Preliminary investigation of a novel breakwater combining coastal defence and energy generation for near shore environments

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Abstract
This paper presents the concept and initial tank testing of a novel low profile floating breakwater incorporating energy generation. The breakwater is intended to be anchored parallel to the coast with a beach at the front of the device to rotate the incoming waves towards collector tubes. The water hammer principle is used to harvest the high water particle velocities, charging a rear mounted high pressure reservoir which is then used to drive a conventional turbine for electrical energy production. The ability to provide breakwater benefits in smaller wave climates should open areas where combined protection and generation give competitive economic returns.

Introduction
The UK Government currently spend around £800 million per annum on flood and coastal defences with future forecasting predicting coastal erosion to increase by three to nine times by 2080 (Foresight, 2010). Coupled to this is the increasing requirement for sustainable energy using low pollution sources. Wave power devices fall into this category, and although many concept and prototype devices exist to convert the energy of sea waves into a useable form, as yet, there is no clear technology winner. To prove attractive, wave power technology devices must survive and provide a reliable source of power. Many have sights set on Atlantic wave climates where systems are remote and operate in vigorous 40 kW/m waves, however starting in smaller more sheltered coastal areas will provide appropriate lessons for further offshore expansion. The added advantage in this instance is that the device provides a robust sea defence.

This breakwater is designed as a floating structure within the near-shore wave zone. As a semi submersible device (figure 1) it remains at wave trough level in larger waves to minimise loadings but fully intercepts smaller design range waves. It takes the waves into surge chambers which capitalise on the water hammer principle to provide a small flow at increased pressure. The surge pressure passes through a one way valve to a spinal collector pipe which gathers the incident energy from several locations along the breakwater length to feed a conventional turbine. The authors are not aware of other devices using this principle.

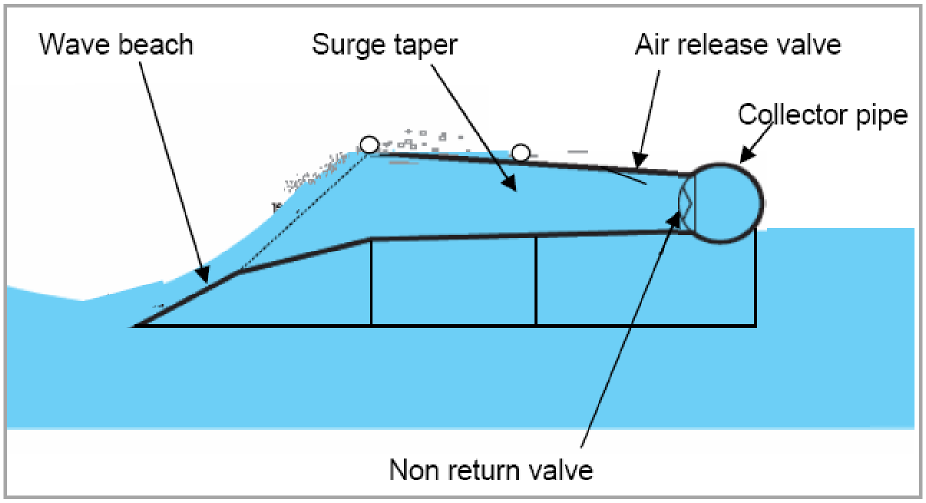


Figure 1 – Cross section through proposed breakwater

Initial wave tank and simulation work have indicated wave attenuation and electricity generation performance. These benefit from the high interception rate of a long device.

A layout similar to that used for segmented shore-parallel breakwaters (SSPBs) (figure 2) is envisaged. These have been used widely to protect coasts by encouraging the accretion of material behind them (Bacon et al, 2007).

Figure 2 – Segmented shore-parallel breakwaters at the Sea Palling, Norfolk

The breakwater can be deployed rapidly to give similar benefits of protection from erosion and flooding as fixed SSPBs and to provide good wave attenuation with minimal visual intrusion. Rapid deployment will also allow their use at marine construction sites to increase the safe working window of sea conditions and limit storm damage during construction.

Floating Breakwater Theory

The breakwater can be regarded as a long horizontal plate at wave trough level. Orientated diagonally to the waves, it is held in place primarily by water inertia and only secondly by the anchors. Waves roll along it, feeding successive inlets and providing a continuous turbine flow.

The wave beach starts by slowing and rotating the waves, improving their approach angle. Upward particle motion is inhibited ahead of the waves and increasing steepness rapidly causes breaking. We have not found a good theoretical treatment for this but used Boussinesq analysis to assess the effect. Wave types and breaking patterns are well described in the literature and the modelling indicates a useful surging break.

Typically for deep water (h/λ ≥ ½) approximations can be made (McCormick, 2007):

$$\lambda = \frac{gT^2}{2\pi} \text{ and } c = \frac{gT}{2\pi} \qquad \text{Eqns (1) (2)}$$

$$u = \frac{\pi H}{T}\, e^{kz} \cos(kx - \omega t) \text{ and } w = \frac{\pi H}{T}\, e^{kz} \sin(kx - \omega t) \qquad \text{Eqns (3) (4)}$$

For shallow water (h/λ < 1/20):

$$u = \frac{H}{2} \sqrt{\frac{g}{h}} \cos(kx - \omega t) \text{ and } w = \frac{\pi H}{T} \frac{(z+h)}{h} \sin(kx - \omega t) \qquad \text{Eqns (5) (6)}$$

Where:

$c =$ wave phase velocity (m/s)
$h =$ water depth (m)
$H =$ wave height (m)
$T =$ wave period (s) $= \frac{2\pi}{\omega}$
$u, w =$ horizontal and vertical water particle velocity components (m/s)
$\lambda =$ wave length (m)
$k =$ wave number $= \frac{2\pi}{\lambda}$

This suggests that as the depth decreases, the elliptical paths of particle travel change so that the surface particle velocity increases. The wave phase velocity, c, decreases with decreasing depth until u=c at which point the wave breaks.

Shallow water wave types (Stokes and Cnoidal) have higher horizontal particle velocities than the deep water wave shapes used in the wave tank. The breakwaters are anticipated as clear of the beach but in water shallow enough for the more vigorous wave types to be present. Even the largest waves should be tripped and broken, with the energy dissipated near the breakwater.

Water hammer (or, more generally, fluid hammer) occurs as the air vent on the collector pipes closes, resulting in a pressure surge or wave in the water column due to the sudden change in momentum. Any remaining air within the collector can act as a cushion to this fluid hammer effect, and hence removal of as much air as possible without release of water pressure is required.

Electricity Generation

Hydraulic ram pumps have been used for many years to generate high heads from small stream flows. They click away in the corners of fields using the water hammer principle to provide a reliable water supply with no electricity and very little maintenance.

This principle is used to take wave surge and convert it to a flow with enough head to run a turbine. The principle has been demonstrated with static wave tank models and with computer simulations, but the interaction of a floating device in the usual wide variety of sea conditions has yet to be confirmed.

Survival

Shoreline and buoyant devices are exposed to the full energy of breaking waves and our preferred shallow water, coastal locations have frequent breaking waves. These are not typically the highest energy, long wavelength, deep water waves as these are already broken, reducing peak forces. Our strategy is to allow semi-submergence in severe conditions. Particle velocities at trough level are far below those at crest level, making this the best way to avoid excessive loading. The device will still break these largest waves, but the energy will be dissipated inshore of the device. In locations where storm wave attenuation is not essential, complete submergence can be triggered by excess pressure, with subsequent re-floating by a small compressor.

Comparison with Other Wave Energy Devices

Many wave energy devices have features that we have sought to avoid:

- Waves can arrive every six seconds for long periods, equivalent to 5 million cycles per year. Joints and pistons that will work satisfactorily in seawater for 20 years or 100 million cycles need a high specification.
- High buoyancy exposes large areas to storm wave forces. The large loading from these waves requires high strength and weight.
- Single point moorings are only useful for point absorbers. Anchored ships lie head to tide or wind, seldom head on to the waves. Storms normally have a change of wind direction as they come through, giving a cross sea with waves from an arc of over 90 degrees.
- Energy available is proportional to collection width. Point absorbers may have an enhanced width in long wavelength waves but are fundamentally small.

Considering some other devices:

Pelamis is shown with a single mooring point. Unless it has two additional moorings at the other end with automatic winches, it will often lie broadside to the waves. Our breakwater has no joints and is anchored parallel to the coast. We hide at wave trough level from the large breaking wave forces that the buoyant Pelamis must experience and which broke its joints in Portugal (Copps, 2009).

The Aqua Marine Oyster is hinged to the seabed which may help survival by retreating from storm waves, but maintenance must be done by divers. All our working parts are above water in calm weather and our valves use conveyor belt technology where 100 million cycles is normal. Like Pelamis, towing our breakwater to harbour for maintenance is feasible.

Wavegen Limpet is a land based system using air as the driving medium. This is costly to build and the number of good sites will be limited. Where they have proposed building them into breakwaters we regard their power output per metre as similar to our anticipated output but would expect our costs to be a fraction of theirs. The suggestion of using their air system on a floating rig must expose a large above water structure to the full wave power, with a greater cost penalty.

Wavedragon uses surge on a floating beach like our breakwater, but is an overtopping device with a costly low head turbine and needs a large structure to support the elevated pond. It has wave collection arms which require a single wave approach direction or an automatic mooring adjustment system. Their wave collection efficiency is claimed to be good. We take this as partly because a beach converts both potential and kinetic energy to a useable form, a benefit we also hope to use. Their survival technique allows large waves to pass above the structure, but without our automatic buoyancy reduction in severe conditions their structure is many times larger and heavier.

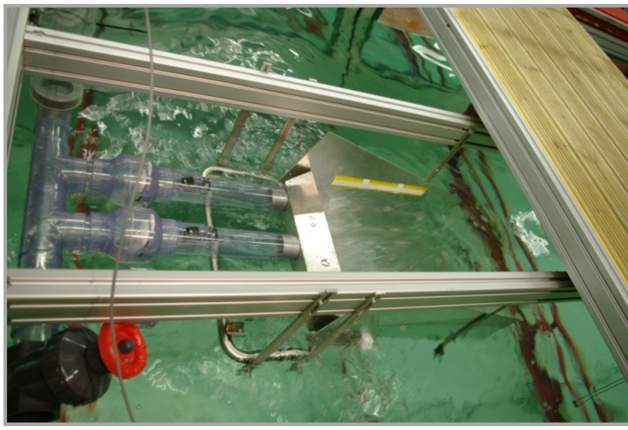
Single point devices such as buoys, floats and propellers will collect from a small sea area and have a small output. Their moorings normally give high loads in storm conditions requiring robust construction with poor output to cost characteristics. Our proposal is for a semi-submersible design giving fixity in the water allowing slack moorings to minimise loading.

Work to Date

Initial design work was followed by computer simulation using Openfoam software (OpenFOAM, 2011), demonstrating the operating principle. This was followed by initial wave tank model testing at Lancaster University. The model scale of 1:10 for Irish Sea test area conditions is equivalent to about 1:30 scale for Atlantic waves.

It has not been possible to test a long breakwater section within the confines of the Lancaster wave tank, and hence the scale model consists of a short beach section and three collector tubes feeding the pressure manifold. End plates are mounted at either end of the beach to act as artificial boundaries, without which water flow would exit or enter at the sides providing inappropriate conditions for what is essentially a long symmetrical structure. The rear manifold is equipped with a vertical reservoir tube open to atmosphere which acts to record the pressure head. The model is mounted by rigid support beams that span the width of the tank (figure 3a) which somewhat contradicts how it will be anchored at full scale. The intention for these initial tests has been for proof of concept rather than assessment of overall performance and hence future models and tests are to include a better representation of the intended floating structure. The wave direction has primarily been in-line with the collector tubes, and although initial tests at approximately forty five degree angle suggested that the beach turns incoming waves towards the collector tubes, no instrumented data was gathered on this. Instrumentation is through a set of amplified wave gauges, four of which measure the incoming wave height and a fifth records the liquid level in the vertical reservoir tube. Sensors are sampled at 20 Hz.

Subsequent high speed video work showed that the draining of surge tapers between the waves was critical so a revised model was prepared using clear plastic to allow a full visual inspection of operating conditions (figure 3b). This revised model shows the move towards flat plate rather than tubular construction.



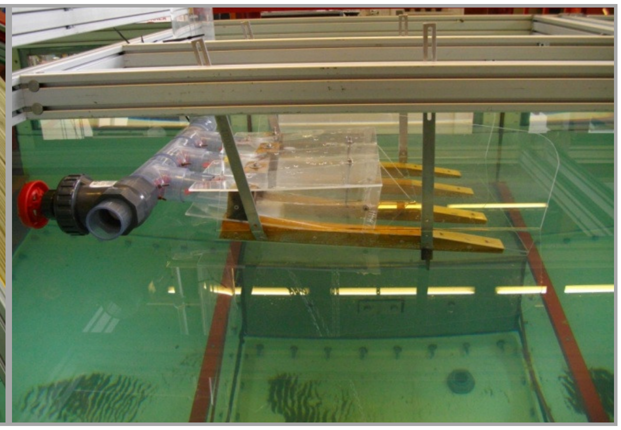


Figure 3a – Original scale model mounted in tank with waves approaching from the right
Figure 3b – Revised model using clear plastic sides to aid in visualisation

Results

Power output from the model device is essentially determined by the pressure in the manifold multiplied by the available flow rate. Pressure in the manifold has been recorded by measuring the fluid height above the SWL. Flow rate is more difficult to measure, firstly because the model has a leakage rate, and secondly because the flow rate varies with pressure within the system, this along with vibration of the model makes recording of an absolute liquid level difficult. Sampling at 20 Hz allows the relevant data to be extracted.

During sensor calibration the leakage rate has been monitored and can be approximated by using a spreadsheet trend mapping function. A typical results plot for varying beach depths is shown in figure 4, where the device was equipped with semi-rigid air valves (without allowance for losses). This figure suggests that a deeper beach performs best for energy capture, however, at different wave heights and frequencies this was found not to be the case and a clear definition of beach design was never concluded within the time frame available. Significant work on beach design for overtopping wave power devices has been completed by Aalborg University (Denmark) on the Wave Dragon device (Kofoed et al, 2000).

The most influential factor on device performance was found to be the stiffness of the air valves on each collector tube. Tests were completed with three simple arrangements consisting of a soft flexible rubber hinge, a semi-rigid membrane, and then a third variant with reinforcement. The softer valves were found to be inappropriate, failing to close and form an appropriate seal during surge. This failure to close correctly significantly reduces the fluid hammer effect and it is clear from figure 5 that significantly lower pressures result. The reinforced valve clearly outperformed the other designs in all sizes and frequency of incoming wave. Future work is to mount these valves on flat plate rather than the curved pipe surface to simplify the seal. A limit on the valve travel may also be imposed.

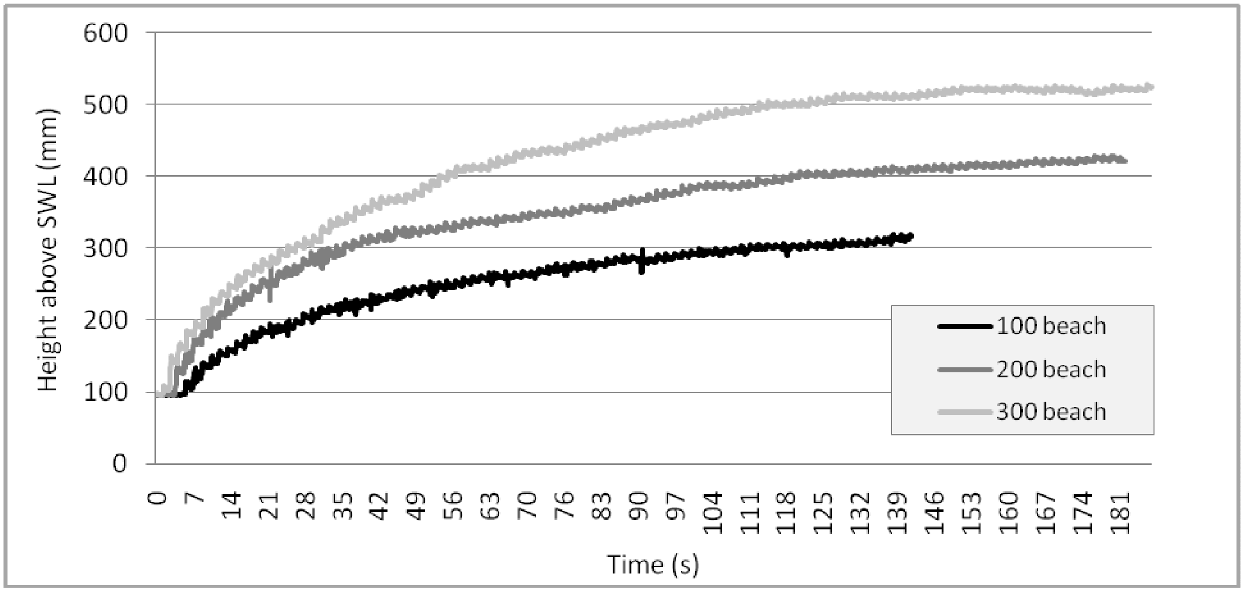


Figure 4 – Effect of beach depth on a 1.5m 5s wave

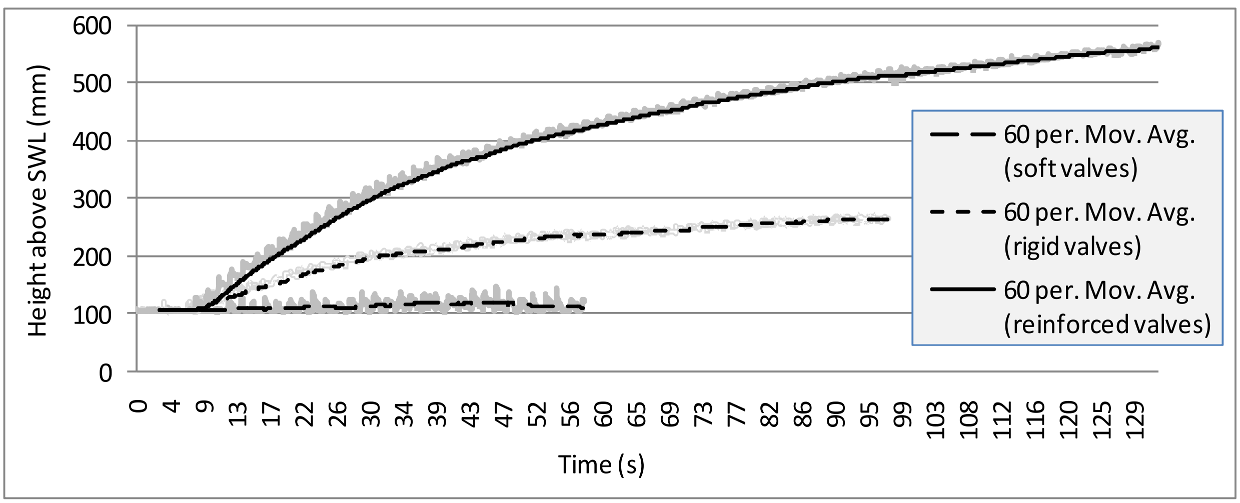


Figure 5 – Influence of air valve material on performance for a 1m 5s wave

Power Capture

The curves shown in figure 6 can be approximated using a second order polynomial expression. By calculating the gradient at a set point, it is possible to calculate an approximate flow rate and hence power output at that instance. The data selected is from the reinforced valves testing with 75mm beach at 10 degrees, using a 5 second 1.5m wave.

The trend line is described by the equation y = -0.0003x2 + 0.7186x + 114.34, hence at y = 300mm, x= 14.73s, and at y = 305mm, x = 15.19s. The flow rate has been calculated to be 72300 mm^3/s, which when added to the leakage rate produces a total flow of 87200 mm^3/s. Model power output at this point is pressure times flow rate, hence at the 300mm height selected power capture is 0.8 w/m, approximately 3% efficient.

A consistent set of operating curves for different positions were obtained. A flat overall output curve indicated that small waves, of a size that initiated water hammer action, had a higher efficiency than larger ones that lost excess energy in turbulence. It is believed with further model modification efficiencies of 5-10% can be readily achieved.

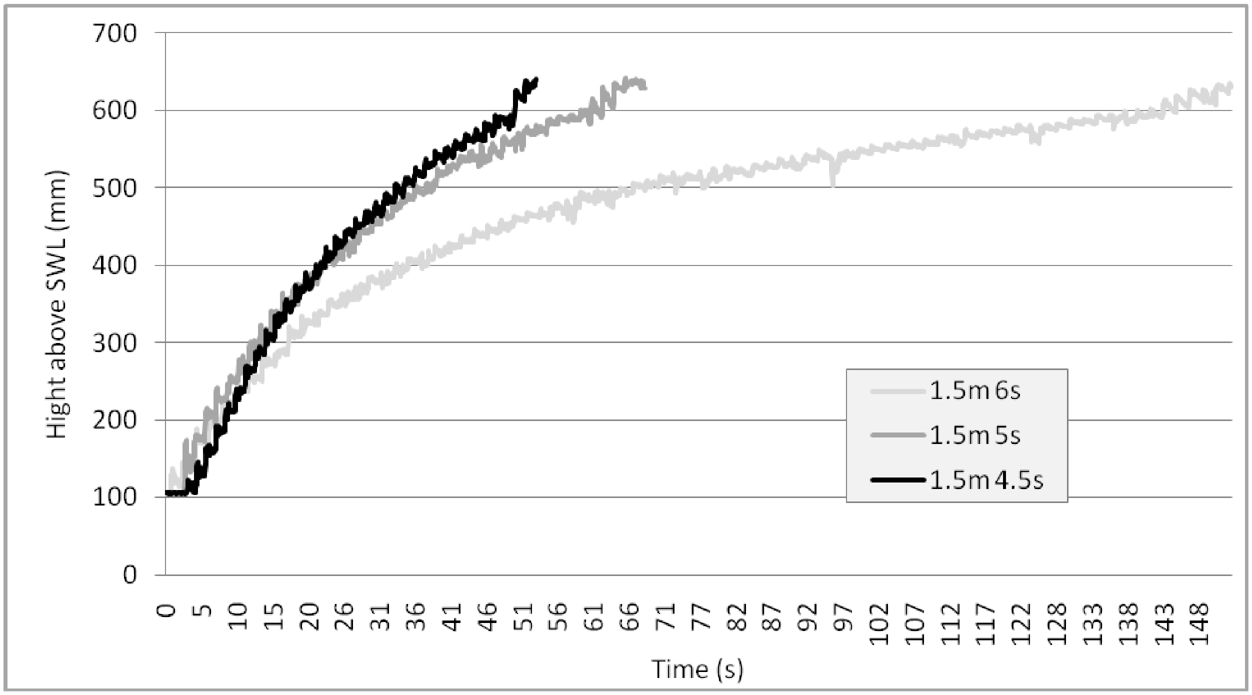


Figure 6 – 75mm beach immersion with 10 degree roof slope, reinforced valves

The initial design assumption of a 1m Irish Sea prototype design wave or 0.1m scaled wave tank design wave was found a little out. The model worked best in the wave range of 0.1 to 0.2m high. Below 0.1m the response dropped off at some wave lengths, although some of these can be attributed to natural frequencies of the tank.

At Liverpool University two studies were done: Offshore wind and wave data from wave buoy and waverider were obtained from CEFAS (CEFAS, 2011) at two potential test sites off the coast of Cumbria. A spectral wave model was used at first to provide the overall wave climate from offshore to the near shore area (Figure 7). This data was then taken into the shallow water sites proposed to give the anticipated shallow water wave energy climate using a Boussinesq Wave module for both monochromatic and random waves. This showed that at these particular locations and using the 6 months of data obtained a 0.7m design wave was more appropriate.

A second computer simulation study used CFD model Fluent (Ansys, 2011) to simulate waves interacting with the structure with various conditions obtained from the first modelling results. The model is based on the volume of fluid approach to compute the instantaneous water surface change and related flow dynamics around the structure and inside the structure. Pressure distribution can be used to evaluate the possible energy generation under the particular wave conditions. Analysis of the model data has shown similar performance as obtained from the laboratory experiments in the Lancaster University wave tank, and will aid in scaling the power capture available.

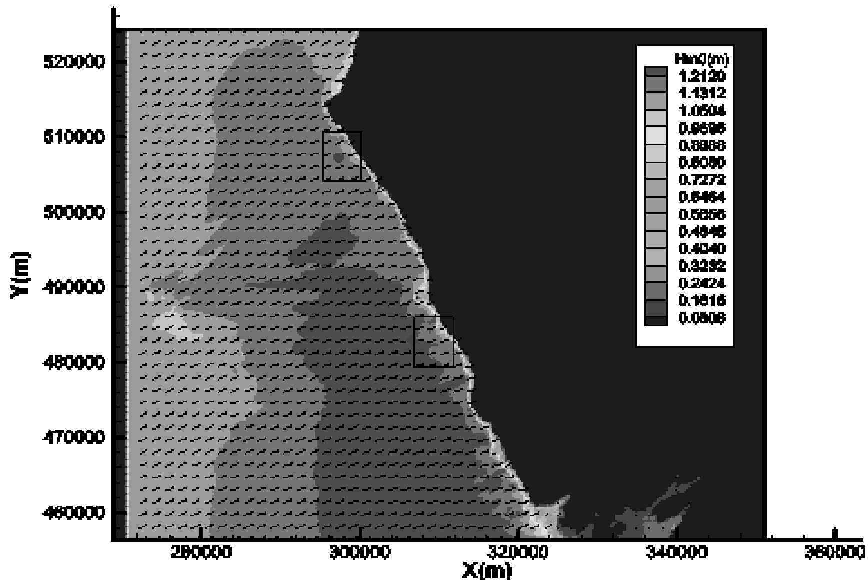


Figure 7 - Spectral wave model results for the wave height distribution near the testing sites off the coast of Cumbria.

Many questions remain:
Froude numbers are used for wave scaling but these do not apply to cavity pressures, particularly at the small laboratory scale experiments (Bredmose & Bullock, 2008). Initial calculations and some simulation work have indicated that this scaling problem should be beneficial to larger scale units.

Mooring loads have still to be established and may be complicated by long wavelength infragravity waves.

Conclusion

Where breakwater benefits are required there will be locations where this may provide a cost effective and more easily installed alternative to conventional solid breakwaters.

The generation performance lies in the interception of all the waves approaching the long device. The Carbon Trust 2006 report (Trust, 2006) suggests a central estimate of 22-25 p/kWh for offshore wave energy converters. It is anticipated that electricity generating costs will be competitive with other devices in large wave energy climates but with the design tailored for the local energy range it should give better returns in smaller climates than existing systems, designed for larger waves but with low interception rates. The ability to provide breakwater benefits in those smaller wave climates should open areas where combined protection and generation give competitive economic returns.

Wave energy economics make areas with a large energy flux more easily viable. The intention is to take the other route and use the breakwater capacity to allow experience to be gained of generation in smaller wave environments. As a new operating principle is used; new problems are anticipated.

Acknowledgements
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