first WEC designs. They discovered this back and forth motion while diving on a wreak, observing a rusted bulkhead door moving backward and forward. Wave Roller found and considered this motion a key to harvesting ocean wave kinetic energy.

Any WEC ranging in size large to small is still tiny relative to the energy field. Of the small number of WECs being developed and tested, most are large and most designed for more offshore installation. If the collector is smaller in size, it can exist and harvest in that most energetic zone closer to shore. In theory a colony of smaller WECs is able to take improved advantage of typical wave activity. A group smaller WECs could be considered more efficient relative to the size of opportunity. Although a smaller collection mitt, being the energy is greatly compressed closer to shore, it is possible the right design can capture this condensed wave energy. A larger number of smaller WECs would be necessary to create a reasonable yield with this approach and have the advantage of being closer to shore.

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When considering ways to harness the energy, we gained invaluable insight from studying ocean craft designs. Surfboards stretching 9 feet in length and scaling 15 pounds can withstand the crushing energy of 20 foot waves. This is to say technology is available that can exist in highly energetic wave zones. Duck diving is a critical technique wave-riders use to paddle under and through incoming waves. This method is used in waves up to 10 feet in height to protect the human body and the equipment being used. Investigation of ocean craft design along with the understanding of the technique of duck diving facilitated consideration of WEC designs that can withstand robust amounts of impact and can survive extreme wave events in this incredibly energetic zone.

A new cottage industry has been created over the last 20 years focused on wave forecasting for customers concerned with swell conditions. Detailed analysis now predicts with great accuracy the location, direction, wavelength, period and size of swell in any location on Earth. Advances in predictability technology are now commonly used and understood by many individuals and mostly surfers. The science is important and daily forecasts could be important to wave energy harvesting. Regional wave climate would be essential to consider if determining the optimal size and slope of a wave-shoaling reef specific to energy harvesting. Offshore bathymetry and inshore features need to be carefully considered as both are critical in constructing a wave-shoaling reef as a wave energy collection field.

The HDPE reef technology is scalable to specify the size and slope of a reef to elicit and optimize wave refraction for any area. Any diameter and wall thickness HDPE pipe up to 54 inches is available and can be used, 12" to 26" inch is typical diameter. Any length and any width can also be utilized. A basic rectangular floating reef form will become a 3D "Y" shaped reef, a 3-D tri-pod form installed with the assist of precise GPS located anchors. The elongated forward section of this unique form initiates and or continues the refraction process and also acts as a natural place for wave energy harvesting. Average reef size would be the size of a football field but will be precisely determined for any location.

We discovered the importance of the forward section of a shoaling reef in the wave tank at Scripps Institute in 1984 [6]. A model of triangular form was built and placed in the tank, which failed in testing as an efficient shoaling reef. The experiment only worked as a shoaling reef when concrete blocks were laid offshore in front of the triangular wave-shoaling model; the triangle or V became a Y. The conclusion drawn from this test is the swell energy is more efficiently amplified when it has a gradual influence from the reef (Y shape). A longer sloping field (Y shape) will be seen by a variety of wave sizes and waves lengths. A smaller object (V shape) can form a surging wave but it tends to be erratic and only effective with waves of specific wavelengths.

Our Scripps Institute discovery helped formalize the forward wave shoaling area as a key component of the shoaling reef design. Many years later, we still see the forward section of reef as a natural opportunity to locate a colony of WECs for collection of focused wave energy. As the swell moves along this reef, each one of many WECs progressively add water and water pressure into the plumbing pipe.

Wave tank tests, along with a reef survey of an ideal natural reef by Fugro Inc provide the valuable insight of forces at work in any shoaling reef [5]. Waves break inshore of a reef and follow the same basic bathymetry of the offshore reef. Accretion of sand on the reef is typical, which increases the influence of the shoaling dynamic. Aside from the structural aspects of the tripod Y shape, the reef produces a sand accretion footprint inshore to form a typical tom bola with the width of inboard legs of the reef [6]. The distance between the inshore legs can define an area inshore that potentially would benefit from shore management, with an expectation of increased or stabilized sand levels on the beach.

The size and placement of the reef is precisely figured to accommodate the location where the largest waves are expected for the specific location. Along with beneficial shore protection, accurate placement of the reef also gives the largest wave energy collection opportunity for the WECs. Additionally correct reef position assures WECs are kept offshore of the breaking waves where abrasion is least. This also considers proper safety for recreation. Exact location, slope and size are developed using all aspects of the bathymetry and history of the area.

Oceaneering Inc. developed structural survival standards preparing for the 100 year storm, times two. This construction standard is primarily considered for the anchor durability, pipe wall thickness, and connector resilience. WECs must also be able to survive direct wave action in epic events.

In following sections, we have reiterated the most important information from our first paper that guided our research as it directly relates to our progress.

II. Background

A. *Ocean Wave Characteristics*

Wind-generated ocean waves transfer energy from one place to another. As waves travel in deep water (3), their velocity depends upon their period.

$$Depth > Wavelength/2 \qquad (1)$$

This has crucial effects on the way swell spreads away from a storm. Longer period waves travel faster than shorter period waves. This results in longer period waves arriving to locations before shorter period waves of the same storm origin appear. A mixed up sea full of different periods will gradually sort itself out as it freely propagates away from the storm center [2]. Ocean waves are unique in that they can propagate immense distances without much energy loss.

B. *Waves as an Energy Source*

It has been estimated that the total combined wave power in all the oceans of the world may reach close to ten terawatts [7]. It would be impractical to attempt to harness all available energy. However, it has also been estimated that about two terawatts of wave power is theoretically available to us in the form of waves that break on the coastlines of the world [2].

There are a few attractive advantages that wave energy possesses. Concentrating the Earth's solar energy input is to some extent shared by wind power, as is its form as mechanical energy rather than heat. The overall wind power flux is much greater, but it is spread over a height of several kilometers, whereas the wave power flux is largely contained in the top 10 to 20 meters of the sea, so that it can achieve power densities about ten times as large [8]. Also, wave power enjoys a theoretical advantage: with wind power the medium travels and there is a limit to the possible efficiency of extraction of 57% [9]; with wave power, the medium only oscillates and 100% efficiency of extraction is theoretically possible and has been nearly be attained in experiments [8]. Another advantage relates to the theory of energy conservation found in oceanic wave energy. For example, a wave with a period of 9 seconds would need to go three times round the world to lose even 10% of its amplitude [1]. Consequently, waves generated from far distances can be harnessed with great efficiency.

C. Best Locations for Wave Energy Collectors

Ideal locations for wave energy collector technology are those found to have the most consistent amount of substantial wave energy year-round [8]. Locations with the highest and most consistent wave power throughout the year are those subjected to the constant westerly winds found between thirty and sixty degrees north and south. For example, the southwest tip of Australia has an average wave power of 60 kW per meter and west of Scotland and Cape Horn over 70 kW [3]. This does not mean the locations with the absolute biggest waves are necessarily the best locations for WECs. The places popular for surfing tend to have relatively small overall wave power potential. The coast on Northern California only has about 30 kW per meter [3].

D. Historical perspectives on wave energy

In the 1970's, researchers used weather data and buoy measurements to determine that the wave energy in depths greater 50 meter in offshore locations yielded an average of 40 kW. This was about double the power density found in 10-meter waves near the shore [13]. Consequently most of the early efforts to harvest wave energy occurred in waters 2-10 kilometers from shore. Recently, it has been determined that waves much closer to shore carry 80-90% of usable energy and are far more reliable because the direction of the waves is consistently toward the shore. This is not the case with offshore waves, which move in all directions due to wind and storms [14].

E. Advantages to Small Scale Resources

Most efforts to date have been focused on high-energy areas but most efforts have yielded disappointing results. If smaller and more sensitive devices can be developed it would be possible to harvest the available energy anywhere and not be restricted to high-energy areas. If we have inefficient collectors or methods we are forced to harvest in high-energy areas to get any yield.

There are certain advantages to using smaller scale resources in wave energy collection. Precise consideration while choosing a location for wave energy collection is vital. Advantage can be taken of geographically special sites, for instance where deep water comes close to the shore. Certain locations may also be 'hot spots' for above average wave power due to refraction of wave energy over variable bottom topography [8]. A hot spot could describe an offshore wave shoaling reef. Whether onshore or in intermediate depths, device sites can be chosen to take advantage of such concentrations, which even averaged over the variety of wave climate conditions can amount to a double of the available resource [15].

This research reinforces the concept to create a hot spot and the goal in moving a shoaling reef offshore to encourage refraction; it still must be done only after very serious consideration of the local wave climate and offshore bathymetry.

F. Historic and Current Attempts Using Wave Energy Collectors

Historic attempts have used various mechanical techniques that utilize wave energy of focusing on the inshore area for harvesting. Now retired Captain John Heinzel of Navy base Ventura assisted in identifying three very simple considerations for the success of any WEC.

1. Consider simplicity to avoid failure as a result of fouling and or periodic huge wave conditions.

2. Consider typical and common sand intrusion to disrupt the function.

3. Consider logistics including cost of bringing electricity to shore.

Most systems that are unsuccessful experience failure because of one or all three of these very basic considerations. Our efforts were guided and shaped by these basic parameters.

G. Erosion Protection Using Artificial Reefs

Offshore breakwater projects have been used to reduce wave energy and erosion. A common result is a salient formation of the beach, meaning a seaward bulging shoreline and a wider beach inshore. Customarily the offshore breakwaters have been planned as partly submerged seawalls or rubble piles parallel to the shoreline [3]. Most recently, attempts have been made to employ artificial reefs as coastline erosion protection devices. Artificial reefs typically encourage ocean waves to expand their energy by breaking offshore, thereby reducing the impact of wave energy on the shoreline [16].

Problems have arisen with some of the current artificial reef designs made of large sand filled bags or tubes. These designs depend on mass to keep an artificial reef in place. Massive weight requires unnecessary effort and cost in the form of material expense and labor costs and intensive deployment efforts. Massive weight becomes a liability on sand or mud bottoms. The nature of sand and mud bottoms can best be described as solid fluids. Any device or object placed on the sea floor which has greater density than the "fluidized solid" bottom will eventually sink. This is one of the most common failures in this type of artificial reef.

The large bag artificial reef designs by nature have relatively small surface areas relative to weight. Relatively small surface area decreases the overall effect on wave formation, littoral current dissipation and energy absorption. These structures have an inability to disperse or absorb energy acting on the structure in the form of waves and/or currents. Littoral currents (currents moving parallel to shore) represent the main force that moves sediment and produces scouring along objects on the sea floor. These monolithic structures tend to redirect and increase the speed of littoral currents. This increased velocity supports even stronger littoral currents with increased carrying capacity. This is contrary to the ideal result of current energy absorption and sediment accretion within the reef structure.

Nature demonstrates that flexibility is a key quality for energy absorption and structure longevity in an ocean environment. Present art does not include this key quality.

HDPE is environmentally inert plastic, and can be made entirely of natural gas while including recycled material. Having extensive use in the ocean, HDPE is a robust building block for a reef and also for a WEC.

III. Biomorphic Wave Energy Collector (WEC) Design

Original intention was to find a suitable WEC design to position on our reef. No system was found, while only a handful of WEC concepts even consider harvesting close to shore. None of the commercial devices we discovered are compatible with our reef platform. We built a proof of concept device that worked to squirt water through a hose, caused by the compression of a flexible bladder pushed by wave energy in an ocean test. Six cycles per minute were witnessed in an environment of 10-second wave intervals. We discovered our parallel-o-gram design is simple and yet very powerful (Fig. 1). Additionally advantageous, the WEC of this design is protected from destructive wave energy when it is pressed down flat after compression. This motion is similar to the duck dive used during wave-riding. The ocean test provided encouragement to continue working on an optimal smaller WEC design closer to the wave breaking zone.

In the upright (uncompressed) position, the WEC is located perpendicular to the wave force. The typical oscillating wave motion is beneficial to the basic WEC design. A buoyant semicircular section on the top of the WEC will always be perpendicular to the base (Fig. 1). If the base of the WEC is attached to the reef, the top will always be flat to include a flotation element to bring the WEC back to towards the surface after compression. This design will only work if the wave energy is directed perpendicular to the beach, which happens naturally due to wave refraction on this wave shoaling reef.

Discussions continued on the energy conversion to consider pressurizing air instead of seawater. Typical check valves can work for both air and water. When testing the WEC using air, the air pushed out was significant. Because air is compressible and more prone to leakage and failure, we decided to continue to consider pumping seawater through the reef to convert the energy, as opposed to a closed system of air. We also considered a closed system with hydraulic fluid using the same basic design we were testing. Although common in oceanic applications, hydraulic fluid is toxic with leaks, giving us another reason to attempt to make it work with seawater.

HDPE is inert, very tough, economical, and can be made of 100% natural gas. The Rotomolding process is a good way to produce larger objects in HDPE. The strengths and weaknesses of rotomolding were considered and viable to produce the core of the WEC. Kayaks, water tanks, and buoys are made using this technique. Flotation is a benefit and structural aspects are also critical. One significant advantage of this molding process is the ability to easily add compressed foam in the walls. Also valuable is the capability of adding a good amount of holes to secure stainless structural plates for added weight and stiffness if needed. Drawings of our latest rotomolded design are shown in Fig. 2. In the drawing A and B are the two sides of the compression walls, D is the molded frame located on the top where the intake valves are located and holding the inflatable element C. The drawing shows E and F in two typical positions these drawing do not show the valves or bladder.

WECs, as in our first concept drawing (Fig. 1), are always submerged, located just offshore of the wave breaking zone, and oriented orthogonal to the shoreline or the incoming water surges. The submerged WECs use a bladder, in a generally bellow-like form. The wave energy pushes the WEC to compress and then expand the bladder, to force seawater through any one reef pipe to shore, and refills with seawater for the next cycle. Check valves trap the water in this bladder in the loading phase. With compression caused by a wave, water is forced out the bottom valves through check valves to the open plumbing reef pipe that goes to shore and provide water, which is then processed with Pelton Turbines [17] to produce energy. Seawater can be sent back to the ocean, or can used for estuary flushing, or even for desalination. Plumbing pipes will be the top most center pipes on the reef. The number of pipes used will be determined by the testing of head pressure and flow. The typical reef may have open or closed pipes. Plumbing pipes will be closed offshore and water movement will depend on what is being pushed by the WECs. The diameter inside the pipe and the number of WECs committed on any reef pipe will play a role to water pressure inside the pipe itself.

The key for energy conversion will be the head pressure achieved with any volume of sea water pushed to shore. The WECs will go from offshore to inshore on a single main pipe. Any number of WECs can be placed on a plumbing pipe. Wave energy will compress as it moves towards shore. This compression of energy will increases the power of the wave, which should maintain or increase the internal reef pipe pressure as the wave moves to shore. Each WEC can only add water if it has enough pressure to equal or be larger than the pressure in the pipe main. With enough head pressure at the shore, we can push the water uphill to a

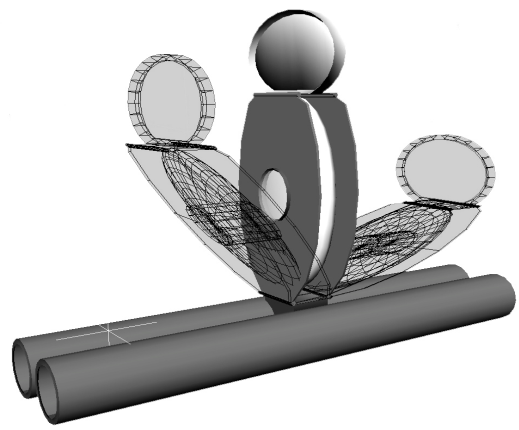

Figure 1. Original concept drawing of a WEC.

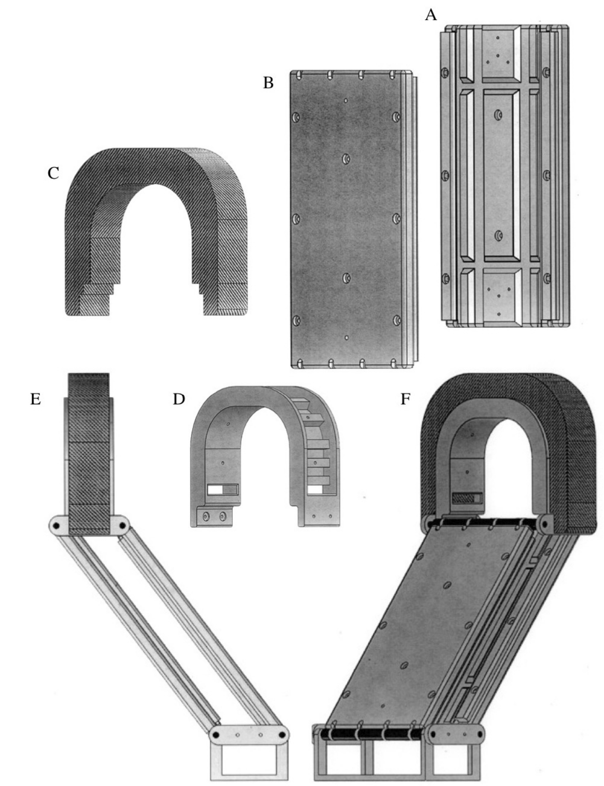

Figure 2. Latest concept drawing of WEC.

reservoir or to holding tanks to manage a constant yield for turbines. If not possible, the water can be processed directly on shore with a river returning back to sea.

A design is shown that would have check valves, a fish screen, and a deformable bladder. The emptied bladder will refill as all sides of the bladder are connected to the parallel-o-gram. The flotation device at the top can assist to re-load the WEC. The optimum balanced WEC design with this concept would translate any kinetic force to either push water or to reload water with either forward or backward forces. These forces are typical in the inshore as it relates to the reef perpendicular to the shore.

If twelve WECs are located per 12” pipe, and we consider 240 WECs total on the reef, we will have 20 dedicated plumbing pipes in the top center of the reef. The capacity of our most current WEC is 25 gallons or .095 cu meters. Given that an average wave can be a 10 second interval having 6 cycles per minute, we expect 150 gallons per WEC every minute. We can expect six cycles every minute in an average 10-second wave interval environment. If we consider only 100 gallons per WEC every minute, 240 WECs can push 24,000 gallons (94.6 cm) per minute, 1.44 million gallons (5678 cm) per hour, and about 34.6 million gallons or 131,000 cubic meters in 24 hours. In order to fit 240 WECs, the reef will be the size of a football field or up to 30% larger depending on slope and wave climate. Tank or ocean testing will determine head pressure and the best combination of the valve size and design and WEC size and WEC design. The pipe diameters can vary and are variable to be balanced for optimum performance and head pressure.

IV. Artificial Reef as the WEC Platform

A portable reef design of floating HPDE pipe design has evolved over the last 30 years can be installed offshore of the breaking waves. The reef would be designed to serve as the shuttle and a platform for the WECs. The pipe matrix structure can be the plumbing or also serve as a secure conduit for hoses for WECs if wanted. Stainless connectors could be included on the pipes with cover plates if not in use to located future WECs. This artificial reef design would allow for easy change and refinement of the WECs and also the ability to invite other designs from researchers to test on this format. Performance baselines can be easily determined. The shoaling reef with wave refraction focuses and increases the energy as typical before the wave breaks [16] which increases the physical wave energy for the WECs to harvest. The elevation of the reef can be determined and installed as optimal for the particular wave climate and local tides.

A. Placement of WECs

All WECs will be located in the elongated forward area of the reef on the body of this underwater arch form and forward of the typical breaking waves by design. The biomorphic WEC units will be located on top of the reef structure to eliminate issues with direct ocean floor substrate, above the turbidly and potential fouling due to actively moving sediment. The slick surface of the HDPE with the active wave wash on the elevated reef will have a greater chance of keeping fouling elements to a minimum and will be better than direct sea floor attachment for fouling issues.

B. Material Selection of Artificial Reef

An offshore reef system made of HDPE pipe was developed because of its hardy nature and longevity of the material and its history of use in the ocean. The use of HDPE pipe has many advantages. Low cost, long life, resilience, ease of construction, neutral buoyancy, environmentally inert properties, lack of corrosion potential, and wide availability all combine for an ideal structural element for inter-tidal use. The use of this material will allow construction of the reef offsite, which reduces logistics, environmental impacts, cost and complexity.

The resilient nature of HDPE and its resistance to work hardening insures dispersion of loads, which would be catastrophic to rigid structures of similar design in inter-tidal environments. This resilience also allows for this structure to “move” or adjust to changes in the sea floor due to sand movement. For instance, in the event of a severe storm where littoral currents are dramatically increased and in turn there is scouring of sand away from the reef; the reef can settle as sand is removed. In this case a ridged structure would become cantilevered and be subject to catastrophic failure. If the sand is deposited around the reef it can adjust to this as well due to its flexibility and buoyancy in the semi-fluid sand environment.

C. Buoyancy

The ability to adjust the buoyancy of the artificial reef is possible. HDPE pipe floats with open ends. Increased buoyancy can be achieved when the ends of the pipes are closed.

Materials such as sand or aggregate can be added as ballast within the HDPE pipes to decrease buoyancy and increase weight. It is possible to adjust the overall and/or specific pipe buoyancy by adding material within the pipes.

The buoyancy can be varied in several ways. At least one or more of the HDPE pipes can be filled entirely with air, at least one or more of the HDPE pipes can be filled entirely with ballast or sand, or at least one or more of the HDPE pipes can be partially filled with air and partially filled with ballast. It is also reasonable to have the pipes open and passive in the final structure as the pipes naturally float in seawater typical density of .9555.

V. Installation and Maintenance

A. Construction Procedure

In contrast to a large sand bag artificial reef design, the pipe matrix can be deployed and anchored with a high level of precision. When filled with air the reef can be towed into position and then "sunk" and anchored to the ocean floor.

Any pipe diameter and thickness are possible with engineering specification. The low specific gravity pipe material and pipe matrix anchoring system prevent the reef from settling into the sand over time.

During the construction phase of this reef all pipes will be fitted with closed ends to create the maximum amount of buoyancy for towing. Connecting clamps would also be installed in calm water within a harbor. In this initial assembly phase, the assembled reef will look like a log/pipe raft floating on the water's surface. Assembly of the reef in a controlled environment such as a harbor greatly reduces construction impacts.

B. Installation

Built in a harbor, the 12" to 26" OD pipe raft has flexible connectors perpendicular to a typical 150-meter length. The parallel pipes define a simple raft form that can travel for a distance in the ocean and can then be installed using GPS assisted precision anchors on the sea floor with minimal environmental disruption on a sand or rock bottom. The flat raft now changes to an underwater structural arch form as pulled down with cables to the anchoring from the deep offshore end first. This arch can split in the middle towards shore to form a larger "Y" shape in the plan view; these legs now fanning out towards the beach can keep a structural curve on both legs in the elevation view.

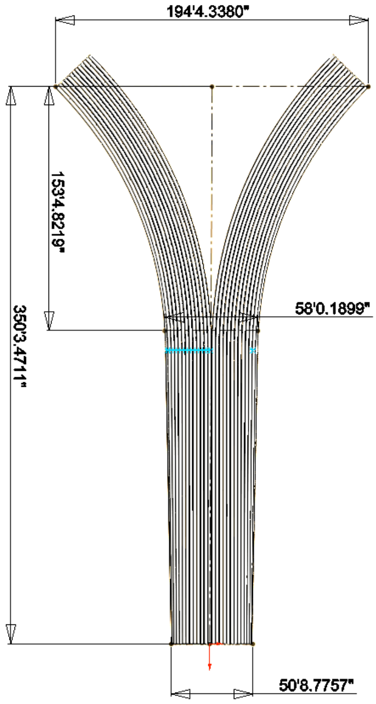

Figure 3. Plan view of typical installed reef, shown here in feet.

C. Deployment / Removal

The offshore leg elevation considers the optimum performance for the WECs for refraction in the specific locations. The anchoring system will utilize screw anchors or other advanced mooring technologies. Anchors will be installed where the perimeter of the structure will locate. Cables on the end points of both sides of the line of structural connector clamps tether the reef downward to the parameter anchoring. This process will start on the most offshore end well away from any breaking waves. The most inshore legs will be last to install and at high water and low swell conditions. After the installation is complete, the reef can be backfilled with sand supplied by a barge to mitigate captured sand from the reef if that is a concern. Tank test modeling shows sand delivered on the offshore section of the reef will eventually settle into the lower sections of the reef matrix. The natural wave action will trap the sand in and inshore of the structure. Sand will be expected to locate and stabilize in and behind the structure as observed in modeling tanks.

If necessary, the reef can be removed by divers jetting the sand out from reef anchors, disconnecting the cables and reversing the screw anchors out of the sand bottom. Removal could also involve displacing the seawater from the reef's dedicated flotation pipes by introducing air back into some of the pipes if the natural floatation was not enough to raise the structure.

D. Portability

Portability facilitates construction, transport and placement of the reef. The benefit of this portable reef design is that it can be removed or relocated. The ability to increase buoyancy of the reef allows the entire structure to be re-floated and moved.

E. Scalability

It is known that in order to encourage ocean waves to break, the size of an artificial reef is critical. In general the larger the reef, the more control over wave action any design will have. The ability to cost effectively add to the size and/or modify the shape of an artificial reef vastly increases its potential to control or modify ocean waves. The modular design of this reef makes it intrinsically scalable. Scalability increases efficacy and also intrinsically lowers cost during both the design and construction phases.

F. Environmental Loading and Structural Engineering

Because the reef will be installed in a dynamic ocean environment, it must be capable of withstanding the forces experienced at such a site. Historical environmental conditions at the study site will be gathered and reviewed to arrive at a set of site-specific design criteria. The environmental conditions of interest will be wave height, period, and direction; longshore current velocity; wind speeds; bathymetry; and sediment type and stratigraphy.

With these data and the size and conceptual shape of reef from the shore processes and wave climatology work, the loads on the reef structure will be calculated. The loads will be calculated using empirical, numerical, or computer-based analysis methods. The anchoring system will be specified based upon the loads applied to the structure. Once the loads are known, they can also be applied to the conceptual structure for sizing and detailing the design of the HDPE pipes, connections, and anchoring attachment points.

Advanced suction piles, screw anchors, or a combination of mooring technologies will be assessed as a part of the final engineering effort and directed by all available expertise. Screw anchors have been proven to be highly reliable in anchoring HDPE outfalls and pipelines in the marine environment. Screw anchors are easily installed in a sand bottom by rotation and result in holding forces of up to 40,000 pounds each. The final step in structural engineering and anchoring system design will be to produce a complete set of fabrication and assembly drawings of the reef.

G. Flexibility

The inherent flexibility of HDPE pipe and the flexibility built into the pipe connection system allow the individual elements and complete assembly to absorb/react to the forces exerted on it in the ocean environment. The flexibility and modularity of the connecting clamps allow the entire structure to share the forces acting upon it. This "load sharing" is a key quality of the reef structure. Highly concentrated loads, such as a wave breaking on the reef structure, are dispersed throughout the structure by virtue of the bending of the HDPE pipe and the elongation and compression of the flexible linking elements. The nature of the design of the connecting clamps adds hoop strength to the HDPE pipes at the connection points. This reduces the tendency of a pipe to collapse or flatten under bending loads. Inclusion of connecting links of various shapes and/or lengths and/or compression struts between pipes and the natural HDPE pipe's flexibility allows manipulation of the pipe elements to non-linear or curved forms. This ability greatly increases design adaptability to location and conditions as well as overall strength.

Figure 4. Example of a simple HDPE pipe connection clamp design.

VI. Shore Erosion Protection

The Y-shaped artificial reef dissipates wave energy over a wide range of wave conditions and directions. The leg that extends in the offshore direction forms a ridge and interacts with the incident waves via refraction and diffraction processes, amplifying the wave height incident to the reef and essentially guiding the waves toward the inboard area of the reef. The waves then break on or inshore of the left and right side of the V-shaped inner reef structure. The sloping and angled shape of the inboard reef results in extensive wave dissipation through an extended distance of breaking along each leg of the reef. Therefore, for a broad range of sea states, the inshore wave energy is reduced, encouraging formation of a shoreline salient and a wider sand beach [28].

A. Shoreline Evolution Modeling

To guide the placement of the reef and to predict the shoreline's response to the new hydrodynamic regime, the hydrodynamic effects of the reef and the resulting impacts to local sediment transport and shoreline morphology will be modeled. The existing waves will be characterized initially using available measured wave data and modeling. Wave refraction-diffraction, shoaling, and breaking are important coastal processes that govern sediment transport and short-term coastal morphology. These physical processes will be modeled using numerical modeling techniques. The wave characterization will serve as input to a shoreline evolution model. Bathymetric and beach surveys will be used to chart the evolution of the existing site condition from the pre-existing site condition. The future wave conditions (post-project) can be modeled, and the future shoreline will be estimated. In addition to providing a basis for design parameters, orientations and geometries, the output of the models will also serve as input to structural design of the mooring and anchoring system.

B. Permeability/Porosity

Permeability is a fundamental element of this design. This reef utilizes a principal similar to that of a snow or sand fence. The flow of wind carrying sand or snow is slowed down and redirected by a "permeable" fence to encourage accretion of snow or sand around the fence. Permeability is achieved by fastening HDPE pipes together with a space between them. This characteristic offers the advantage of increased surface area, which is otherwise not directly exposed to ocean forces. This means any force acting on the structure is dispersed over a larger area equating to lower force per unit area on the reef itself.

The circular cross section of pipe tends to disperse or redirect forces from any given vector. Flow around a pipe slows down as it passes the pipe and changes direction to random vectors. Another advantage is sediment that is being carried in the decreasing flow precipitates or falls to the ocean bottom within the reef structure.

A primary function of this design is to accrete sediment within its structure. Sediment accretion adds to the stability of the reef structure and its effectiveness to encourage ocean waves to break offshore, while primarily assisting in shoreline erosion protection.

In locations where sand is not available for accretion the reef's permeability and cylindrical pipe form elements are used primarily for energy absorption and distribution throughout the structure. Without permeability effective sand accretion and efficient load sharing would not be possible.

VII. Recreational and Marine Life Benefits

A. Recreation

A wave that breaks simultaneously along its entire crest is called a 'close out' in surfing. Due to the wave focusing effect, waves passing over the reef are amplified and wrap around the reef. Thus wave crests curve as they approach the reef (refraction) and slow down above the reef because of the wave's interaction with a shallower depth. Due to the focusing effect of the reef, the wave height is now greater in this section of the wave crest [16].

When waves approach from a direction straight on to the reef, the amplified section of the wave over the offshore leg eventually become a breaking wave "peak" with a progressive breaking zone "peeling" to the left and right along or typically inshore of the V shaped reef section. When waves arrive at an angle, the amplified wave crest propagating along the offshore arm interferes constructively with the wave crest approaching from the inboard portion of the reef, resulting in waves breaking over the inboard section [16].

Surfing waves have local economic benefits and offshore reefs typically have stable beaches. The benefit of the recreational aspect adds value that could be the amenity to give stakeholders support for ease of permitting especially in the USA. WECs on the reef will absorb energy and will act to lower wave heights to some degree and promote greater and promote more accretion of sand inboard of the reef.

B. Marine Life Considerations

The reef, if left installed in any location, can become a skeleton for a natural living reef. It was discovered that adding texture on the HDPE would encourage attachment and marine growth. If the HDPE is left polished where the collectors are located, the surface will remain mostly free of fouling in active wave areas.

The offshore portion of the reef will provide the opportunity for attachment and potential for marine invertebrates and inter-tidal fish habitats. Abalone habitats have been designed and informally tested with success in Proteus Marine Laboratories in Port Hueneme, California [28]. Passive reef pipe can provide unlimited selective habitat for many native species.

References

[1] G. Crapper, "Introduction to water waves," Ellis Horwood, Chichester, 1984.

[2] World Energy Council, "Renewable energy resources: opportunities and constraints 1990-2020," London.

[3] T. Butt, "The WAR report: Waves are resources," Surfers Against Sewage, Wheal Kitty Workshops, St. Agnes, Cornwall, TRD 0RD, 2010, pp. 2-45.

[4] http://aw-energy.com/about-waveroller/waveroller-concept, accessed 2013.

[5] http://www.fugroconsultants.com/locations/ventura, accessed 2013.

[6] G. Ross and S. Pleskunas, "High density Polyethylene pipe reef for surfing and shore protection," Proceedings of the 3rd International Surfing Reef Symposium, Raglan, New Zealand, June 22-25, 2003, pp. 5-7.

[7] J. Brooke, "Wave energy conversion (Elsevier ocean engineering series)," Elsevier Science, 2003, pp. 204.

[8] D. Mollison, "Wave climate and the wave power resource," Hydrodynamics of Ocean Wave- Energy Utilization, IUTAM, Symposium, Lisbon, 1985. pp. 133-156.

[9] N. Lipman, P. Musgrove, and G. Pontin, "Wind energy in the eighties," Peregrinus, Stevenage, 1982.

[10] R. Bagnold, "Motion of waves in shallow water: Interaction between waves and sand bottoms," Proc. R. Soc, Lond, A 187, 1946.

[11] D. Mollison, "Wave energy losses in intermediate depths," Appl. Ocean Res. 5, pp. 234-237, 1983.

[12] O. Shemdin, K. Hasselmann, S. Hsiao, and K. Herterich, "Nonlinear and linear bottom interaction effects in shallow water, In turbulent fluxes through the sea surface, wave dynamics and prediction," Plenum Press, New York, 1978, pp. 347-372.

[13] C. Barras, "Plenty of Wave Energy to be Harested Close to Shore," New Scientist, May 2011

[14] M. Folley, "Near or Far- Siting Wave Energy Converters," International Water Power Magazine, 27 October 2010.

[15] E. Mehlum, "Wavetrack," Norwave AS, Forskningsvn 1, Blindern, Oslo 3, Norway.

[16] A. West, "Wave focusing surfing reefs – a new concept," Department of Civil and Geotechnical Engineering, Delft University of Technology, Delft, the Netherlands, Proceedings of the 3rd International Surfing Reef Symposium, Raglan, New Zealand, June 22-25, 2003, pp. 360-370.

[17] http://www.newmillshydro.com/products/item/6/pelton-turbines/, accessed 2011.

[18] R. Inger et al., "Marine renewable energy: potential benefits to biodiversity? An urgent call for research," Journal of Applied Ecology, vol. 46, issue 6, December 2009, pp. 1145-1153.

[19] A. Gill, "Offshore renewable energy: ecological implications of generating electricity in the costal zone," Journal of Applied Ecology, vol. 42, 2005, pp. 605–615.

[20] D. Croll, C. Clark, J. Calambokidis, W. Ellison, and B. Tershy, "Effect of anthropogenic low-frequency noise on the foraging ecology of Balaenoptera whales," Animal Conservation, vol. 4, 2001, pp. 13–27.

[21] P. Madsen, M. Wahlberg, K. Tougaard, K. Lucke, and P. Tyack, "Wind turbine underwater noise and marine mammals: implications of current knowledge and data needs," Marine Ecology Progress Series, vol. 309, 2006, pp. 279–295.

[22] A. Popper, J. Fewtrell, M. Smith, and R. McCauley, "Anthropogenic sound: effects on the behavior and physiology of fishes," Marine Technology Society Journal, vol. 37, 2003, pp. 35–40.

[23] B. Wilson, R. Batty, F. Daunt, and C. Carter, "Collision Risks Between Marine Renewable Energy Devices and Mammals, Fish and Diving Birds," Report to the Scottish Executive, Scottish Association for Marine Science, Oban, Scotland, PA37, 1QA, 2007.

[24] M. Marchesan, M. Spoto, L. Verginella, and E. Ferrero, "Behavioural effects of artifical light on fish species of commercial interest," Fisheries Research, vol. 73, 2006, pp. 171–185.

[25] J. Petersen and T. Malm, "Offshore wind farms: threats to or possibilities for the marine environment," Ambio, vol. 35, 2006, pp. 75–80.

[26] G. Rilov, and Y. Benayahu, "Rehabilitation of coral reef fish communities: importance of artificial-reef relief to recruitment rates," Bulletin of Marine Sciences, vol. 70, 1999, pp. 185–197.

[27] J. Bohnsack, D. Harper, D. McClellan, and M. Hulsbeck, "Effects of reef size on colonization and assemblage structure of fishes at artificial reefs off south-eastern Florida, USA," Bulletin of Marine Science, vol. 55, 1994, pp. 796–823.

[28] W. Musial, S. Butterfield, and A. Boone, "Feasibility of floating platform systems for wind turbines: preprint," Report number NREL/CP-500-34874, National Technical Information Service, US Department of Commerce, 2003.

[29] G. Vella et al., "Assessment of the effects of noise and vibration from offshore wind farms on marine wildlife," DTI/Pub URN 01/1341, 2001.

[30] J. Castro, J. Santiago, and A. Santana-Ortega, "A general theory on fish aggregation to floating objects: an alternative to the meeting point hypothesis," Reviews in Fish Biol. and Fisheries, vol. 11, 2002