Seasteading Engineering Report:
Floating Breakwaters and Wave Power Generators

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Our Mission: To further the establishment and growth of permanent, autonomous ocean communities, enabling innovation with new political and social systems.

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1. INTRODUCTION

Many fixed and floating breakwater systems have been developed to protect coastal areas and harbors from waves. These structures were primarily designed to resist or absorb wave energy in relatively shallow water and mild wave conditions.

The location of the first seasteads will likely be the exclusive economic zones off the coast of supportive countries. However, independent and quasi-autonomous communities that want more freedom in the future will likely establish themselves in the middle of the sea. Hence the need to build seasteads that can tolerate the deep seas where wave periods and energies are usually much larger than those close to the shores.

New types of effective breakwater devices adapted for offshore applications need to be developed in order to create zones of calm water and harness the tremendous wave energy to generate power. Since no such device has yet been tested and approved at large scales, the work presented highlights some of the major floating breakwater and wave generator systems that have been patented in the last few decades.

In this paper, the different types of existing and developed wave power generators and breakwater systems will be presented. An assessment of the most promising and compatible concepts, with a potentially high wave damping and energy production capacity will then be carried out (with approximate mass and material cost estimations). Finally, recommendations on future areas of research and improvements will be explained in further details.

2. OBJECTIVE

The main purpose of this study is to conduct an investigation into the current state of the art related to floating breakwaters and wave energy generators. The research also aims to provide a preliminary engineering assessment of the size, effectiveness and applicability of deployment for the potential breakwater and energy devices, in the open ocean, at a scale consistent with the floating mega-city scenario.

3. WAVE POWER GENERATORS

The oceans cover 70 percent of the world and harbor a vast untapped source of renewable energy that can be transformed into electricity. There have been many ideas to try to extract some of the energy potential from the ocean through the years. The oldest ones are several hundred years old, and on a global basis there are more than 1000 patents on different constructions to harness this potential [1].

The forms of ocean renewable sources can be broadly categorized into: a) Ocean Tides b) Ocean Waves c) Ocean current d) Ocean Thermal Energy Conversion (OTEC) and e) Salinity Gradient. Of these, the three most well developed technologies are ocean tides, ocean waves and OTEC [2].

OCEAN TIDES

Tidal energy is harnessed from the rise and fall of seawater caused by the gravitational action of the Sun and the Moon. As tide ebbs and flows, underwater turbines spin like windmills. The turbines are mounted on a gearbox shaft, which generates electricity. There are three different generating methods of tidal energy: tidal stream generator, tidal barrage and dynamic tidal power.

Tidal stream generator uses a similar principle to ocean currents. Tidal barrage is only cost effective to install in those parts of the coast where the sea high and low differ more than 16" [2]. Tidal barrage power plants store the water in a reservoir, similar to a dam with floodgates that allow water to flow into high tide and release the water back during low tide. In favorable places like straits and inlets, large volumes of water can reach high speed and provide energy density in the area of 500-1000 W/m2.

OCEAN WAVES

Wave energy is the use of energy produced by the movement of the waves. Waves are formed by winds blowing over the water surface, which make the water particles adopt circular motions. Wave power has a high energy density, typically 30-60 kW/m along the coast (see figure 1 below). Out in the open sea, energy density can be up to 100 kW/m. A variety of technologies have been proposed to capture the energy from waves; however, most are in an early stage of development. This makes it difficult to predict which technology or mix of technologies would be most prevalent in future commercialization. Some of the more promising designs that have been the target of recent developmental efforts and are appropriate for seasteading being considered in this assessment are terminators, attenuators, point absorbers, and overtopping devices.

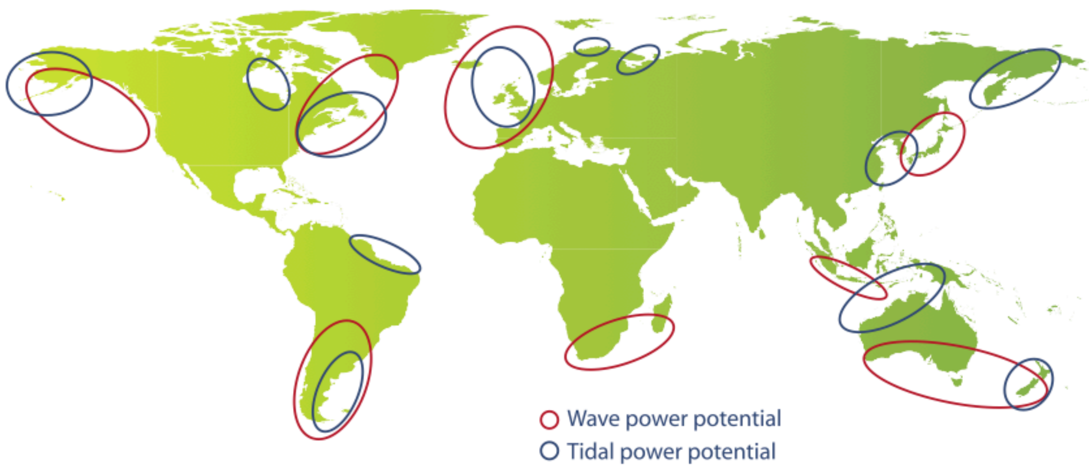

Figure 3.1 Tides and waves can provide us with enormous amounts of renewable energy worldwide. Source: Renewable Energy: R&D Priorities IEA 2006/red. Illustration: Endre Barstad [3].

OCEAN CURRENT

Ocean current power has many similarities with tidal power. It harnesses the kinetic energy contained in ocean currents. The process is based on kinetic energy converters similar to the windmills in this case using subsea installations. Ocean current power probably won't be economically viable until 2020 at the earliest.

OTEC

OTEC is based on the use of thermal energy from the sea based on the temperature difference between the surface of the sea and deep waters. The use of this type of energy requires that the temperature gradient is at least 68F [4]. OTEC plants transform energy into electrical energy using the thermodynamic cycle called the "Rankine cycle" to produce electricity. In the long term, this can give an energy output of 0.04 W/m, but commercial technology will probably not be accessible before 2020 [1].

SALINITY GRADIENT

Osmotic Power or salinity gradient power is the energy obtained from the difference in salt concentration between seawater and river water through the process of osmosis. Energy density can be 1MW/m3 of fresh water. The technology needed to utilize this energy source commercially is still 5-15 years away at the earliest [1].

According to the International Energy Agency, the potential for total global resources from ocean-related energy sources is up to 100,000 TWh/year. To put this into perspective, humanity's total energy consumption is 13,200 TWh/year [3].

	Resource	Technologies	Estimated global resource	Cost estimate
Wave power	Onshore, Along the coast, offshore	Coastal tidal reservoir, straits	8000-80,000 TWh/year	99-137 USD/MWh
Tidal power	Coastal tidal reservoir, straits	Propeller, turbines	200 TWh/year	-
Ocean currents	Offshore	Turbines, reciprocating wing	800+ TWh/year	56-168 USD/MWh
Salt power	By river mouths in the ocean	Semipermeable osmotic membrane	2000 TWh/year	-
Ocean thermal Power (OTEC)	Offshore deep sea	Thermodynamic Rankine-cyclus	10,000 TWh/year	-

Table 3.1 Resources, technologies and cost estimates for ocean power technologies. Source: Renewable Energy: R&D Priorities IEA 2006 [3].

4. CATEGORIZATION OF TECHNOLOGIES

This report outlines the current progress and breadth of ocean energy technologies by providing a brief overview of the different ocean renewable energy systems in development, with emphasis on systems based on waves energy converters (WEC).

There are a large number of concepts for wave energy conversion; over 400 wave energy conversion techniques have been patented in Japan, North America, and Europe [5]. Despite this large variation in design, WECs are generally categorized by location, type and operating principle. Please note that this technology is rapidly evolving so the devices mentioned are by no means a complete list of all available wave energy converters.

4.1 LOCATION

WECs were initially developed on the shoreline and thus are defined as first-generation devices. These devices are easy to maintain and are less likely to be damaged in extreme conditions. This leads to one of the disadvantages of shore-mounted devices, as shallow water results in lower wave power.

Later, near-shore or seabed anchored second-generation devices were developed. Near-shore devices are defined as devices that are in relatively shallow water. Like shoreline devices, a disadvantage is that shallow water leads to waves with reduced power, which limits the harvesting potential.

Utilizing concepts from first- and second-generation devices, third generation or offshore WECs evolved. It takes longer to develop third generation devices due to the harsher sea environment these WECs must be able to withstand. Offshore devices are generally in deep water although there is little agreement about what constitutes 'deep' water. Descriptions range from 'tens of meters' [6], to 'greater than 40 m (130ft)' [7], or 'a depth exceeding one-third of the wavelength' [8].

The advantage of siting a WEC in deep water is that it can harvest greater amounts of energy because of the higher energy content in deep water waves [9]. However, offshore devices are more difficult to construct and maintain, and because of the greater wave height and energy content in the waves, need to be designed to survive the more extreme conditions adding cost to construction.

4.2 TYPE

Despite the large variation in designs and concepts WECs can be classified into three predominant types: 1) Attenuator or Hinged Control Device; 2) Point Absorber or Buoyant Moored Device; and 3) Terminator.

4.2.1 Attenuator or Hinged Control Device

An attenuator is a floating device oriented parallel to the direction of the waves which effectively rides the waves. Movements along its length can be selectively constrained to produce energy. The differing heights of waves along the length of the device causes flexing where the segments connect, and this flexing is connected to hydraulic pumps or other converters.

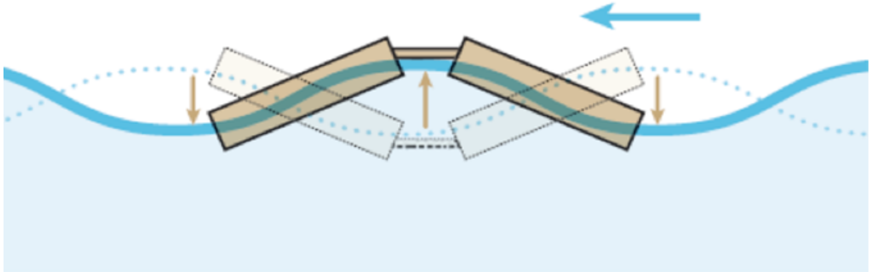

Figure 4.1 Attenuator device.

Pelamis

The Pelamis wave energy converter is a huge "sea snake" in the water. It generates power in the hinged joints that connect its cylindrical tube sections. As waves move the joints up and down and side to side, hydraulic rams drive an electrical generator.

The electricity is carried to shore via a sub-sea cable [10,11].

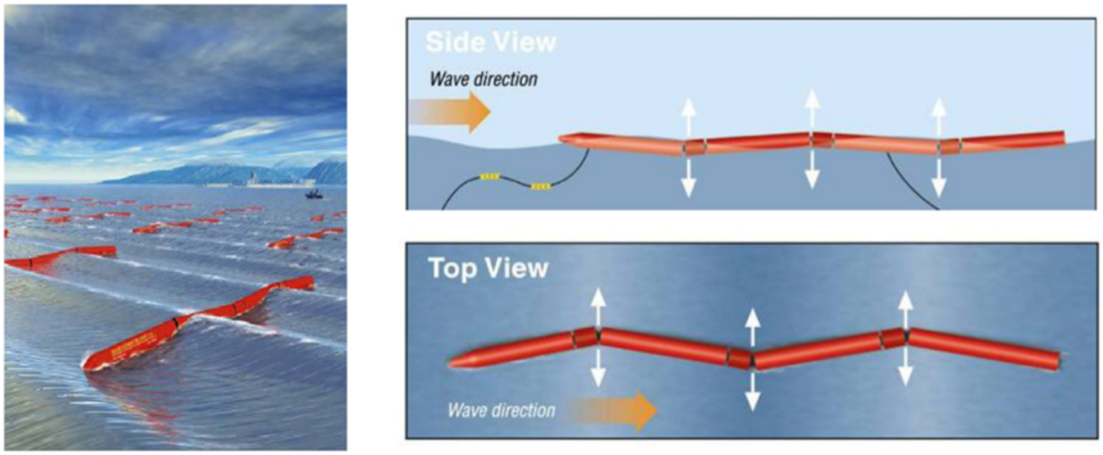

Figure 4.2 The worm-like structure called Pelamis WEC (Wave Energy Converter) consists of cylindrical steel sections that are hinged together. (Source: Ocean Power Delivery Ltd. 2006)

Anaconda

The system essentially consists of a rubber tube filled with water, which is placed in the sea. Both ends of this rubber tube are sealed and it is anchored with its head to the waves. It is squeezed or enlarged locally by waves causing pressure variations along its length.

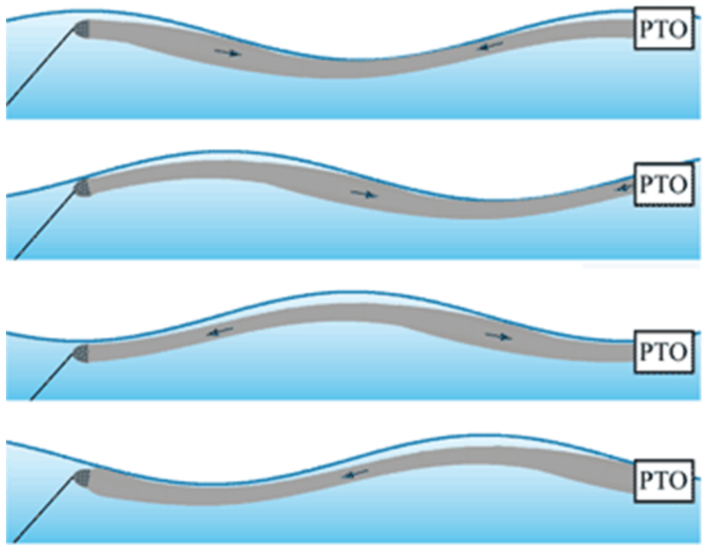

Figure 4.3 Anaconda wave energy converter - sketches of the device in waves travelling from left to right, at four phases of the motion, with a power take-off system at the downwave end. Arrows indicate the direction of the oscillatory internal flow [15].

As a wave passes, the bulge tube is lifted with the surrounding water and causes a bulge wave to be excited, which passes down the tube's diameter like a pulse in an artery, gathering energy from the sea wave as it goes. Continuous energy gathering results from resonance between the bulge wave and the sea wave. Energy from the sea wave is stored in the rubber as it stretches. The bulge wave travels just in front of the wave rather like a surfer, picking up energy as it progressively increases in size. At the end of the tube the bulge wave energy surge drives a turbine [12, 13, 15].

OceanStar

OceanStar captures the wave to accelerate and collapse through a series of small turbine generators. This is an elegant, rugged, and energy- and cost-efficient solution to harnessing the power of waves. The OceanStar's high level of scalability is essential to reach the large surface areas required to reach utility-scale ocean power generation.

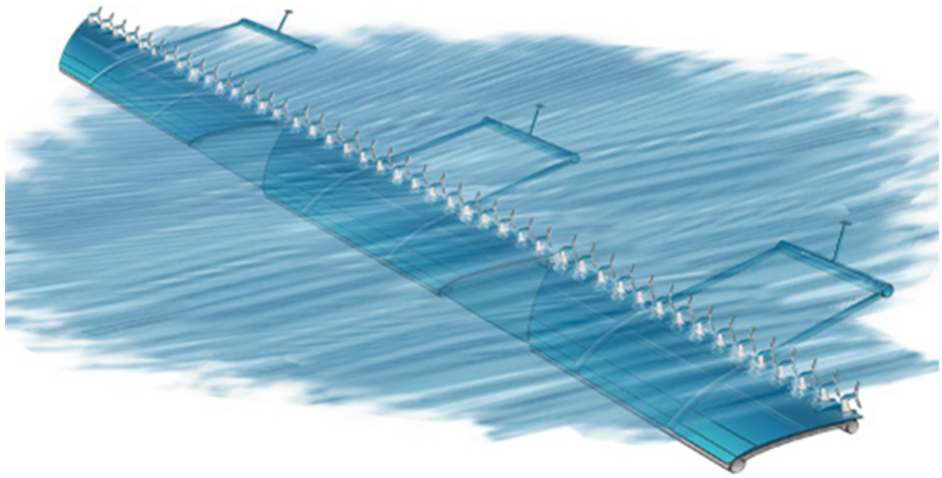

Figure 4.4 OceanStar wave energy converter [16]

Wavestar

The Wavestar machine draws energy from wave power with floats that rise and fall with the up and down motion of waves. The floats are attached by arms to a platform that stands on legs secured to the sea floor. The motion of the floats is transferred via hydraulics into the rotation of a generator, producing electricity. Waves run the length of the machine, lifting 20 floats in turn. Powering the motor and generator in this way enables continuous energy production and a smooth output. This is a radical new standard and a unique concept in wave energy; it's one of the few ways to convert fluctuating wave power into the high-speed rotation necessary to generate electricity [17].

Figure 4.5 Wavestar

Centipod

Centipod technology is designed to harness the power available from waves, in a similar way as the Wavestar, Hidroflot [18] and Poseidon. The multi-megawatt Centipod system is based on a stable floating platform, which is actively yawed to wave front exposure. As waves travel across the Centipod, pods rise and fall, generating electricity. The Centipod provides a viable method for delivery of competitively priced energy [19].

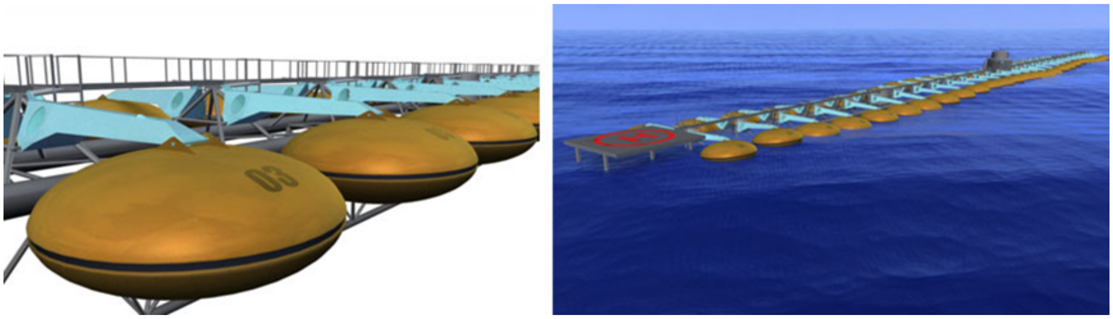

Figure 4.6 Centipod.

Poseidon

Poseidon is a concept for a floating power plant that transforms wave energy into electricity. The power plant furthermore serves as a floating foundation for offshore windmills, thus creating a sustainable energy hybrid. It is designed for location offshore in areas with considerable flux and has significantly higher efficiency and energy production compared to other wave energy systems.

Poseidon utilizes and absorbs the energy from the waves, reducing the height of the waves and creating calm waters behind the front of the plant, making the platform easily accessible (acting as a floating breakwater) [20, 21].

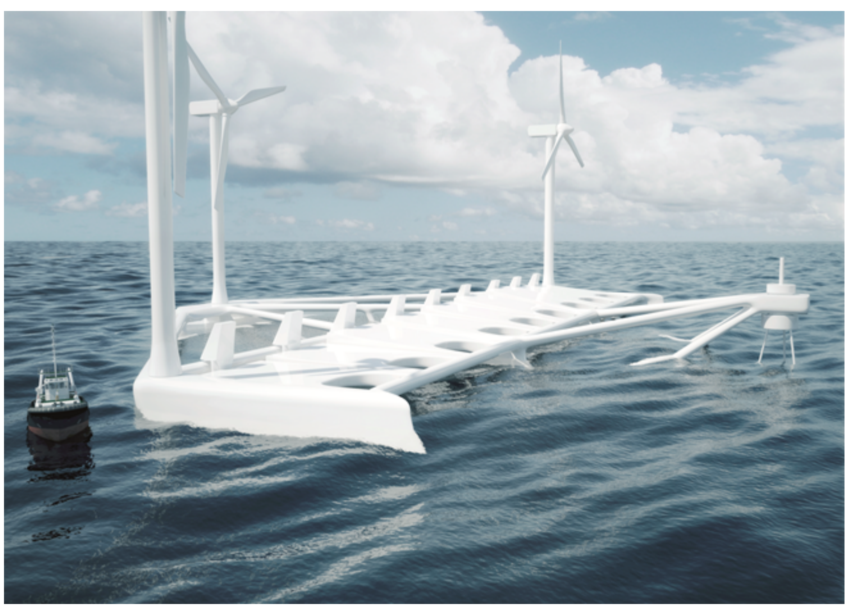

Figure 4.7 Poseidon [20]

4.2.2 Point Absorber or Buoyant Moored Device

A point absorber is a floating structure that absorbs energy in all directions through its movements near the water surface. The power take-off system may take a number of forms, depending on the configuration of displacers/reactors. The device possesses small dimensions relative to the incident wavelength.

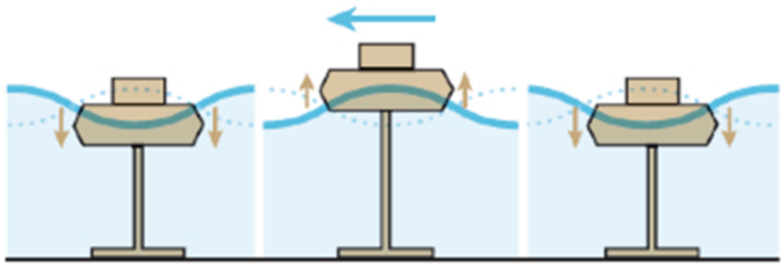

Figure 4.8 Point Absorber.

FO3

FO3 is the Norwegian wave power project that is more advanced than most of its competitors. The wave-powered generator is integrated in a floating platform construction, which is built in composite. Under the platform there are a series of plastic bridging boats that move with the waves. The bridging boats run a hydraulic system that again generates electric energy. The full-scale platforms will be 36 meters (118 feet) wide and 18 meters (59 feet) high. They will be placed together with common monitoring and control systems and common connection to the distribution grid on shore through a deep-sea cable. Installed output from the plant is planned to be 1.5 MW per platform. The platforms will be unmanned and have an expected minimum service life of 15 years [22, 23].

Figure 4.9 1:20-scale FO3

PowerBuoy®

OPT's PowerBuoy® wave generation system uses a "smart," ocean-going buoy to capture and convert wave energy into low-cost, clean electricity. The rising and falling of the waves causes the buoy to move freely up and down. The resultant mechanical stroking is converted via a sophisticated power take-off to drive an electrical generator. The generated power is transmitted ashore via an underwater power cable. The buoys are spaced to maximize energy capture.

There are similar systems to PowerBuoy, such as Euro Wave Energy [24] and WaveBob [25]. PowerBuoy is made out of simple steel and utilized conventional mooring systems. The simple design allows a high level of scalability (100+ MW) [26,27].

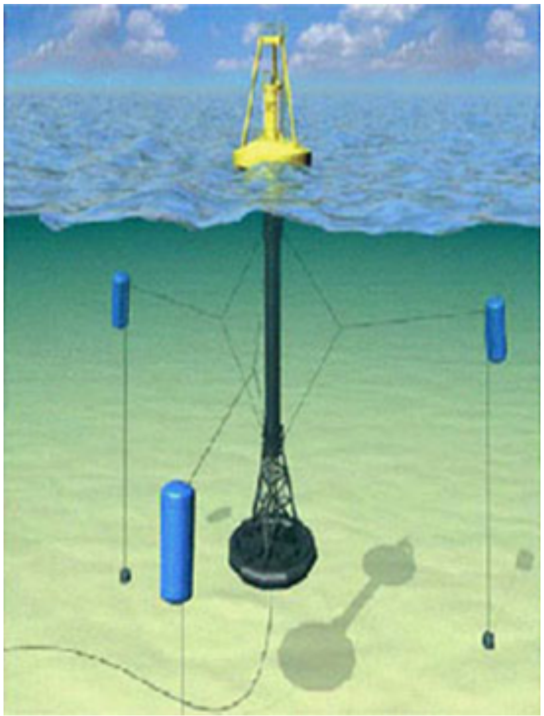

Figure 4.10

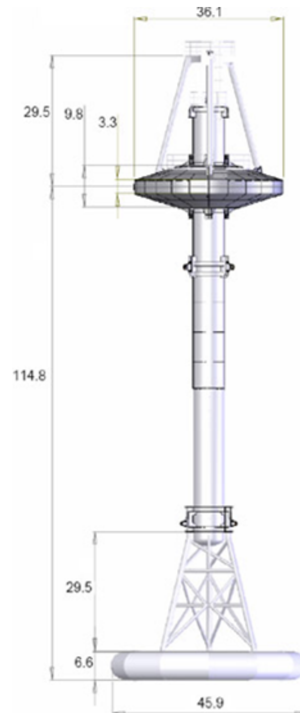

Figure 4.11

4.2.3 Terminator

Terminator devices have their principal axis parallel to the wave front (perpendicular to the predominant wave direction) and physically intercept waves. One example of a terminator-type WEC is the Salter's Duck, developed at the University of Edinburgh [28].

Salter's Duck

The wave device opposite incorporates an electricity generating system based on a pendulum connected to a generator. As the Salter Duck 'bobs' up and down on the waves, the pendulum swings forwards and backwards generating electricity. Salter Ducks are large in size and are arranged in set patterns to take advantage of wave formations [29].

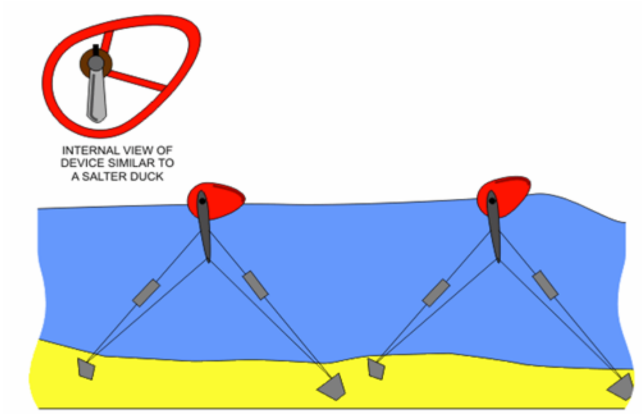

Figure 4.12 This diagram shows how the Duck's head would bob with waves [30].

4.3 Operating principle

Within the categories identified above, there is a further level of classification of devices, determined by their mode of operation. Some significant examples are given below.

4.3.1 Submerged Pressure Differential

These devices are typically located near the shore and are attached to the seabed. The motion of the waves causes the sea level to rise and fall above the device, inducing a pressure differential in the device. The alternating pressure can then pump fluid through a system to generate electricity.

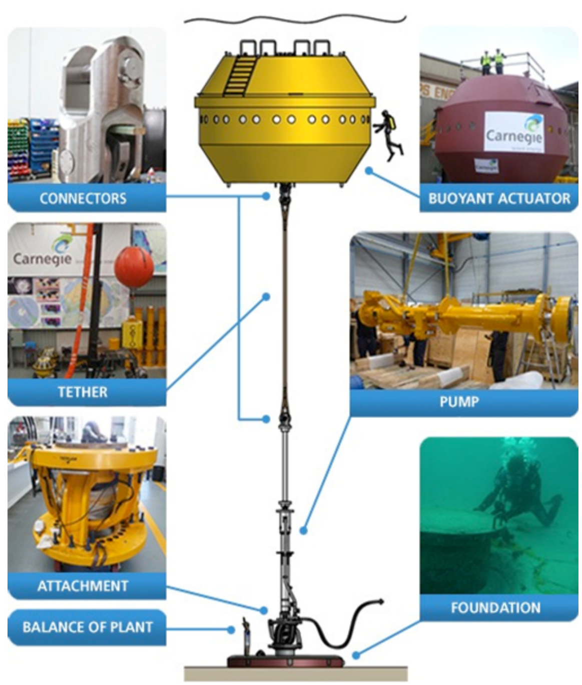

Figure 4.13

CETO

Unlike other wave energy systems currently under development around the world, the CETO wave power converter is the first unit to be fully submerged and to produce high-pressure water from the power of waves. This compressible sub-sea device expands and contracts in response to the changes in pressure exerted by a passing wave. Therefore the motion (and hence swept volume) is not limited to wave height, but is related to the change in relative pressure.

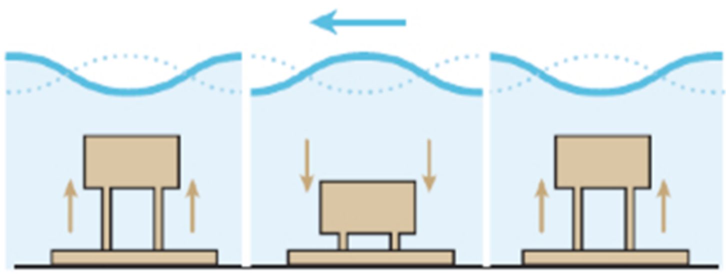

Figure 4.14 CETO Commercial Scale Unit [31]

By delivering high pressure water ashore, the technology allows either zero-emission electricity to be produced (similar to hydroelectricity) or zero-emission freshwater (utilizing standard reverse osmosis desalination technology). The system can also be used for co-production of zero-emission electricity and freshwater, ideal for future seasteads.

4.3.2 Oscillating Wave Surge Converter

This is a near-surface collector, mounted on a pivoted joint near the seabed. The joint/arm oscillates as an inverted pendulum in response to the movement of water in the waves. This device extracts the energy caused by wave surges and the movement of water particles within them.

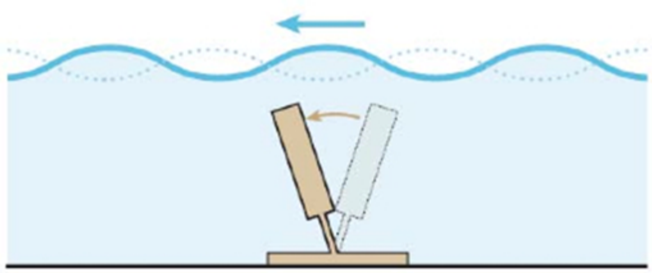

Figure 4.15

Oyster

AQUAmarine Power's Oyster wave power technology captures energy in nearshore waves and converts it into clean sustainable electricity. Essentially Oyster is a wave-powered pump that pushes high pressure water to drive an onshore hydro-electric turbine.

The Oyster wave power device is an 18m (59ft) wide oscillator that is attached to the seabed at depths of between 10 and 15 meters (32 – 49ft). The device is designed to harness the wave energy around half a kilometer from the shore benefiting from the more consistent seas and narrower directional spread of the waves in this location [34].

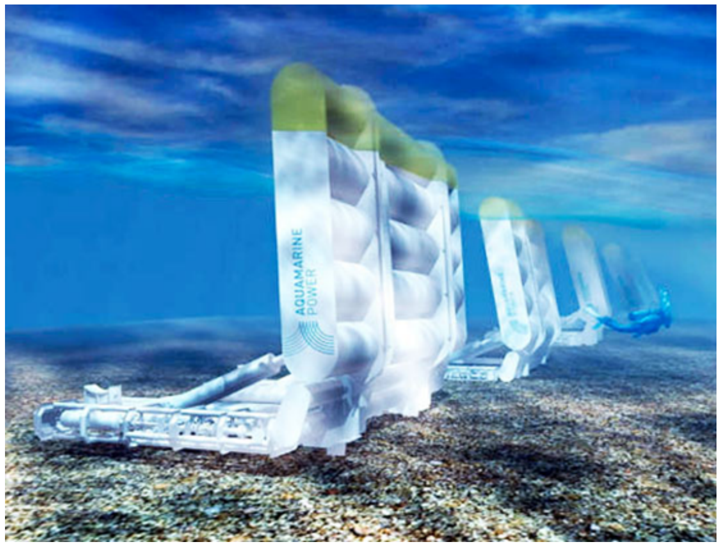

Figure 4.16 Oyster is a simple mechanical hinged flap connected to the seabed at around 10m depth. Each passing wave moves the flap, driving hydraulic pistons to deliver high pressure water via a pipeline to an onshore electrical turbine. (Credit: Aquamarine Power Ltd.) [32,33]

Pendulum

The Pendulum was an early design of an oscillating wave surge converter. This Japanese wave-power device consists of a flap hinged over the opening and the action of the waves causes the flap to swing back and forth. The motion powers a hydraulic pump and a generator. The Pendulum can be integrated in a breakwater construction. This will be a cost effective wave converter, utilizing the foundation of the breakwater (see figure below).

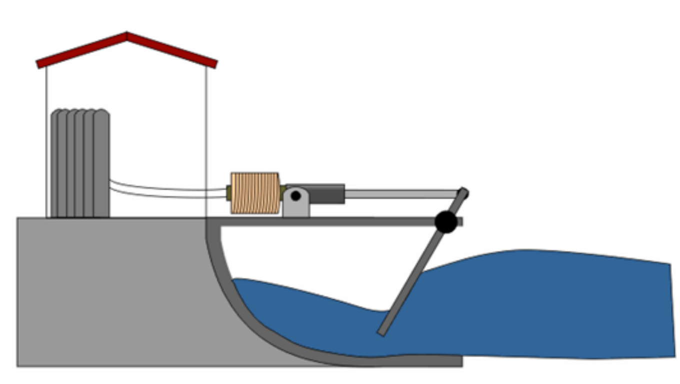

Figure 4.17 Pendulum concept [35]

Langlee E2

The Langlee wave power converter concept is revolutionary. Sea waves move the hinged water wings of each submerged Langlee module, analogous to the way sound waves move the diaphragm of a microphone. Energy absorbed from wave motion by the moving water wings drives a hydraulic system, which powers electric generators.

For maximum energy capture, Langlee power converter modules float, while the system is moored to the seafloor. Each Langlee module has two pair of water wings, located one-half wavelength apart, which move in opposing directions as waves pass through the Langlee array [36].

Wavepiston

The defining feature of the WavePiston concept is to harvest energy along a string mounted with numerous vertical plates, the string having a length larger than a typical wavelength. The plates are moved by the horizontal component of the oscillatory wave movement, and energy is harvested from the movement of the plates.

Due to the stochastic nature of the ocean waves acting on each plate, the forces on the individual plates will tend to cancel each other out with the net result that even very long WavePiston systems can be moored using only moderate means, thus making the WavePiston system relatively cost-efficient to install [39].

Figure 4.18 Langee E2 Fledging wave power technology [37,38].

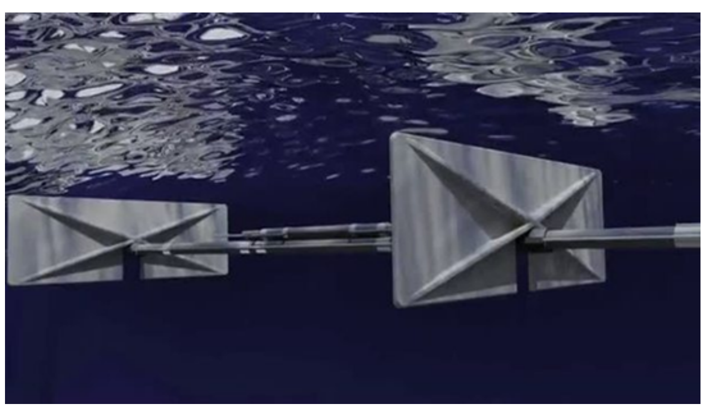

Figure 4.19

WaveRoller

A WaveRoller device is a plate anchored on the sea bottom at its base. The to and fro water movement allows the plates to transfer the kinetic energy to a piston.

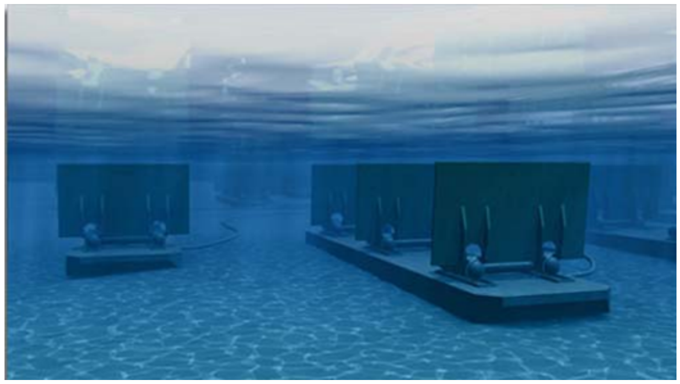

Figure 4.20 WaveRoller concept [40]

bioWAVE

The bioWAVE is mounted on the seafloor, with a pivot near the bottom. The array of buoyant floats, or "blades", interacts with the rising and falling sea surface (potential energy) and the sub-surface back-and-forth water movement (kinetic energy). As a result, the pivoting structure sways back-and-forth with the waves, and the energy contained in this motion is converted to electricity by an onboard self-contained power conversion module, called O-DriveTM [41]. The O-DriveTM contains a hydraulic system that converts the mechanical energy from this motion into fluid pressure, which is used to spin a generator.

Figure 4.21 bioWAVE system in operation [42]

4.3.3 Oscillating Water Column

An Oscillating Water Column (OWC) is a partially submerged, hollow structure. It is open to the sea below the water line, enclosing a column of air on top of a column of water. Waves cause the water column to rise and fall, which in turn compresses and decompresses the air column. This trapped air is allowed to flow to and from the atmosphere via a turbine, which usually has the ability to rotate regardless of the direction of the airflow. The rotation of the turbine converts this air movement into electrical energy [43]. This concept has been used in the last two decades in some ports and breakwater systems around the world. The Vizhinjam OWC in Kerala, India [44]; the mouth of Douro river, in Porto, Portugal [45] and Mutriku in the Basque country, northern Spain [46].

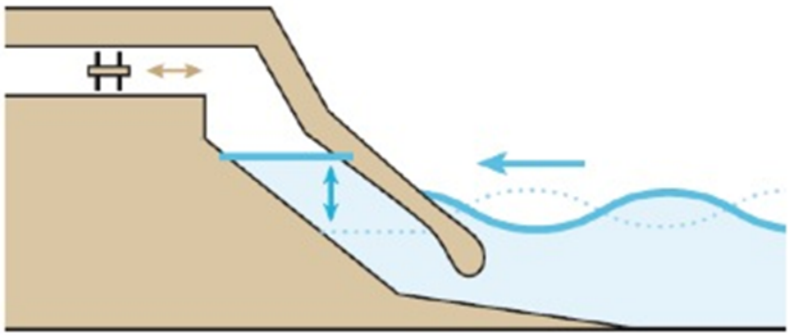

Figure 4.22 OWC Concept.

SPERBOY

The SPERBOY is based on the 'oscillating water column' principle. As the buoy moves up and down on the waves, air is displaced from a chamber within the buoy, which then drives turbine-generators situated on top. Maintenance requirements are kept to a minimum due to a limited number of moving parts, which are located above the sea's surface making them more easily accessible. The planned design will use advanced laminated concrete in its construction and has a 40-50 year life expectancy [47, 48].

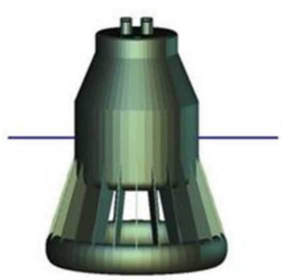

Figure 4.23

blueWAVE

Oceanlinx has developed proprietary technology for extracting energy from ocean waves (using OWC) and converting it into either electricity or desalinated seawater.

The company has developed three prototypes of the OWC concept in the last decade. In 1997 the Mk1 was developed. It was a full-scale evaluation unit (fixed to seabed) capable of producing 500 kW. After this in 2007, they introduced the Mk2 with an offshore design. It was a 1/3-scale research unit (floating) producing 15 MW. In 2009, they released their most ambitious model, the Mk3. It is a pre-commercial scale unit with two turbines (airwave) with a >2.5 MW rated capacity [49].

Figure 4.24

AWS-III

The AWS-III is a multi-cell array of flexible membrane absorbers that convert wave power to pneumatic power through compression of air within each cell. The cells are inter-connected, thus allowing interchange of air between cells in anti-phase. Turbine-generator sets are provided to convert the pneumatic power to electricity.

The AWS-III is designed for practical operation and maintenance by utility power generators. The large, stable vessel structure provides a safe environment for on-board maintenance of generation equipment and ancillaries whilst the patented system for cell maintenance allows rapid exchange of the flexible wave absorber cells. It has no exposed moving parts and uses simple, proven power take-off technology and is designed for practical maintenance – key factors for high availability.

Figure 4.25 1:9 Scale model of the AWS-III under test on Loch Ness, June 2010 [50]

Limpet 500

The LIMPET 500 (Land Installed Marine Pneumatic Energy Transformer – 500kW) is an OWC built into the shoreline near Portnahaven, on the island of Islay off the west coast of Scotland. This project is similar to the Pico project in Portugal [51] or the Vizhinjam OWC in India [44]. The Construction began at the end of 1998, with the civil structural works substantially complete by the end of August 2000. The plant was commissioned at the end of 2000. Limpet was the world's first grid connected commercial-scale wave energy plant. It comprises an in-situ concrete collector, with the generation unit installed immediately behind the rear collector wall. Self-rectifying Wells turbines mounted directly on the generator shaft have been used, enclosed by a small turbine hall. The process air exits the turbine hall via an acoustic attenuator, installed behind the turbine hall [53 & 54].

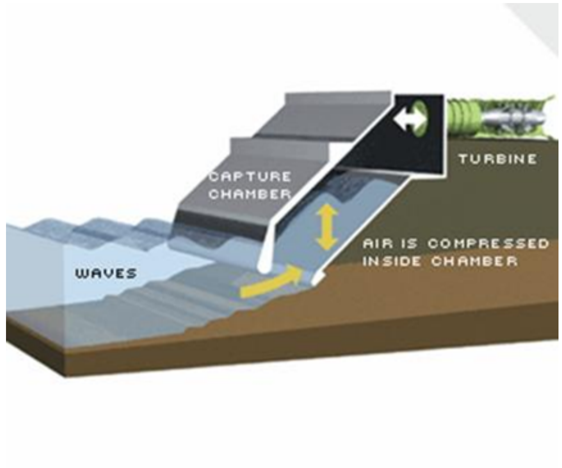

Figure 4.26 Limpet 500 [52]

Rho-Cee

Float Inc. is the company under the design of the Offshore Ocean Energy System. The system is able to exploit the renewable resources of the oceans (wind, wave and ocean currents) in the same structure, similar to the Poseidon [20] or the hexi-float floating system [55]. This revolutionary system accelerates the offshore market development and reduces the overall cost for the ocean energy exploitation. This system also integrates the Potential Energy Storage (PES) system to reduce the principle objection to renewable energy sources intermittency.

The Rho-Cee, as Float Inc. has named their wave energy converter system, is a large, floating oscillating water column to be moored in deep water. The Rho-Cee is integrated with Float's pneumatically stabilized platform (PSP) to take advantage of controllable stability, load capacity and the deck area that it provides.

Float is currently proposing to develop a 30MW, 1250m long Rho-Cee floating breakwater for installation in Northern Iberia. The Float PSP is now being considered for the basic platform in the Urbanisme sur Mer Programme of the Principality of Monaco [56].

Figure 4.27

4.3.4 Overtopping Device

This type of device relies on physical capture of water from waves released from a reservoir above sea level, the water being returned to the sea through power-generating low-head turbines. An overtopping device may use collectors to concentrate the wave energy.

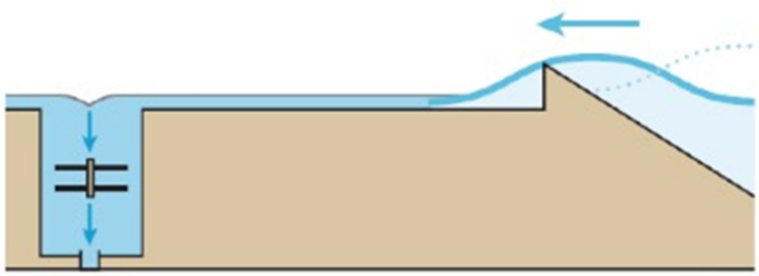

Figure 4.28 OD Concept

Seawave Slot-Cone Generator (SSG)

SSG is a wave energy converter based on the wave overtopping principle utilizing a total of three reservoirs placed on top of each other, in which the potential energy of the incoming wave will be stored. The water captured in the reservoirs will then run through the multi-stage turbine. This turbine has the advantage of utilizing different heights of water head on a common turbine wheel. The multi-stage technology will minimize the number of start/stop sequences on the turbine, even if only one water reservoir is supplying water to the turbine, resulting in a high degree of utilization [57].

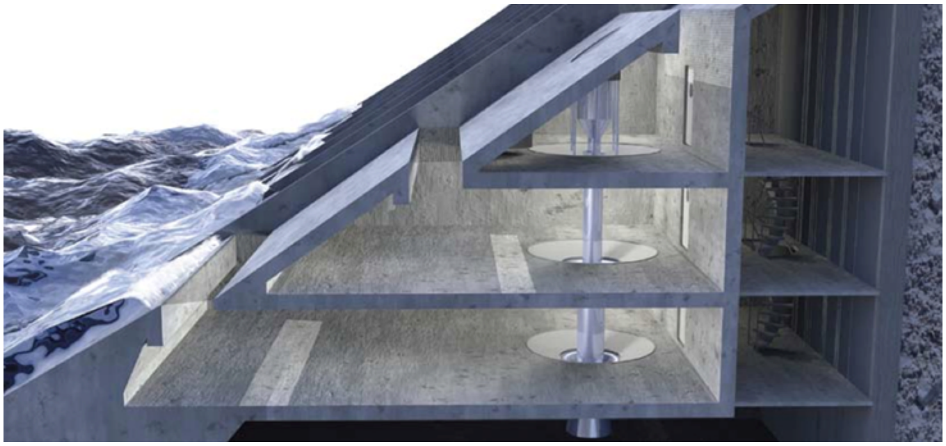

Figure 4.29 SSG has the advantage of harvesting the wave energy in several reservoirs placed one above the other, resulting in high hydraulic efficiency [57].

Wave Dragon

The basic idea of the Wave Dragon wave energy converter is to use proven principles from traditional hydro power plants in an offshore floating platform.

The Wave Dragon device allows ocean waves to overtop a ramp, which elevates water to a reservoir above sea level. This creates a 'head' of water, which is subsequently released through a number of turbines and in this way transformed into electricity. Water is returned to the vents in the base of the unit.

The first prototype connected to the grid is currently deployed in Nissum Bredning, Denmark. Long-term testing is being carried out to determine system performance [58, 59].

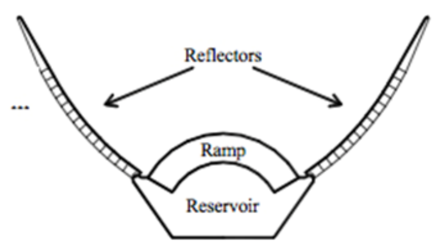

Figure 4.30 Overtopping devices have been designed and tested for both onshore and floating offshore. The Wave Dragon (shown above) is an example of an offshore overtopping device [58].

5. FLOATING BREAKWATER SYSTEMS

The design of such devices remains a complex and iterative process due to the interdependency of each design factor. Both the breakwater structural integrity and wave transmission performance depend on the breakwater geometry, mass, and mooring properties. Similarly, mooring forces also depend on the breakwater geometry and mass.

The wave loadings generally dictate the design of a floating breakwater. However, other types of loads such as those associated with currents, water-level variations, ice, wind, and vessel impacts should also be evaluated in the design process.

Presented below is a short list of the main factors to be considered in the design/selection of breakwaters at an early stage:

- Layout of breakwaters
- Environmental conditions
- Utilization conditions
- Executive conditions
- Costs of construction
- Construction terms
- Importance of breakwaters
- Available construction materials
- Maintenance

5.1 FLOATING BREAKWATERS

Four fundamental factors which greatly influence the design of floating breakwaters are the following: (1) buoyancy and floating stability, (2) wave transmission, (3) mooring forces, and (4) breakwater and structural integrity.

FDN engineering [60] lists four main types of floating breakwaters that the company has developed and installed over the years. They are constructed from fixed-shape modules, allowing almost any configuration and length to be achieved. The product range for different wave conditions is shown in the following figure.

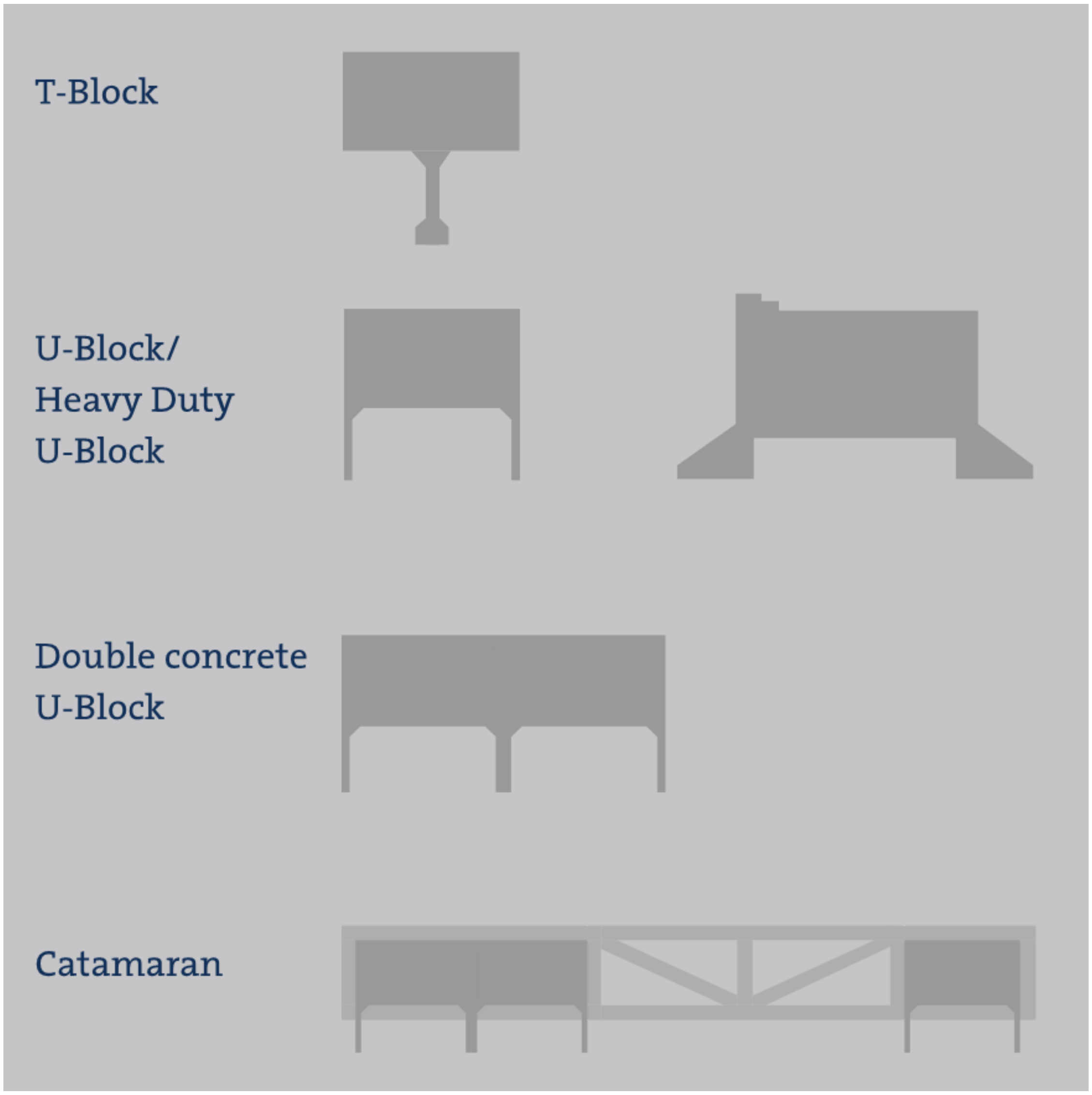

Figure 4 FDN Breakwaters

For floating breakwaters, the specific gravity is usually controlled in order to alter their hydrodynamic response, hence improving its wave breaking efficiency. In general, the performance of a floating breakwater depends on the strongly non-linear interaction of the incident wave with the structure dynamics. The assessment of that performance can also be very complex due to the forces induced by the mooring system and the connections between the modules.

A brief description of the main types of floating breakwaters that have been patented over the last few decades is presented below.

Tazaki et al [61]

One of the simplest floating breakwaters consists of a single or multiple pontoons attached together to damp the waves action. Here it is composed of both a floating material (outer pontoon on the figure) as a floating source and a weighting material (central pontoon on the figure).

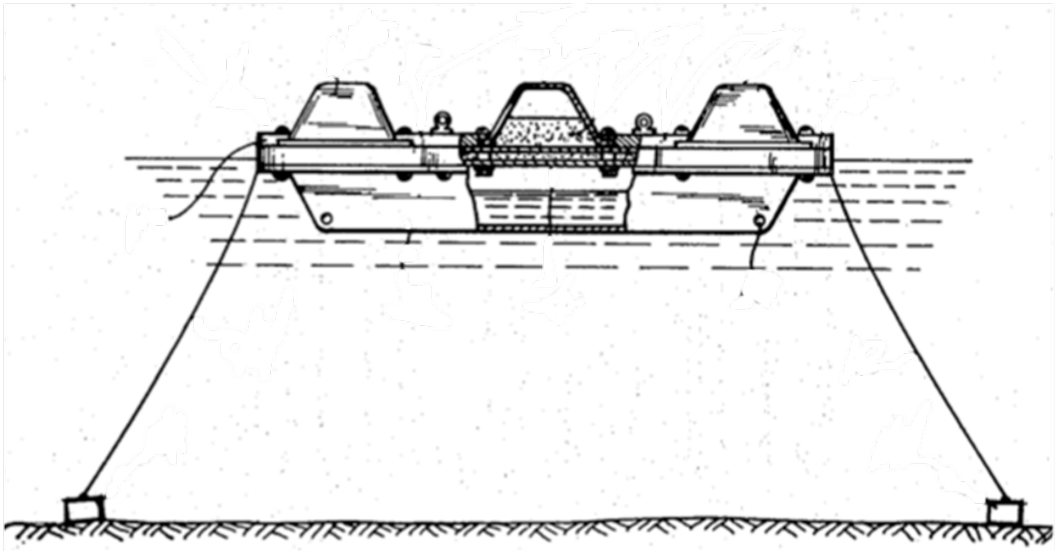

Figure 5.1 Tazaki et al Breakwater

The breakwaters shown in the two figures below represent an ameliorated version of the original device with improved wave breaking efficiency, thanks to rigid plates attached to the main floating body. This extra underwater structure is subject to a viscosity resistance, which tends to reduce the motion of the device. The inside space of the breakwater may be filled with metal, plastic or concrete, to help reducing the rotary motion of waves under the water level.

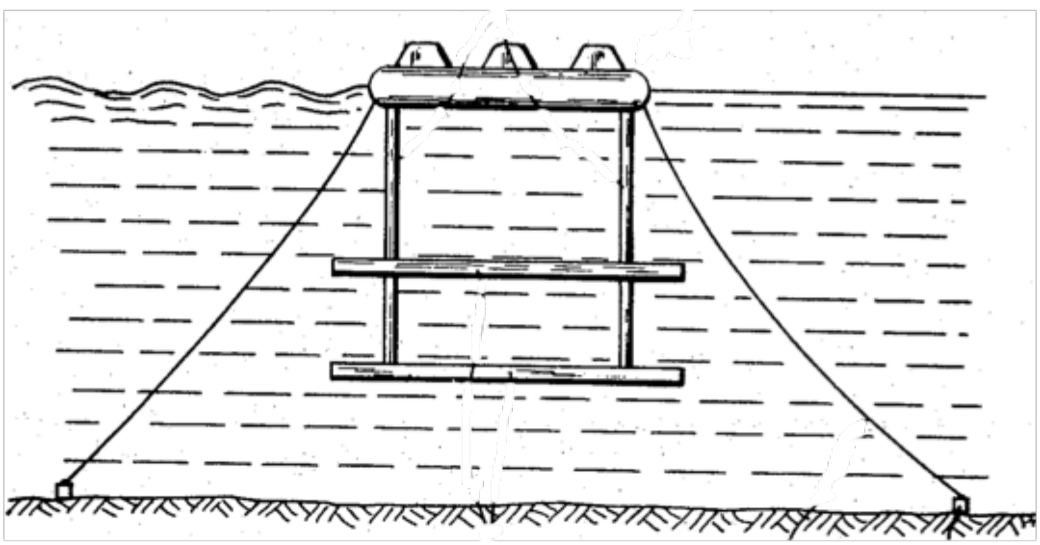

Figure 5.2 Tazaki et al Breakwater 2

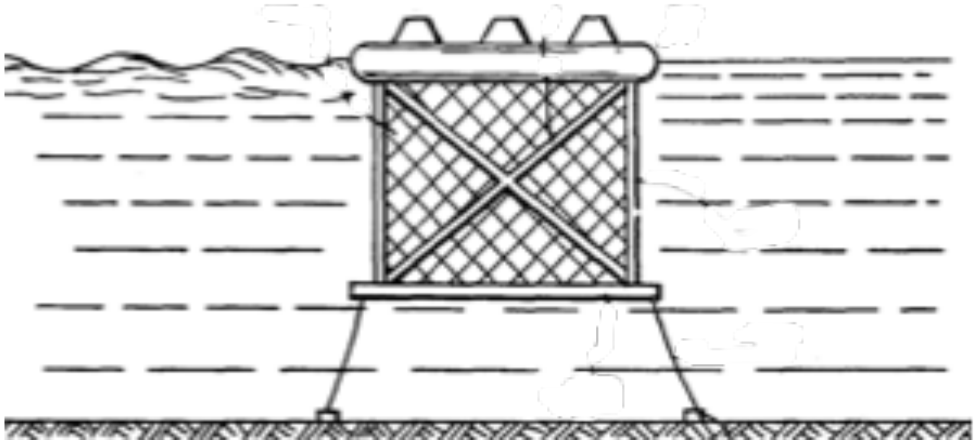

Figure 5.3 Tazaki et al Breakwater 3

Dougherty [62]

This breakwater consists of a series of parallel tanks interconnected to each other's ends to provide an undulating apparatus. Each tank's buoyancy may be adjustable to optimize the response and therefore the efficiency of the device, depending on the wave and current conditions.

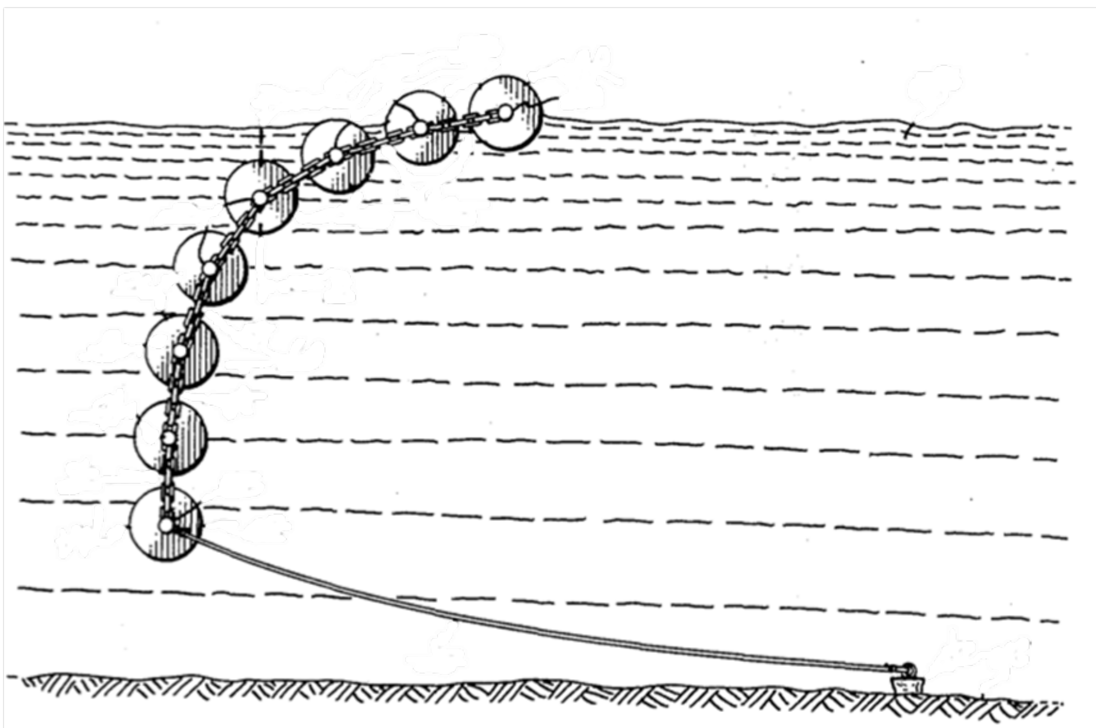

Figure 5.4 Dougherty Breakwater

Richey [63]

Even though originally designed for installation closed to the shores, this concept shows some interesting features. Outriggers are incorporated into the structure to help break up the waves, while a large keel provides stability and acts as a screen to reduce orbital velocities. The floating structure can be ballasted up to any level of submersion with a system of opening valves connected to a compressor

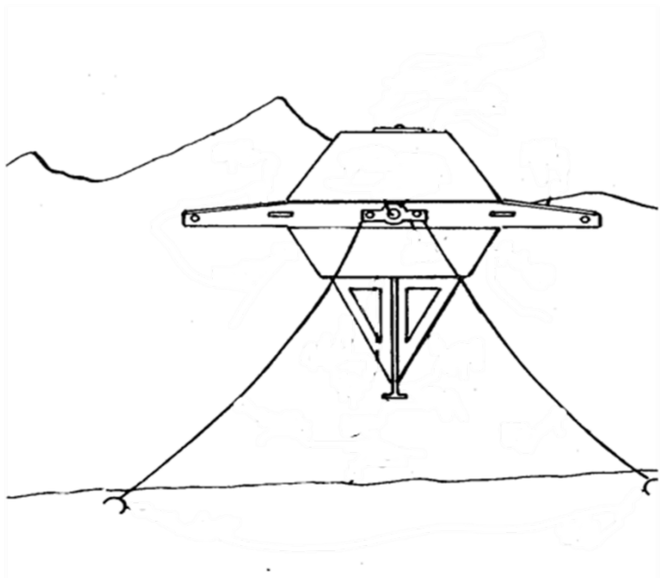

Figure 5.5 Richey Breakwater

Papadakis [64]

This system was specifically designed to act as both an efficient breakwater and a power generator by transforming the wave kinetic energy.

The breakwater has a sloping front wall acting as a beach, to dissipate the wave forces. Some passages with turbines mounted inside, extend through the breakwater to a lower "Seastead side". The water is conducted to those passages by the wave forces, and falls through turbines connected to an electrical generator.

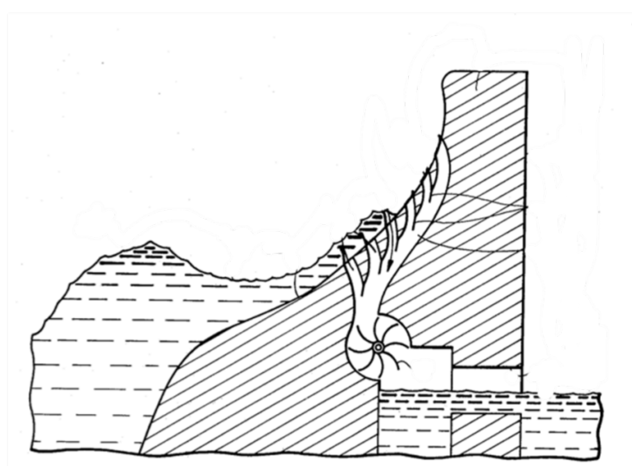

Figure 5.6 Papadakis Breakwater

Loeffler-Lenz [65]

The "T-shaped" breakwater offers some interesting advantages with both its platform and large keel member. The density of the structure varies from the top to the bottom, with the keel being the heaviest.

When encountering waves, the pivoting and vertical motions of the device create an anti-wave, which cancels or largely reduces the oncoming waves. The orbital velocities of the waves may be significantly reduced with a deep keel acting as a screen. A turbine connecting ballast tanks could be installed on the breakwater as a middle of wave energy generator.

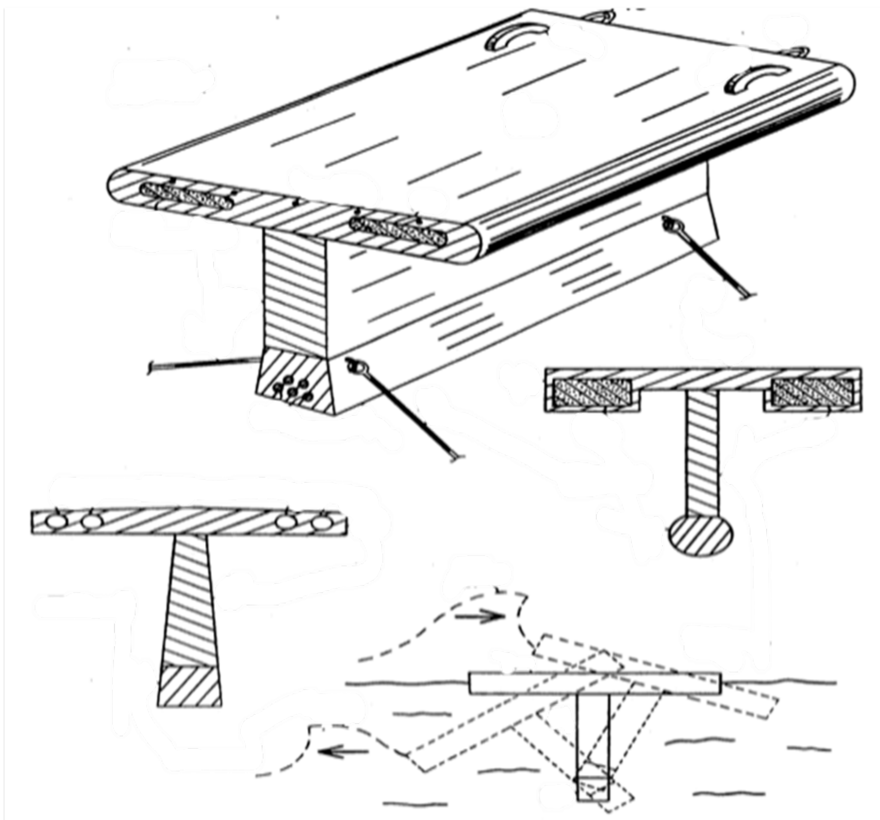

Figure 5.7 T-Shape Breakwater

Bishop et al [66]

The energy dissipating assembly consists of a plurality of modules, each having multiple surface facets, arranged in a way to break the oncoming waves. The waves are then redirected into eddies and vortices which interfere with each other, reducing the total initial wave energy.

The whole assembly was particularly designed for use with ocean waves, and can be tuned to the wave conditions by adjusting the shape and size hence the mass and buoyancy of the breakwater.

The numerous modules are all interconnected to form one unique assembly. All modules are resiliently connected in a horizontal direction to allow for spreading and concentration of the individual modules in response to hydrodynamic forces exerted on the system. The modules may be filled with air or seawater to adjust the response of the breakwater according to the wave conditions. The movement of the breakwater induced by the wave energy may then be converted to heat or mechanical motion for other applications.

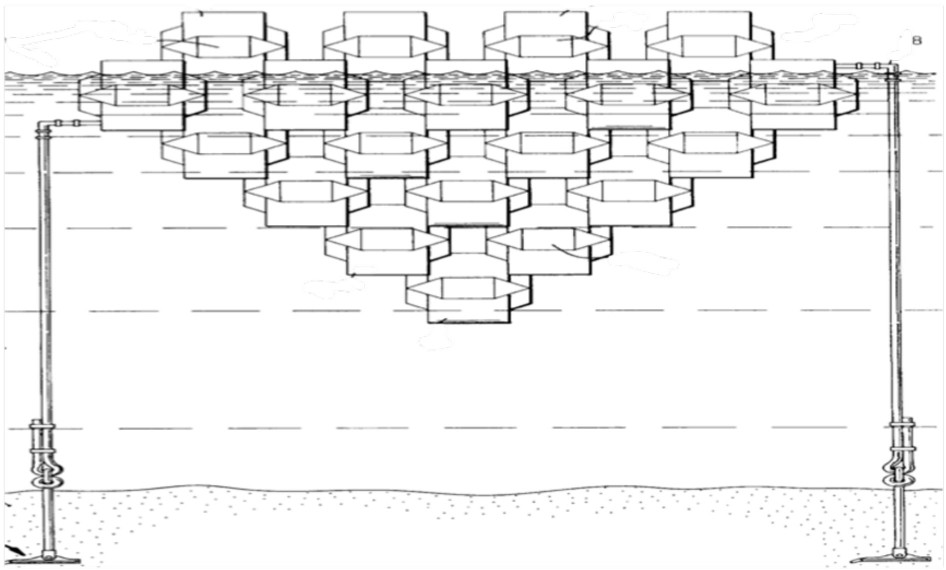

Figure 5.8 Modules Breakwater.

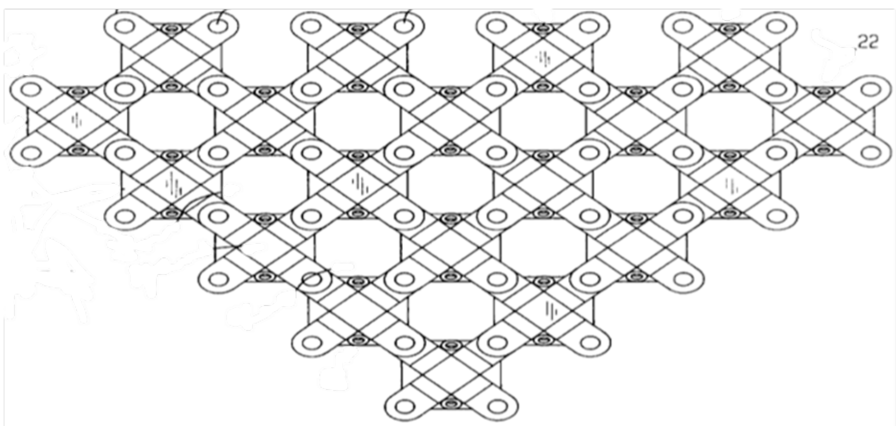

Figure 5.9 Side View of Modules Breakwater

Budd [67]

The following design consists of two floating walls/pontoons connected by a device absorbing energy from the displacement of the two structures relative to one another when hit by waves. The absorbed energy may then be extracted to drive a generator to produce electricity, or do other forms of work. The energy absorber may be a water choke arranged to squeeze water through a throttle and dissipate the energy from the waves.

Other types of energy absorber may include a cylinder arrangement acting as a dashpot, a bi-directional hydraulic pump, an electromagnetic arrangement generating an electromotive force, and many others. The space between the walls should be adjustable and ideally set to a distance equivalent to half of the wavelength (l/2). What may cause problems with such a system are the position of the energy absorber, as well as its outer pin type connections, since the forces on the floating walls may not be uniform.

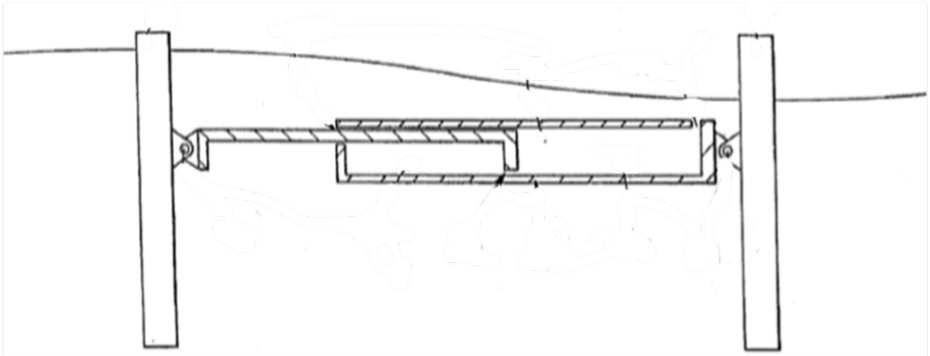

Figure 5.10 Budd Breakwater

Bishop et al [68]

This wave-dissipating apparatus comprises a multiplicity of modules aligned together to form a very large floating breakwater. The number of vertical and horizontal panels can easily be altered thanks to the high flexibility of the structure, and the air volume in the panels may be controlled to adjust the mass/draft of the structure. Therefore, the buoyancy tuning as well as the row/column spacing control gives this breakwater a high degree of flexibility desirable to dissipate a larger range of waves.

However it may be more complicated to integrate wave generator systems within the structure, and the buoyancy tuning may require complex control systems due to the very large number of modules involved.

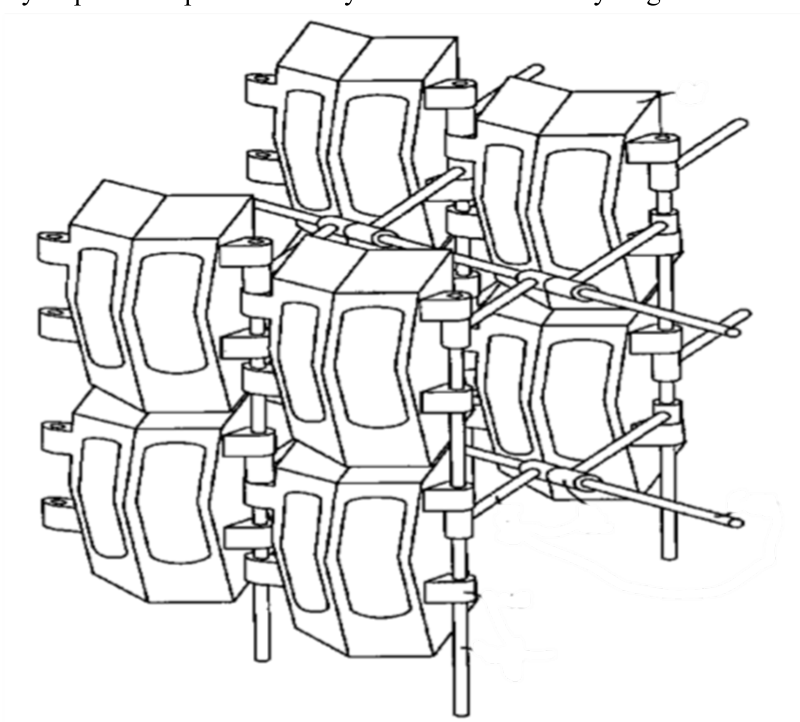

Figure 5.11 Front View of Bishop Modules Breakwater

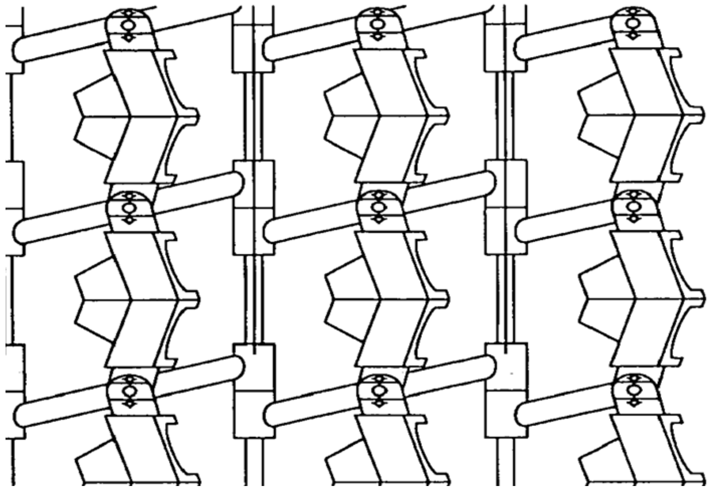

Figure 5.12 Top View of Bishop Breakwater

Petrie

The floating apparatus presented is composed of multiple breakwaters, each being specifically tuned to cancel a range of waves of a particular wavelength. By combining these two or three breakwaters together, a greater range of waves may be attenuated. As depicted in the figure below, the first and second breakwaters reduce the energy of the high and low frequency waves respectively.

The breakwater devices also include a dynamic control system to adjust the mass/draft of the structure, and a wave generator system working with ballast water flowing through turbines as the structure heaves and pitches.

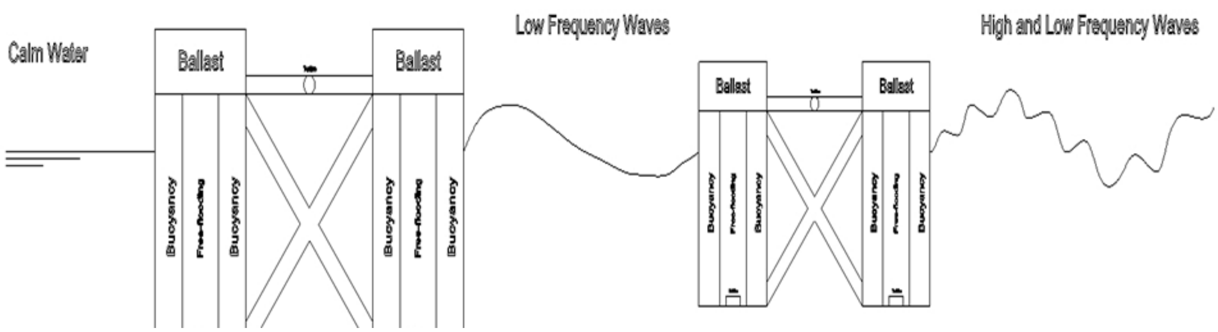

Figure 5.13 Double Breakwater

Hann Ocean: Hexifloat [69]

This huge floating system integrates four different types of energy generators: wind, wave, tidal and solar. Originally designed as an offshore energy production platform, its shape, size and modularity make it a very attractive concept for seasteading. By redesigning the underwater part of the platform and integrating a controllable ballasting system, the whole apparatus may also work as an efficient floating breakwater in addition to its exceptional energy generator. In addition, the combination of multiple Hexifloats would produce a huge structure (approximately 60 meters wide) with an improved wave damping capacity.

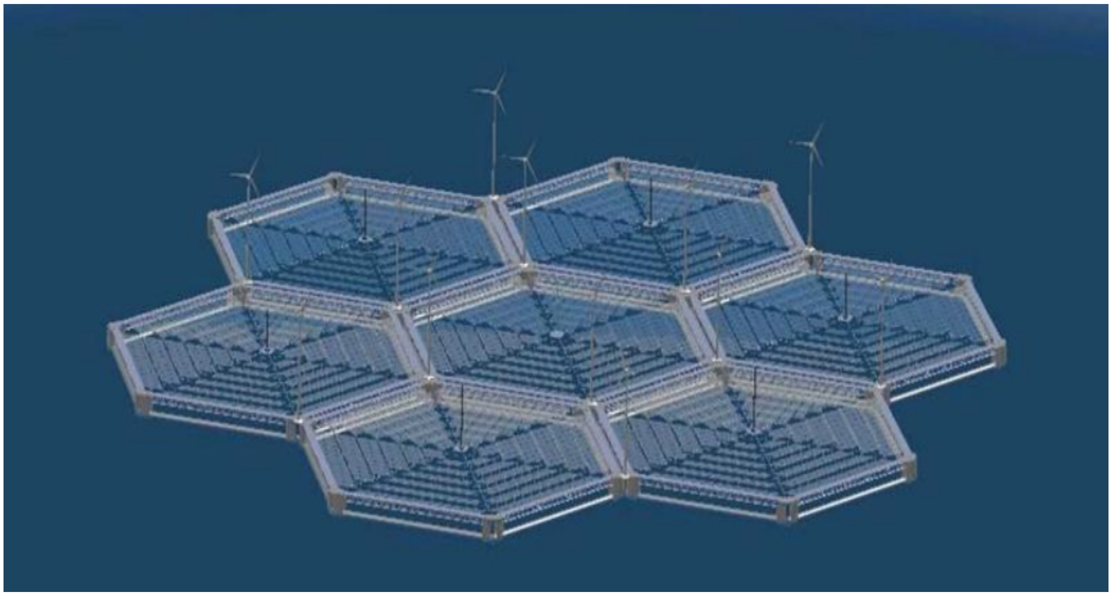

Figure 5.14 Top View Hexifloat

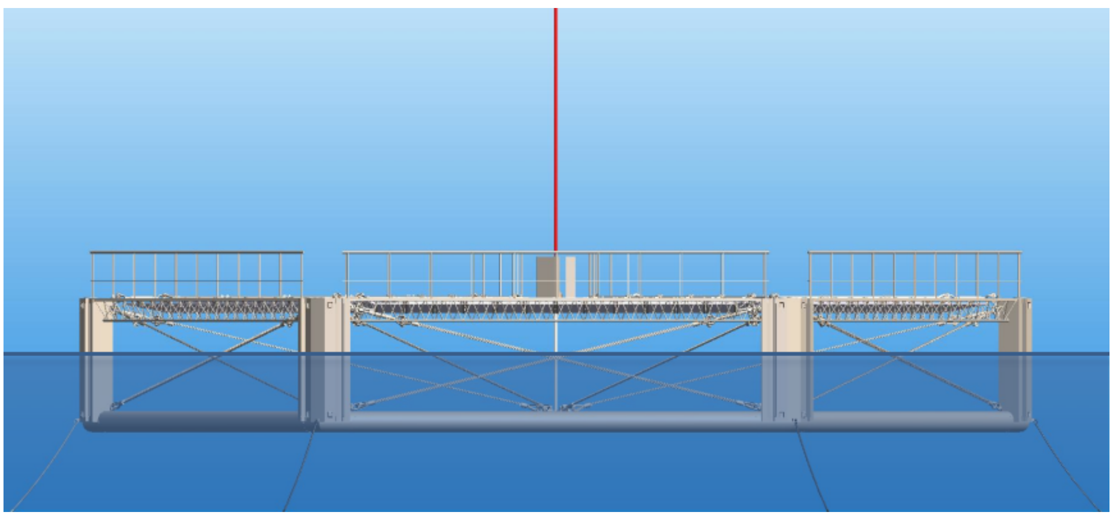

Figure 5.15 Side View Hexifloat

Hann Ocean: Drakoo [70]

Drakoo is a newly developed wave energy converter that also acts as a floating breakwater. The system was designed to absorb, concentrate and transform wave energy into electricity while cancelling/reducing the oncoming ocean wave energy.

Both the dimensions and performance properties of this concept are available, since Hann Ocean has so far built, installed and tested Drakoo prototypes. According the results obtained, it has a broad operational wave range and high survivability in extreme sea states. The device switches to survival mode with wave crests larger than 8m.

The machine is based on the latest iteration of WEC, making it more efficient than any other type of wave energy generators. It was designed to capture both the kinetic and potential energy of the swell, driving hydro turbines to generate electrical power. It also reduces the reflection or "bounce-back" occurring after the contact between the wave and the device, to ensure that the energetic forces of the following oncoming waves are not diminished.

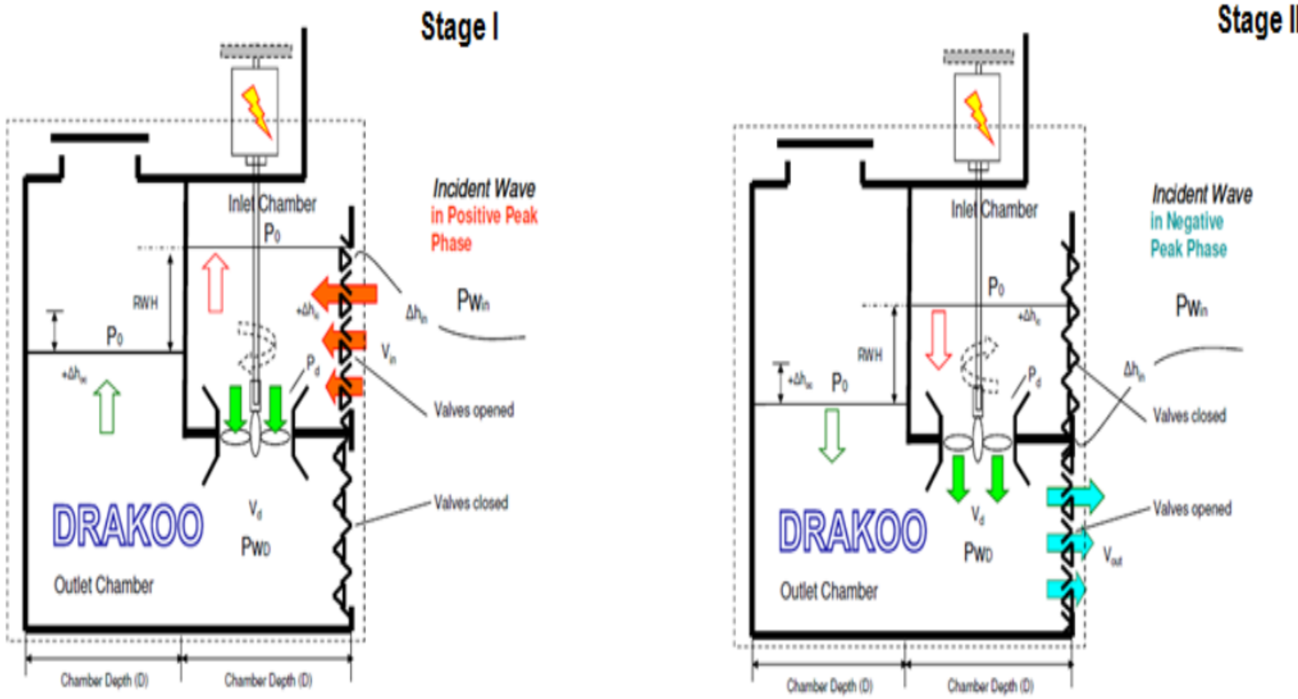

Figure 5.16 Drakoo System

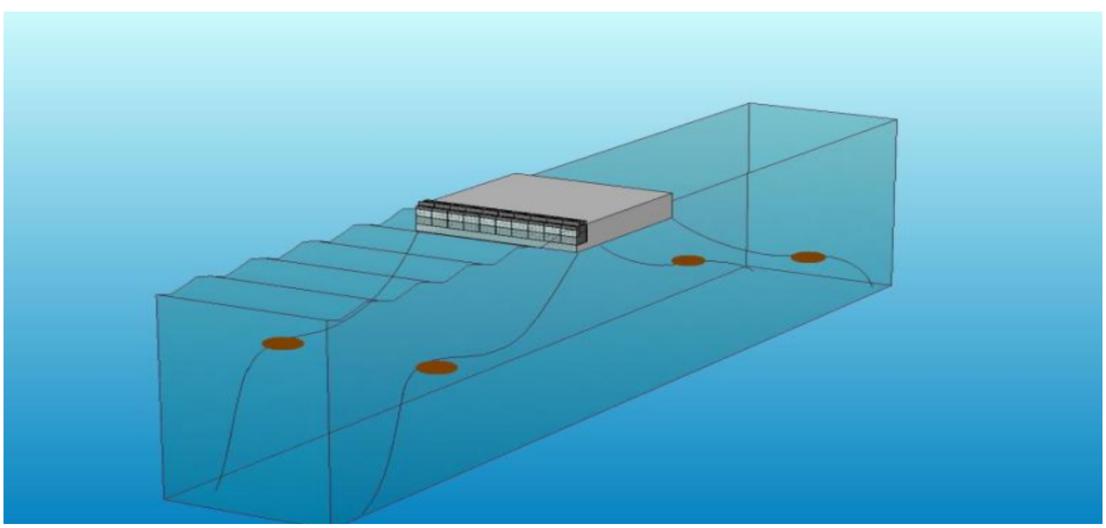

Figure 5.17 Drakoo

5.2 ALTERNATIVE CONCEPTS

Various concepts of alternative wave breaking systems have been developed over the last few decades. None of the ones described below have yet been built for large-scale applications, but they still hold a potential attraction for future projects.

Gross [71]

This method to diminish wave height relies on a device that causes the waves to tumble over into the preceding troughs, reducing the initial height of the oncoming waves.

The main idea of this concept relies on the observation that waters at different temperatures act as if they had different viscosities and resist mixing. Therefore a stream of water at one temperature discharged into a body of water (of a different temperature) tends to remain as one stream without mixing with the other body of water. Discharging water at a specific temperature into the oncoming waves should overall diminish the wave height.

As shown on the figure below a motor pump is connected to jet pipes from which the streams of water are discharged through the openings. Obviously for deep-water applications, floats could support the whole apparatus. For this breakwater to be efficient at a large scale, very large motor pumps and deep/long jet pipes system would be necessary.

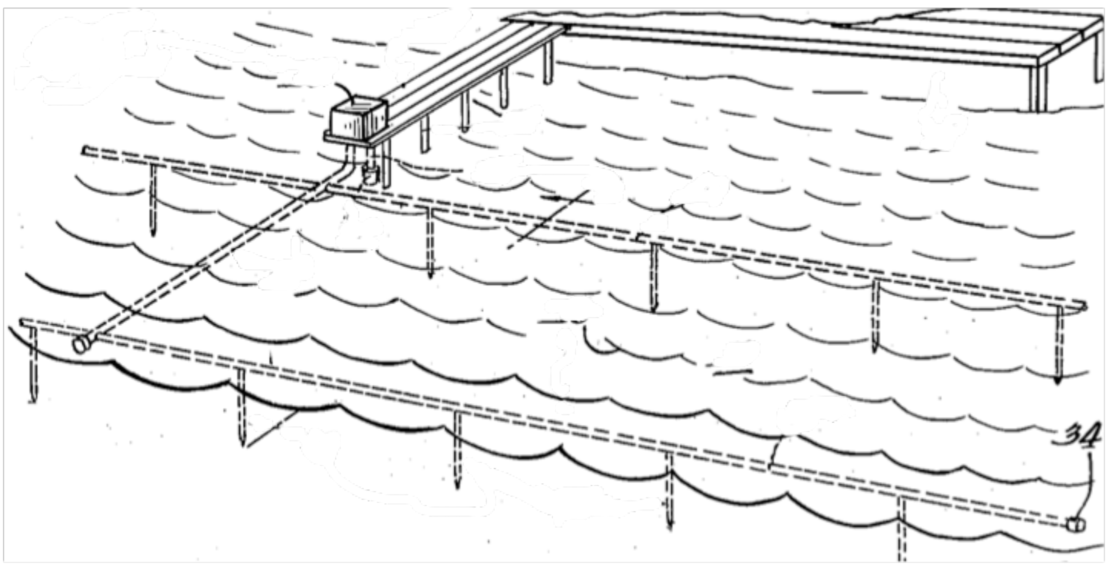

Figure 5.18 Top View Gross Breakwater

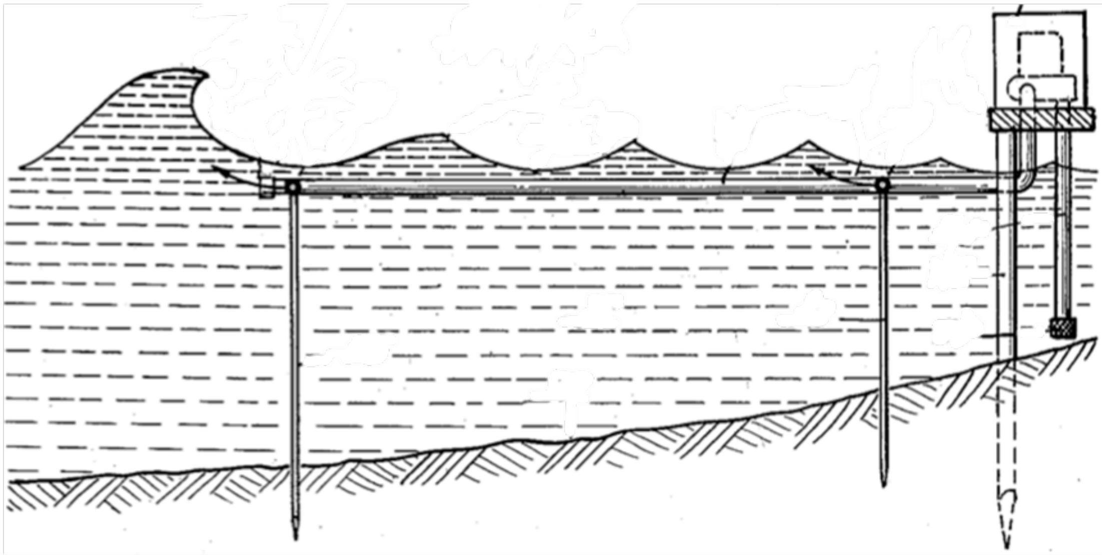

Figure 5.19 Side View Gross Breakwater

Discharge of Air Bubbles

This surprising method to absorb the wave energy seemed like an interesting, futuristic concept, which could address secondary problems involving water circulation and fish migration around the seasteads. However, the whole device may require a large amount of energy, and the installation of wave energy generators would not be included as part of the breakwater system (such as the Pelamis, Ceto, Oyster, and other wave energy generators that can be installed in parallel with some breakwater designs).

Brasher [72]

Invented in 1926, Philip Brasher's invention discharges blasts of air at specific intervals and pressure. The intervals and pressure can be adjusted depending on the state of the waves to be dissipated. Basically, the apparatus works with a set of perforated pipes linked to a manifold or chamber containing air under pressure, with means to adjust the air discharge.

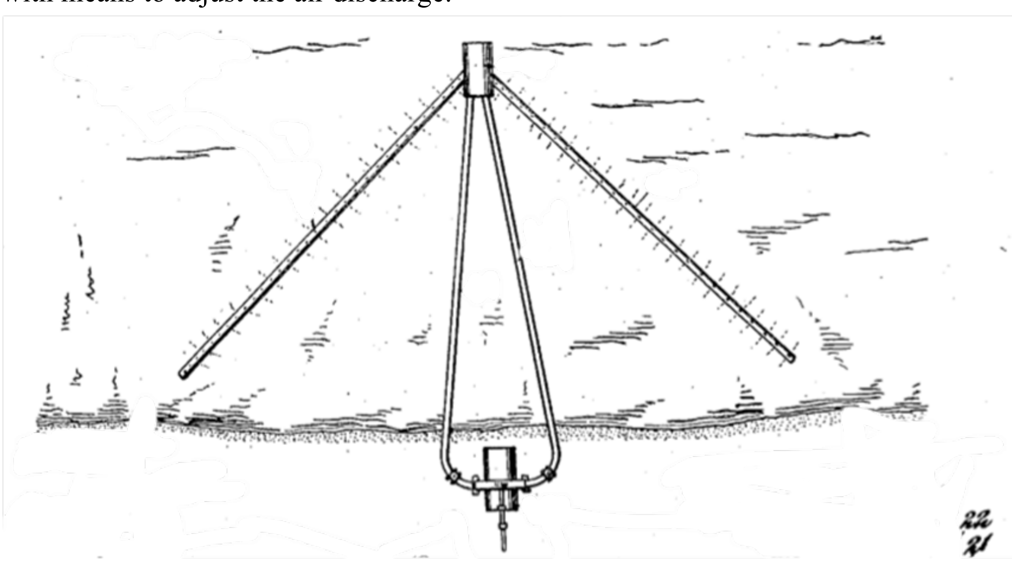

Figure 5.20 Side view of Brasher's Breakwater

Bryant [73]

Similar to the Brasher, this more recent one also uses the discharge of air bubbles to reduce the wave energy. It is thought that the injection below the surface of the water of minute, discrete air bubbles in sufficient quantity will significantly damp the waves action.

"Bubbles which are sufficiently small and thus present large surface interface with the water cause the damping by being thermo-dynamically compressed and expanded, and thereby convert the kinetic energy of the water to thermal energy to dissipate the energy of the waves."

The apparatus consists of a compressor duct connected to the bubble generating system to provide the air to be injected underwater at the required pressure. For deep water applications, the bubble generating device may be supported at a chosen depth (slightly below the lowest portion of the orbital motion of the water due to wave action) by adequate floating means.

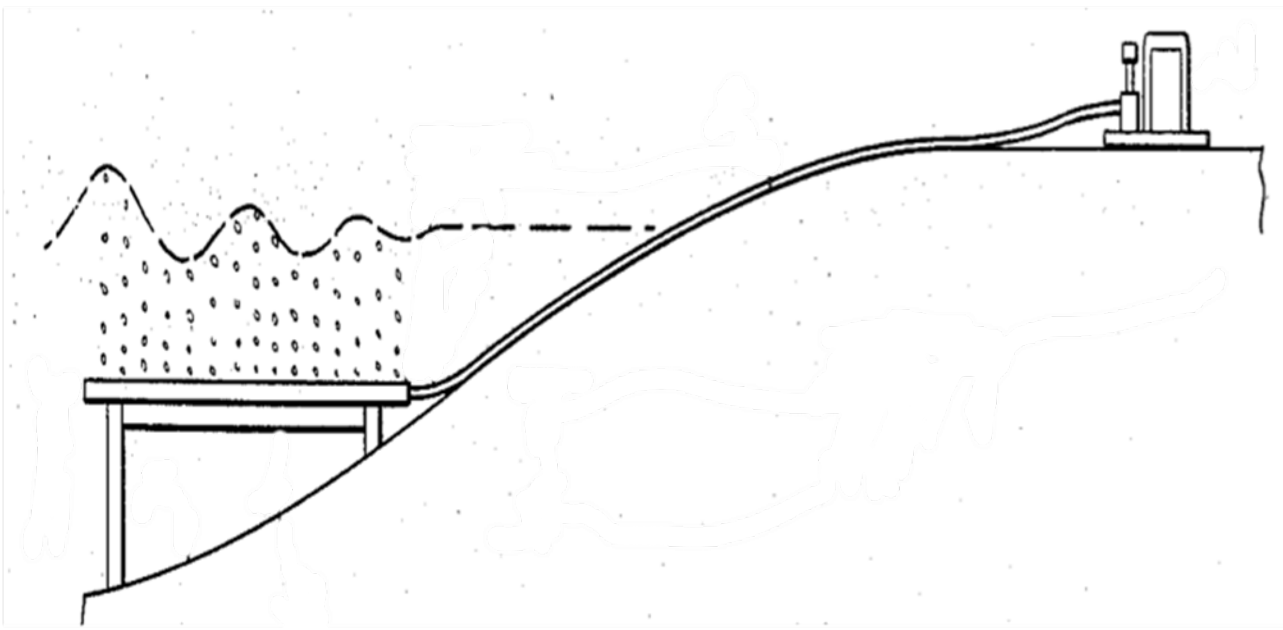

Figure 5.21 Side View of Bryant's Breakwater

6. CONCLUSION AND RECOMMENDATIONS

In the current study, state of the art research on floating breakwaters and wave energy generators was investigated, as well as a preliminary engineering assessment of the size, effectiveness and applicability to deployment in the open ocean of the said systems, at a scale consistent with the floating mega-city scenario.

The beginning of the report highlighted some of the recent developments within the field of wave energy generators. So far, a large number of tank tests and full-scale prototype sea trials confirmed preliminary estimates on the performance of the devices. Numerical models approximated test results, but a large range of practical issues are only solvable through more extensive engineering analysis. Demonstration plants are in development to further improve the testing method and research in the wave energy generator fields. Within the next 3-5 years, full size demonstration plants should be deployed in the oceans, in the aim to commercialize some of the prototypes developed.

The research suggested that overtopping devices (concept nº3) and oscillating water columns present superior advantages compared to other types of wave energy converters.

Regarding the construction material, concrete was selected as it appeared marginally more cost-effective than steel for an application of this magnitude. However, it should not be concluded that steel should be discounted when examining future WECs potential.

The main concern for floating breakwater is developing models that can be deployed in the deep seas. At the scale of a 50,000-person seastead, dimensions of the floating structure take huge amplitude, and no such design has yet ever been realized. Even at much smaller scales, no floating breakwater has for instance been installed in 5000 feet of water to damp large ocean waves. The actions and performance of such a device in deep water remain unknown.

All design factors such as the mass, mooring forces and scantlings are inter-dependent with each other. All these also depend on the location of the breakwater. To precisely estimate the environmental conditions the structure will be subject to, the wave statistic data of that specific location must be analyzed.

Even with this knowledge, accurate structural calculation and numerical models, some uncertainties may remain when considering for example the resistance and efficiency of such devices in a hurricane. However, with more research in the field, tank tests, and other practical tests at increasing scales with prototypes, enough confidence may be gained to implement a system able to protect future seasteads from waves.

For the moment, the Dutch engineering company "FDV" seems to be the most advanced in the field of simple floating breakwaters. Both their experience and technical knowledge allow them to assembly breakwaters of theoretically any shape, configuration, and length.

When considering hybrid systems, breakwaters with energy generators incorporated, the technology group "Hann Ocean" has developed some very interesting and innovative prototypes. Both the "Hexifloat" and the "Drakoo" hold serious advantages compared to other existing wave energy convertors, and could resist severe sea states.

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