NUMERICAL STUDY OF WAVE FOCUSING ABOVE A SUBMERGED PLATE

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Abstract

The increase in demand for a clean and abundant energy source has resulted greater interest in the ocean, and more specifically waves, as a potential resource. The apparent unlimited potential held within our oceans has sparked more research and development into how to efficiently harness said potential. This paper is concentrated the focusing ability of the submerged plate and how the energy harnessed by a Wave Energy Device can be increased by using a flat submerged plate at various plate lengths and submergence depths. The alterations to the plate configuration will be compared with 3 different wave types. This will show trends and definitive conclusions on the effects the plate has over the wave, with regards to surface elevation. This shall be carried out numerically using Computational Fluid Dynamics, where the test shall take place in a numerical wave tank and measured with virtual wave gauges.

Acknowledgments

I would first like to thank Dr. M. Hayatdavoodi for his role as my supervisor. His help and guidance throughout this project allowed me to better understand the subject matter. Due to him always offering his help, I was able to progress past obstacles that presented themselves throughout the research conducted. His willingness to provide resources and time out with the required amounts, allowed my understanding and ability to conduct the experiments to increase. Without his help I wouldn't have been able to produce the work I have.

I would also like to thank my girlfriend, Nadia, for her help and understanding throughout this project. Without her help I would not have been able to complete the work presented.

A thanks also goes out to my friends and family, who provided the encouragement throughout the collation of data and writing of this paper.

Declaration

I hereby declare that the work contained in this document is my own work and has not been presented in a previous application for a higher degree.

10/04/2020

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1. Introduction

Renewable Energy

The global demand for energy is steadily increasing (Administration Energy Information, 2007) (Pout, et al., 2008). This is due to both an increase in population and the demand required by a singular person (Administration Energy Information, 2007). With this demand, the strain on fossil fuels and more common energy production methods have increased, (Hook & Tang, 2013) thus causing an increase in the emissions of CO_2, which has a detrimental effect on the environment (Figure 1) and uses finite world resources.

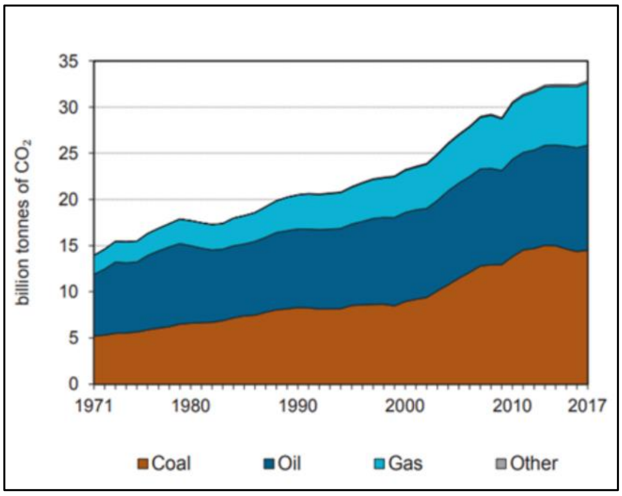


Figure 1 – World CO_2 emissions of non-renewable energy sources from 1971-2017 (International Energy Agency, 2019).

A solution to this is using renewable resources to generate energy, which lessens the impact on the environment. Renewable Energy (RE) has been used since the 1970s, which introduced a cleaner alternative to electricity generation over conventional finite fuel methods (Dincer, 2000). The subsequent increase in its use by governments around the world has resulted in a surge in the percentage of energy produced by RE as shown by Figure 2.

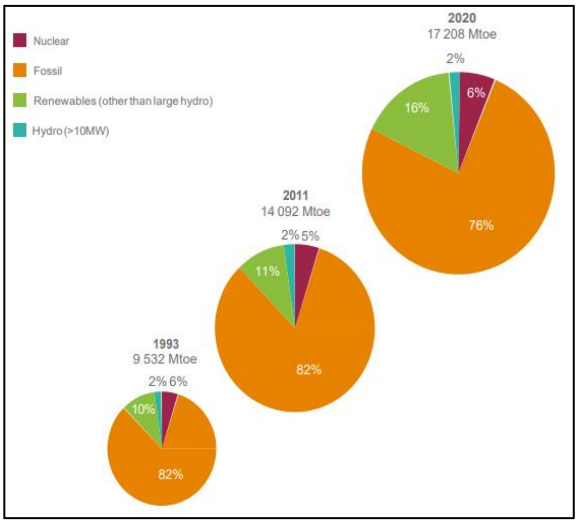
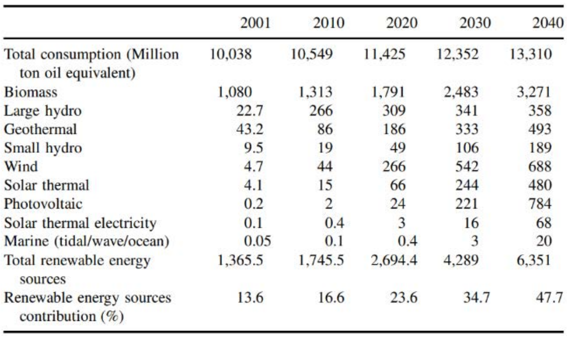


Figure 2 - World energy production by various sources from 1993 to 2011 and projected to 2020 (World Energy Council, 2013).

RE sources can be broken down into several categories as shown by Figure 2. The largest energy production coming from biomass, geothermal and hydropower. Although RE can produce large amounts of energy, conventional RE generation techniques pose several issues: many RE generation techniques impact local communities and wildlife due to a larger infrastructure, they can alter the environments in which people and wildlife are situated and are often not efficient enough to be deemed effective energy sources replacement (Azarpour, et al., 2012).



	2001	2010	2020	2030	2040
Total consumption (Million ton oil equivalent)	10,038	10,549	11,425	12,352	13,310
Biomass	1,080	1,313	1,791	2,483	3,271
Large hydro	22.7	266	309	341	358
Geothermal	43.2	86	186	333	493
Small hydro	9.5	19	49	106	189
Wind	4.7	44	266	542	688
Solar thermal	4.1	15	66	244	480
Photovoltaic	0.2	2	24	221	784
Solar thermal electricity	0.1	0.4	3	16	68
Marine (tidal/wave/ocean)	0.05	0.1	0.4	3	20
Total renewable energy sources	1,365.5	1,745.5	2,694.4	4,289	6,351
Renewable energy sources contribution (%)	13.6	16.6	23.6	34.7	47.7

Figure 3 - Global usage of RE categorised into energy sources.[10]

Despite these issues, the estimated energy production of 133,000 MWh (projected from when the study was conducted in 2009 to 2020 (Demirbas, 2009)), can dramatically cut down on fossil fuels. With today's current estimated global demand of 200,000 MWh as demonstrated by Figure 3. Additionally, the projected increase in future demand, the need to establish alternative, renewable and environmentally sustainable sources of energy is further reinforced.

Ocean/Wave Energy

One way in which RE can be generated is by harnessing the power of the ocean and its waves. Waves in the ocean most commonly occur when wind interacts with the free surface of the water, which then carries a wave over the free surface. Similarly, waves can alternatively occur through gravitational pull. This occurs most commonly from the moon acting on a volume of fluid, moving a volume of water. The motion of the water moves a device which then converts that movement into electricity. Thus, the production of energy depends on the movement of the fluid (Bryden & Couch, 2006). However, this is not the only way in which the ocean/sea can generate electricity, other chemical and geothermal techniques can also be considered.

Although the production of electricity via the ocean and sea is not limited to the conversion of fluid work to mechanical work, it is the most prosperous process with an estimated energy production potential of ~230,000 MWh. With this estimate, the ocean has the capability of fulfilling the demand, cleanly and in abundance (Lund, 2007). Energy generated via the ocean and waves have many other positive qualities that are typically not found in conventional 'on-shore' RE sources. Wave energy is a clean energy resource that doesn't require large infrastructure to begin harnessing. This is unlike many other renewable energy resources such as hydro-power and solar farms. This presents opportunities for wave energy to be implemented in many different economic and geographical environments, opening possibilities to provide energy to many different countries (Brooke, 2005).

Many RE devices can impact the people and environments that surround it by creating visual and noise pollution (Kupolati, 2010). Although RE sites such as windfarms and solar farms can be positioned in remote areas, they can still be visible and impact the surrounding environment. As with many aspects of engineering, the misuse of land for its intended purpose can often lead to detrimental effects on the surrounding environment and wildlife (Kupolati, 2010). This can also be applied to offshore structures, which many ocean Wave Energy Devices (WED) are. However, it has been found that the introduction of marine structures, can have beneficial effects on the surrounding marine areas, resulting in environments which thrive. The addition of a marine structure provides an artificial climate for new marine life. Materials in the structures can provide nutrients and a habitat for corals and seaweed, which then in turn, draws in other species of fish and crustaceans (Techera & Chandler, 2015). It is therefore suggested that the implementation of marine structures within our oceans (providing that these are done in a responsible manor) can have beneficial effects in terms of its support in marine life, cleanliness and sustainability, which provide further advantages to the implementing of ocean and wave energy.

Wave Energy Devices

WED's can vary in many ways, which allows for its application in many different environments and conditions. This versatility means wave energy is 60-70% more productive than other RE sources (Economist, 2020). This, in conjunction with the high potential energy stored within the ocean, means there an increased capacity to harness large amounts of energy for a prolonged period (Clement, et al., 2006).

The devices can also be used in many different environments ranging from:

- On-shore (shoreline), being situated very close to or on the shoreline,
- Nearshore, being further out ranging from close to shore to shallow waters,
- Off-shore, situated within deep waters.

The versatility of WED’s allows for its implementation within most environments, assuming access to the ocean/water is available, giving it an advantage over conventional RE devices (Brooke, 2005). These three locations come with several advantages, as well as disadvantages.

As the devices move into deeper waters, the waves interacting with the device contain more embodied energy, thus, the amount of electricity produced can increase. This however leads to issues with durability and maintenance, as the more remote the device, the larger and more powerful the waves become. This, however, can lead to issues regarding durability, which increases the likelihood of repairs being required. Another issue encountered when moving further into deep waters relates to the device is ‘locked’ to one position. Like other offshore structures, the devices require more attachment to the seabed as the velocity of the fluid flowing around the device increase. This is commonly be done by using foundations, thus making it less flexible to changes in wave direction and lowers the ease in which it can be moved to different sites (Drew, et al., 2009) (Folley, et al., 2007).

Though issues arise when devices are placed in deeper waters, moving the device closer to the shore also brings issues. Having the device exposed to people on the shore, where shoreline tourism is a key aspect to the economy of the country, can be a major determining factor when selecting the site. Although most devices sit relatively low to the water surface, there is typically still an exposed infrastructure above the surface. Depending on the area, this can cause issues to the aesthetics of the shoreline/coast. The variation of wave behaviour along the shoreline can also determine the suitability of the site. As many devices require a specific wave condition, a proposed site may not be compatible with the device. Finally, shallower water can also result in less embodied energy within the wave. This lowers the potential energy that can be harnessed as the waves propagate over the device (Drew, et al., 2009) (Folley, et al., 2007).

Types of Wave Energy Devices

WED’s come in many varieties, using different mechanisms to generate electricity. They can be categorised into 3 types (Drew, et al., 2009):

- Attenuators, when the whole system traverses the wave,
- Point Absorbers, where a part of the system moves due to the wave and the electricity generator is typically attached to the seabed,
- Terminators, which have a component that rotates around an axis.

Each of these WED’s, have restrictions on where they can be placed. As some WED’s sit on the seabed, deeper waters are less suitable as the wave is present close to the free surface and therefore works more effectively in shallower waters. However, the depth of the water impacts on the amount of energy the devices can generate, with deeper waters producing more energy than shallower waters. The location can also affect the durability of the devices, as with higher energy, more frequent waves typical of deep waters, damage to the device is more likely (Folley, et al., 2007). This is also an issue with upkeep of the devices, as with a device further away from the shore the maintenance, inspection and retrieval for more serious issues, become more difficult. The remoteness of the device in deeper water can also have increased cost implications. Far offshore devices incur increased costs in respect to transportation of electricity generated and maintenance. Deep water ocean waves pose another problem with the use of WED’s. Due to the random nature of deep-water waves, the orientation and optimal input wave properties of the device lowers its efficiency (Drew, et al., 2009).

As the amount of energy generated is most dependant on the power held within the wave, increasing the power and regularity of a wave in shallow water will offset the loss of the advantages gained by placing it in deep waters. Hence, influencing the wave to have as much energy as possible will allow for the most effective placement for the device.

Overview of Wave Focusing

Wave focusing is a method in which waves are amplified using a submerged object, in which alterations to the wave can be influenced by the dimensions of the object. The optimal scenario of wave focusing is where the surface elevation above the object is amplified to a greater value than the incident wave. Due to this ability to influence the surface elevation of a wave, the use of a Wave Focusing Device (WFD) is a simple solution to increasing the local energy that can be harnessed by a WED (Murashige & Kinoshita, 1992).

2. Literature Review

Wave Focusing

Wave focusing is a process in which the free surface elevation of a wave is transformed. Wave focusing occurs when a sharp sudden decrease in water depth due to an irregular sea floor is present (Murashige & Kinoshita, 1992). This has been recorded off the coast of Norway, where the water depth from the free surface dramatically changes as the waves propagates over the seafloor (Grue, 1992).The ridged surface of the sea floor was observed to alter the surface elevation of the waves as they travelled over them (Grue, 1992). It was also seen that the surface elevation decreased the further they travelled from the ridged seafloor. This phenomenon was then recreated by fully submerging an object below the free surface of a water volume and then passing waves over it. The sharp sudden decrease in water depth that is created by introducing a submerged object, accurately recreates the conditions observed in Norway (Murashige & Kinoshita, 1992).

Use of a Submerged Object

The surface elevation of the wave as it propagates, changes at different positions along the object. The object initially increases the surface elevation slightly. This then increases more severely the further along the object the wave propagates. Once the wave reaches the maximum amplification of the surface elevation, it begins to decrease (Teigen, 2009). This maximum can be said to be the focal point of the object. This submerged object can be said to be a WFD, due to its ability to focus a wave.

The submerged objects have been studied to determine the most effective form to achieve Wave Focusing. The form of the submerged object shows some advantages and disadvantages when the conditions being tested vary (Murashige & Kinoshita, 1992). The testing of multiple chevron and chevron-style shaped mounds were carried out. The chevron shaped mounds, showed to be effective when focusing waves, but submerged circular lenses were found to amplify the power of the waves up to a factor of two (Murashige & Kinoshita, 1992).

A flat plate was found to be the ideal form for a WFD, due to its thin shape, ease of construction and relative cheapness over other WFD's (Hayatdavoodi, et al., 2017). The use of a flat plate as a WFD works similarly to the ridged seabed found in Norway, by dramatically decreasing the water depth, the waves surface elevation begins to change (Grue, 1992). Due to the plate acting similarly to an aerofoil, the fluid can continue flowing both over and under the plate. This sudden splitting of the two fluids allows for the wave to continue propagation over the plate while the fluid present on the underside continues with a uniform flow (Hayatdavoodi, et al., 2017).

The study of a circular arc shaped plate was conducted by Mciver, *et al.*(1995) who suggested the effects on reflection from the wave of a fully circular plate poses no advantages over a plate with a semi-circular plan. This would allow for a reduction in material costs and reduce the area taken up by the plate.

This then prompted Li, *et al.*(2020) to study the effects of a crescent shaped plate, Figure 4. It was determined that unless the wave incident on the plate acted perpendicular to the convex edge of the plate, the location of the focused wave was varied in relation to the direction of the wave. Due to this uncertainty in the location of the focal point, no consistency within the waves propagating over the plate could be determined. Suggesting that a plate of disk shape would be better suited.

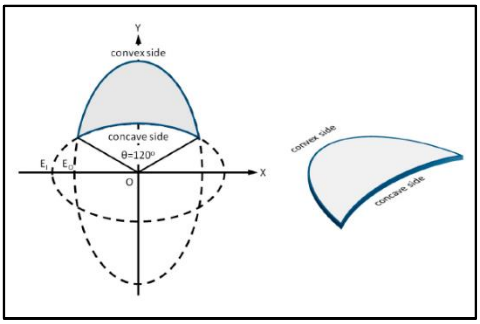


Figure 4 – Crescent shaped plate [30].

A study conducted by Newman (2015) explored the planimetric shapes of these flat disks. He found that symmetrical shape a diameter equal to the wavelength of the wave propagating, provided the biggest amplification factor for 3-dimensional waves propagating over the plate (Newman, 2015). This suggests that a symmetrical disk with a diameter close to the wavelength of the wave produces the largest increase in surface elevation. The use of elliptical plan disks has also been considered. This where the lengths in x-y are not equal. It was found that with a disk with ratio of x-y lengths equal to one produced the larges relative increase in surface elevation (Zhang & Williams, 1996). Teigen (2008) also suggests that a disk of circular plan produces a larger amplification of the waves surface elevation compared to a plate of rectangular or hyperbolic shape.

The effects on the plate's submergence depth has also been studied. It was found that as the water depth from the free surface to the plate decreased, the waves surface elevation increased. This suggests that with smaller submergence depths the wave's surface elevation can be amplified greater than that of greater submergence depths (Brossard, et al., 2009) (Lo & Liu, 2014). With a decrease in submergence depth, comes more reflections propagating towards the incident waves (Patarapanich, 1984), this decreases the regularity of the waves (Lo & Liu, 2014). As reflected the reflected waves are traveling back upstream against the propagating incident wave, loss of energy is likely. Therefore, having the plate closer to the surface of the free surface can lower the energy held within the wave, decreasing its effectiveness as a wave focusing device. The amount of reflection can be said to be product of the length of the plate to wavelength, wavelength to water depth and submergence depth to wavelength. Reflections tend to be at their maximum when submergence depth, water depth and wavelength are all equal. To minimise the reflections back upstream, use of a submergence depth 0.7 times that of the wavelength should be used (Patarapanich, 1984).

The thickness of the plate has also been of interest. It has been shown that the thickness of the plate has no real effect on the wave propagating over the plate, in relation the forces and surface elevation (Hayatdavoodi, et al., 2017) (Brossard, et al., 2009). Though this is the case, the use of a thinner plate will reduce the material use, thus potentially lowering the cost of the plate. However, this decrease in thickness could cause issues with rigidity of the plate. Therefore, by decreasing the thickness a more rigid material would be required. This lack of rigidity could be solved by adding rigid strips on the underside of the plate. This addition of rigidity would allow for the plate to be thin while not having large deflections. It has been found that with the addition of the of these strips on the underside of the plate, produced no detrimental effects on the forces present on a flat fully submerged plate (Hayatdavoodi, et al., 2014). Due to this it can be assumed that by the addition of rigid strips on the underside of a plate, a rigid but thin plate can be used.

Effects of Wave Focusing Downstream

The effect that a flat horizontal plate has on the wave the further it travels downstream, has also been of interest for its potential use as a breakwater and for aquaculture reasons (Hayatdavoodi, et al., 2017). As discussed by Grue (1992), once the wave had propagated over the ridged seafloor, a dramatic overall decrease in surface elevation occurred (Grue, 1992). This decrease in surface elevation is said to be the result of the two water mediums meeting, increasing the total water depth to greater than that of the water depth above the plate. This sudden increase in water depth dampens the wave, lowers the surface elevation and potentially decreases the velocity (Hayatdavoodi, et al., 2017). The effectiveness of a plate as a breakwater has been shown to decrease the more submerged the plate becomes. This suggests that increasing the submergence depth of a plate will yield greater benefits when looking at decreasing surface elevation downstream of the plate (Brossard, et al., 2009).

Using multiple plates has also been considered. The stacking of two plates splits the water volume into three layers. The splitting of the water into three layers, decreases the water depth more dramatically. Therefore, when the water volumes are reintroduced, the increase in water depth is more significant. It was found that with a twin plate system, the breakwater effects are between 22-23% more effective than that of the single plate (Usha & Gayathri, 2005).

The use of a mound structure is generally used as a breakwater. The interest in submerging the mound has been of interest to minimise visual pollution. The introduction of a plate as obstruction to the wave leeward of the mound has been explored. As the plate is capable of being used as a breakwater, its introduction to a more typical breakwater system has been found to add beneficial effects. In addition to the plates configuration of submergence depth and plate length, the distance to the mound has also been suggested to influence to transmission of wave downstream of the system. With an increase in distance from the plate, bellow 4 times to water depth, decreasing the transmission of the wave downstream. Indicating the introduction of a submerged mound within a submerged horizontal plate breakwater system will have beneficial effects on the severity of the wave downstream (Hsu & Wu, 1998).

Challenges

There has been a significant amount of research into the implementation of a submerged plate in a WED’s system to amplify the surface elevation of a wave. This has resulted in a greater understanding of the wave-plate interaction. This, however, has not been fully understood. The water wave conditions considered in much of the research undertaken concentrates on periodic waves, where the effects of reflections on propagating waves is not considered and deep-water waves, where the water depth is much greater than that of the wave height, $h \gg H$. This has allowed for the impact of the plates effects to be identified when these conditions apply, but not when considering intermediate and shallow water. Therefore, the effects of a plate in shallower water conditions as both a wave focusing device and a breakwater haven’t been determined.

The research carried out has also tended away from irregular (random) waves. Understandably the complexity increases as the conditions become more irregular due to the potentially undefinable relationship between the wavelength and plate length.

Project Outline

This project aims to observe how the use of a submerged plate can transform waves as they travel over the plate. The manipulation of the flat submerged plate shall be carried out to determine how, by using the plate, wave properties can be affected to provide a more favourable outcome both over and after the plate. The use of Computational Fluid Dynamics (CFD) shall be utilised, iteratively solving for the Navier-Stokes equation, to monitor the effects the plate has over the waves.

3. Methodology

This section will provide the method used to obtain the surface elevation, which is will be linked to the energy embodied, of a wave propagating over the mid-point of a flat fixed plate using various wave conditions and parameters, as a function of time. Using CFD to simulate waves propagating within a 2-dimensional computational wave tank, the effects of a submerged plate on the surface elevation shall be observed. 3 different wave cases shall be studied, focusing on the effects of a plate in shallow to intermediate waters. These cases will be repeated changing the submergence depth and length of the plate. The surface elevation can then be monitored using 5 wave gauges, two before the plate, one at the midpoint of the plate and two after, this will allow for the surface elevation to be determined throughout the tank.

Wave Parameters

The waves being utilised for testing are split into 3 cases. These simulate different conditions in which the waves would be found, shallow, intermediate and intermediate linear water conditions. The wave parameters used for testing presented in dimensionless form are:

Case	Wave Height (H/h)	Wave Number	Angular Velocity (rad/s)	Wavelength (λ/h)	Period (t√(g/h))
1	0.015	1.223	4.825	9.339	10.00
2	0.050	1.223	4.825	9.339	10.00
3	0.050	0.462	1.930	24.737	25.00

Table 1 - Wave parameters being used in tests cases. Case 1: Intermediate (Linear) Water, Case 2: Intermediate Water and Case 3: Cnoidal (Shallow) Water.

These values were determined using stokes wave theory graph. This dictates what the wave parameters should be selected to satisfy the various wave conditions. The points chosen are illustrated within Figure 6.

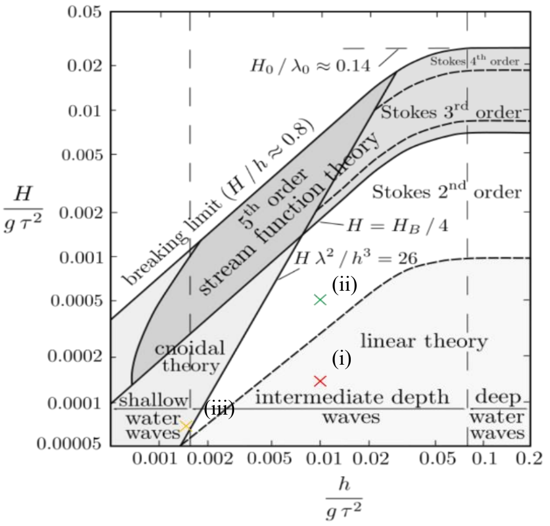


Figure 5 - Stokes wave theories. (a) Case 1 – Intermediate (Linear) Water, (b) Case 2 – Intermediate Water, (c) Case 3 – Cnoidal (Shallow) Water.

By maintaining a constant water depth throughout the cases, the graph allows for the wave parameters to be determined neglecting the depth of the water. This allows the for the comparison of the 3 wave conditions to take place, showing the effects of a specified plate on 3 different input wave conditions.

Plate Parameters

The plate can be altered in two ways, length (L_P) and the submerged depth (S). These parameters are independent of one another and can be altered freely. The thickness of the plate is fixed and not been considered as a variable due to its effects on the waves being negligible. Thus, is assumed to arbitrarily small (Hayatdavoodi, et al., 2017) (Brossard, et al., 2009).

Plate Length (L_P/h)	Submerged Depth (S/h)
3.00	0.10
6.00	0.20
9.00	0.30

Table 2 - Plate Lengths and Submerged Depth used in conjunction with wave parameter within wave tank.

The case is presented as a 2-dimensional case, where the plate is a flat plate of length (L_P), which in a 3-dimensional case would become the diameter of the plate. The planimetric shape of the plate can then be assumed to be disk shaped. This offers the greatest amount of consistency, due to waves being capable of interacting with the device at any angle. This planimetric shape of the plate offers the ability to gain similar results regardless of the direction of the wave.

Tank Layout

The tank geometry is based on a real-world laboratory case, this follows the standard layout of a long rectangular tank, with a wave maker at one end and a relaxation zone on the other. With this layout, the waves, created by the wave maker, can freely traverse the length of tank and once interacting with the relaxation zone, dissipate all energy, thus mitigating any reflections traversing back into the incident wave. This standard geometry can be altered by using a numerical approach to allow for more control over the tank conditions. Relaxation zones, which typically follow the form of a beach in laboratory tanks, can have their geometry changed to better suit the case easily by using a numerical approach. The addition of a relaxation zone in the input side of the tank can also be introduced, to limit any reflections from objects within the tank influencing the incident wave. A numerical approach also allows for the easy implementation of obstacles, such as a submerged plate, from being added and manipulated.

The gauges are shown to be in a 2:1:2 configuration, this is a modification of the method proposed by Grue (1992), allowing for understanding of the surface elevation of the wave to be determined before, after and as the wave propagates over the plate. Gauge 1 is located at the far-left side of the tank and allows for an input wave to be determined. The length before the plate has been kept at a constant 3λ/h, this mitigate any reflections from the plate reflecting towards the propagating waves.

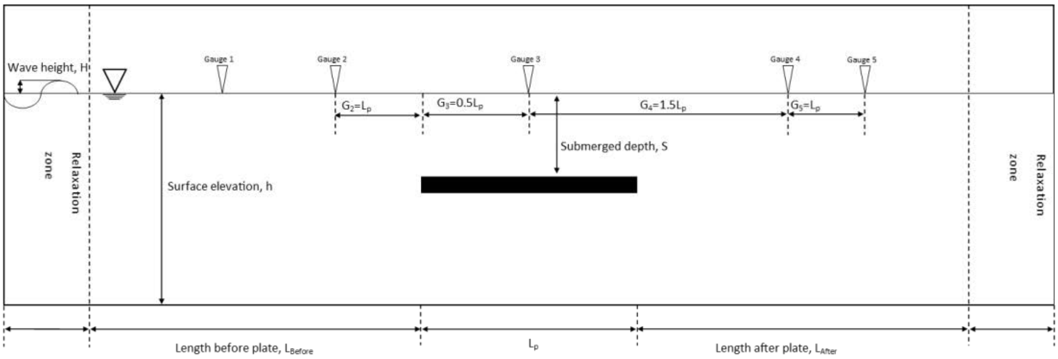


Figure 6 - Tank schematic displaying the layout of the numerical wave tank used for testing.

Computational Analysis

The code used to simulate this problem was provided and was based on a modified Green-Naghdi (G-N) code used to find forces and pressures acting on the plate. The code uses a mesh, to which the calculations can be carried out within. The spacing of the mesh is 0.1 in both the length and height of the tank. Within these mesh boundaries the Navier-Stokes momentum equations can be solved iteratively for each subdivision of the mesh.

$$\rho\frac{Du}{Dt} = -\nabla\bar{p} + \mu\nabla^2 u + \frac{1}{3}\mu\nabla(\nabla \cdot u) + \rho g \qquad (2.1)$$

Where:

- ρ is the density of fluid,
- g is the gravitational force,
- μ is the fluid viscosity,
- u is the fluid flow velocity,
- $\frac{Du}{Dt}$ is the change in fluid velocity,
- p is the pressure,
- ∇ is the divergence vector.

This can then be used to determine the surface elevation and by use of 2-dimensnsional G-N equations are at and output it via the wave gauges, this can be seen further by (Seiffert & Ertekin, 2012).

$$\eta_{,t} + (h + \eta - \alpha)u_x = \alpha_t, \tag{2.2}$$

$$\dot{u} + g\eta_x + \frac{\widehat{p_x}}{\rho} = -\frac{1}{6}[2\eta + \alpha]_x\ddot{\alpha} + [4\eta - \alpha]_x\ddot{\eta} + (h + \eta + \alpha)[\ddot{\alpha} + \ddot{\eta}]_x \tag{2.3}$$

Where:

- ρ is the density of fluid,
- g is the gravitational force,
- $\eta(x, t)$ is the surface elevation.
- u is the fluid flow velocity,
- $\hat{p}(x, t)$ is the pressure,
- $\alpha(x, t)$is the vertical location of the bottom of the fluid sheet.

The domain in which the calculations are carried out is created within an INPUT file. This generates the boundaries in which the calculations should take place, defines the wave parameters to be simulated and locations of the gauges to extract data.

As the calculations take place within the mesh domain. The finer the mesh, the more calculations can take place, increasing the resolution of the simulation. With more calculations comes a greater degree of accuracy. Hence, increasing the fineness of the mesh, will result in a truer to life representation of the experiment. The increase in calculations shows there is a dramatic increase in computation time, thus, limitations are set to find the best mesh size offering accuracy and not requiring large compute times.

The addition of wave gauges allows for the extrapolation of surface elevation to take place. Unlike a laboratory experiment, the number of wave gauges isn’t limited to equipment available, thus using the INPUT file, an unrestricted number of gauges can be utilised. The programme will then output a text file, which contains the raw data to which the surface elevation at the point in which the gauge is located at a constant time interval. This can be extrapolated and analysed, and results discussed.

Validation of Code

The validation of the code should be carried out to ensure the results are calibrated precisely and the input parameters are defined correctly. This will validate the calculations and the resolution of the mesh, thus, allowing for the code to be deemed a good representation of the case being studied. The following case was selected from (Hayatdavoodi, et al., 2017), showing a Cnoidal wave propagating over a plate of length 20 L_P/h.

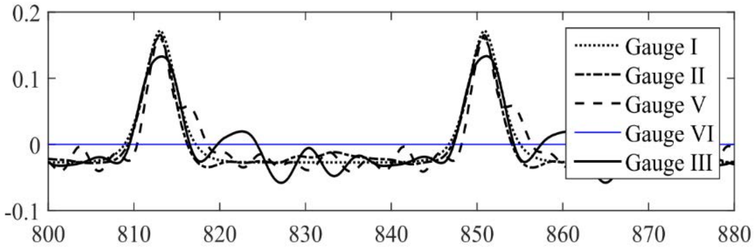


Figure 7 - Graph of surface elevation for a Cnoidal wave interacting with a submerged plate. H/h = 0.2, d/h = 0.5, L_P/h = 20, λ/h = 40 (Hayatdavoodi, et al., 2017)

This graph was then digitised to extract the surface elevation output by Gauge I, the same case was then carried out using the G-N code and compared with the numerical output from the Gauge I within the code.

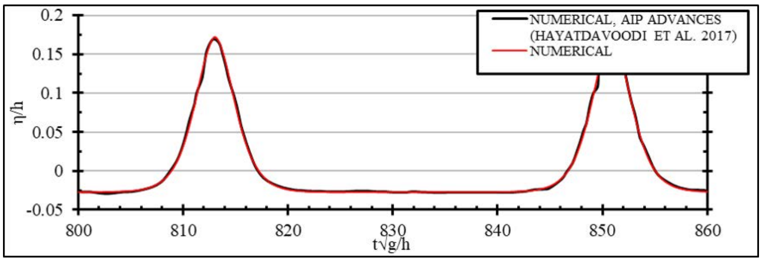


Figure 8 - Surface elevation of Cnoidal wave from software validated against data extracted from AIP Advances 7. H/h = 0.2, d/h = 0.5, L_P/h = 20, λ/h = 40

As both results follow the same trend and are within ±7% mean error, the software is assumed to produce an accurate recreation of the case. The error displayed within the results are most likely a product of the digitisation of the original graph. Digitisation is not a full-prof process of determining the values of a graph as there is an aspect of human error when selecting the points within the graph, thus, meaning the values selected will not be the approximate value of the original data.

Complications with Testing

The tests were initially to be carried out using an open source CFD solver software called OpenFOAM. This software, in conjunction with an add-on software, Waves2Foam, would allow for the simulation of waves propagating over a submerged plate to be carried out using a standardised software package. As OpenFOAM is used by numerous professionals in many different fields of work, its recognition as being reliable solver is well renowned along with being user-friendly. As with the G-N code used within for the testing in the project, the OpenFOAM software can simulate a boundary in which a fluid can be analysed and with the addition of Waves2Foam, the simulation of waves propagating within a boundary and the ability to add relaxation zones within the boundary can take place.

OpenFOAM is a Linux based software in which command prompts are used to run the cases by using files within the case folder. Within these files, the boundary, mesh, environmental and wave parameters could be defined. The measurement devices could also be specified and their location within the boundary defined.

As OpenFOAM is a Linux based software, the download is done via the command terminal and involves downloading and compiling specific applications. This can be a very tedious and exact process in which any errors in the download can be fatal in the running of the programme. Although care was taken to ensure this was done properly, issues were encountered, in which the knowledge of the error was not able to be obtained. Despite extensive troubleshooting, the error could not be overcome, resulting OpenFOAM not being utilised within the testing of these cases. Due to this complication, a modified G-N code was provided in which the same wave parameters were input. This though only still produced the results that were required, but with a less user-friendly experience.

4. Results and Analysis

The surface elevations of a wave propagating over the mid-point of a submerged plate under wave conditions expressed in the above section are shown in this section. The data is split into wave conditions to show the effects of a submerged plate on the individual wave. Within this the length and submerged depth of the plate and the effects they have on the surface elevation was explored. As all values prior to tested were provided in dimensionless form, the results too are presented in dimensionless units. This will allow for further works to be carried out within a laboratory environment and allow for the comparison of the results.

Surface Elevation at Midpoint of Plate

Case 1 - Intermediate (Linear) water

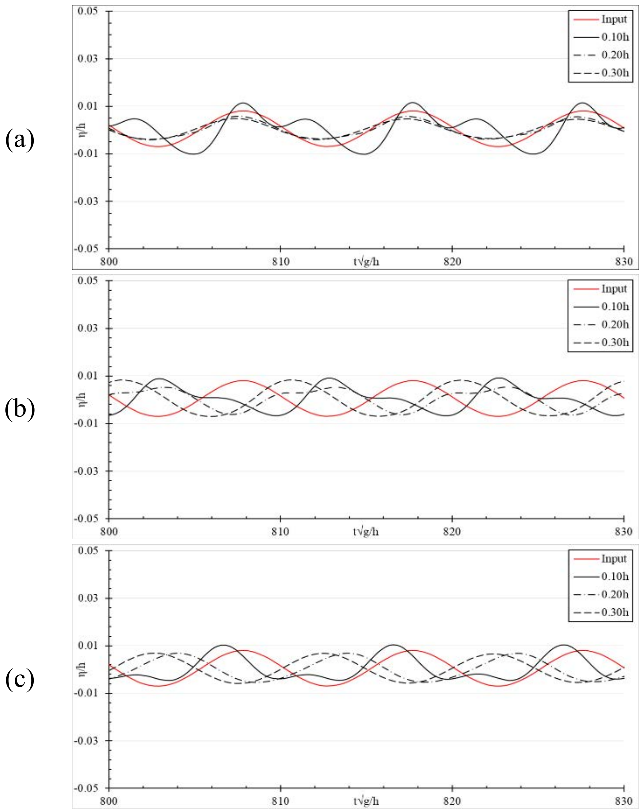


Figure 9 - The Surface elevation of a wave propagating over a submerged plate of depth, (a) L_P=3h (b) L_P =6h (c) L_P =9h, for Intermediate (Linear) water conditions (H/h=0.015, λ/h=9.339, t√g/h=10.00)

Case 2 - Intermediate Water

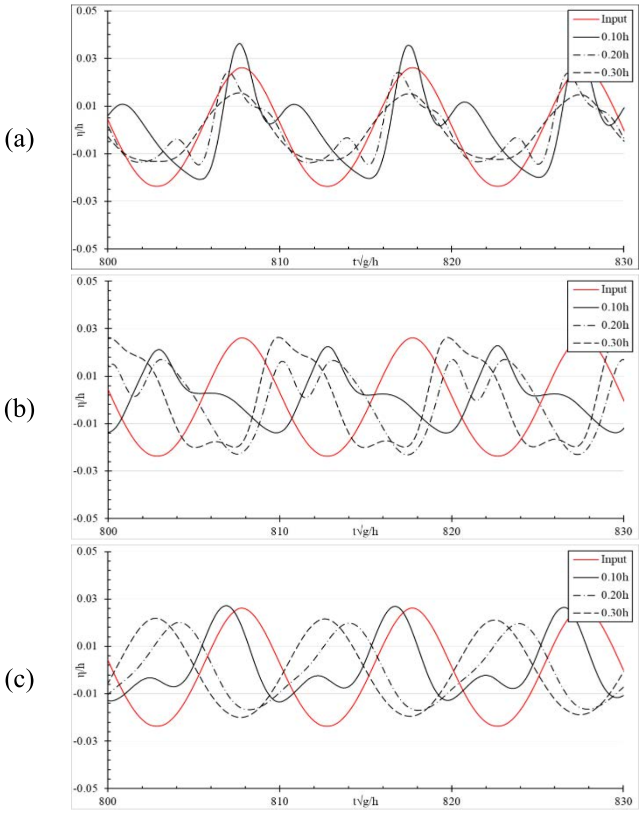


Figure 10 - The Surface elevation of a wave propagating over a submerged plate of depth, (a) $L_P = 3h$ (b) $L_P = 6h$ (c) $L_P = 9h$, for Intermediate water conditions ($H/h=0.050$, $\lambda/h=9.339$, $t\sqrt{g/h}=10.00$)

Case 3 - Cnoidal (Shallow) Water

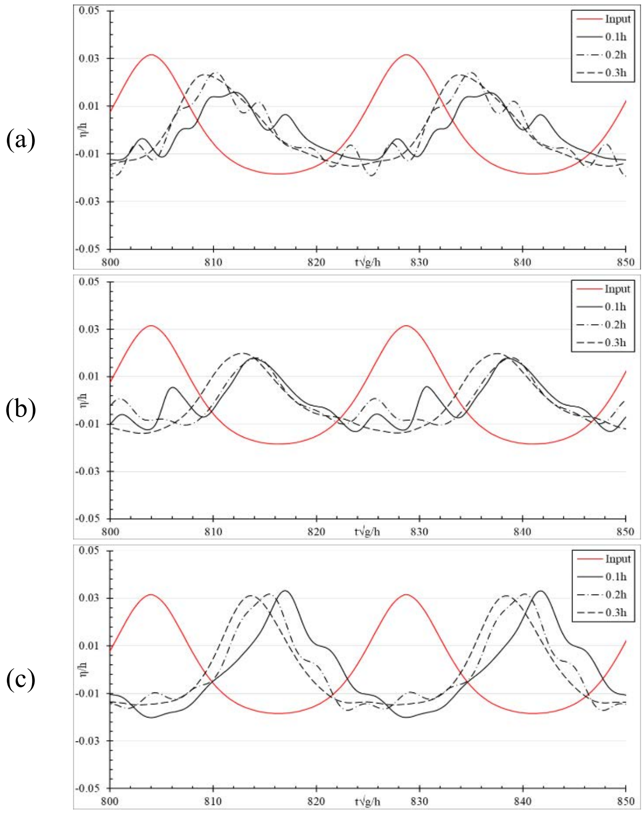


Figure 11 - The Surface elevation of a wave propagating over a submerged plate at depth, (a) L_P =3h (b) L_P =6h (c) L_P =9h, for Cnoidal (Shallow) water conditions (H/h=0.050, λ/h=24.737, t√g/h=25.00)

Discussion of Results at Mid-Point of Plate

The tests were run within the same test conditions, using the same code, altering one variable at a time. The placement of the gauges remained constant as per Figure 6. The tests were carried out and results plotted on Excel to aid in the visual analysis of the effects the plate has on the surface elevation. Shown in red is the unaffected input wave, to allow comparison of the waves as they pass over the plate to the incident wave input into the test. The time shown within the graphs is near the end of the test, this allows the plots to display the results after any anomalies may have occurred to do the wave beginning to propagate down the tank. The time range has also been selected as it allows for the visualisation of 2 full waves within the plot.

We can see from all graphs there is a difference in surface elevation when the plates length and submergence depth is changed. The peak in surface elevation also occurs at different time steps within the tests as the plate parameters are changes suggesting some change in the phase of the waves.

The biggest increase in surface elevation is seen in Case 1, where the surface elevation of the wave at the midpoint of the plate is much greater than that of the input wave, by a factor of 1.48. The waves typically have two peaks, as seen in the figures above. This shows there are at least two points in time where the wave is focused. This is called the harmonics of the wave and they can be defined as the ratio between the plate length and wavelength:

$$Focal\ point\ occurs\ when, \frac{L_P}{\lambda} = \frac{1}{N} \tag{5.1}$$

Where:

- N = A real number.
- L_P = The plate length,
- λ = The wavelength of the wave.

This shows the ratio between the plate length and wavelength directly corresponds to the when a focal point occurs. The surface elevation also seems to show that as the plate length to wavelength ratio tends 1:N, where N is the smallest real number, the amplification of the wave increases.

It can also be seen that the closer the plate length and wavelength ratio is to 1:1, the fewer harmonics can be seen to occur. Thus, to increase the effectiveness of the plate, the length must be that of the wavelength to allow for the most energy must be focused in a singular point. This is achieved when the wave altered by the plate contains as few harmonics as possible, therefore, a ratio of plate length to wavelength of 1:1. It can also be seen that as the ratio of plate length to wavelength moves further away from a 1:1 case, the less pronounced the wave becomes. This is seen in Case 3 with a plate length of 3h. within this case the plate length to wavelength ratio of roughly 1:8. The lower ratio results in a broader spread of the wave and decreased surface elevation, resulting in less energy being present at the peak.

The phase of the wave is also seen to change as the ratio of plate length and wavelength tends away from the ratio 1:1. The phase of the peak of the focused wave to the incident wave can be seen to be a function of:

$$Phase = f(L_P, \lambda, S) \tag{5.2}$$

Where:

- L_P = The plate length,
- λ = The wavelength of the wave
- S = Submergence depth.

As can be seen in the figures above, the submergence depth of the influences the phase of the wave more so than the surface elevation, with the phase increasing from the incident wave when the submergence depth is increased. Resulting in a tighter variation on the phase of the wave the shallower the water becomes.

The surface elevation can also be seen to gradually decrease from the peak of the largest submergence depth (for all cases 0.1h) as the submergence depth increases. This decrease in surface elevation becomes less, the more the wave tends towards a shallow water condition. Therefore, showing that the shallower the water conditions, the less effect the submergence depth has on the amplifying the wave and further shifting the phase of the wave.

Surface Elevation After Trailing Edge

Case 1 - Intermediate (Linear) water

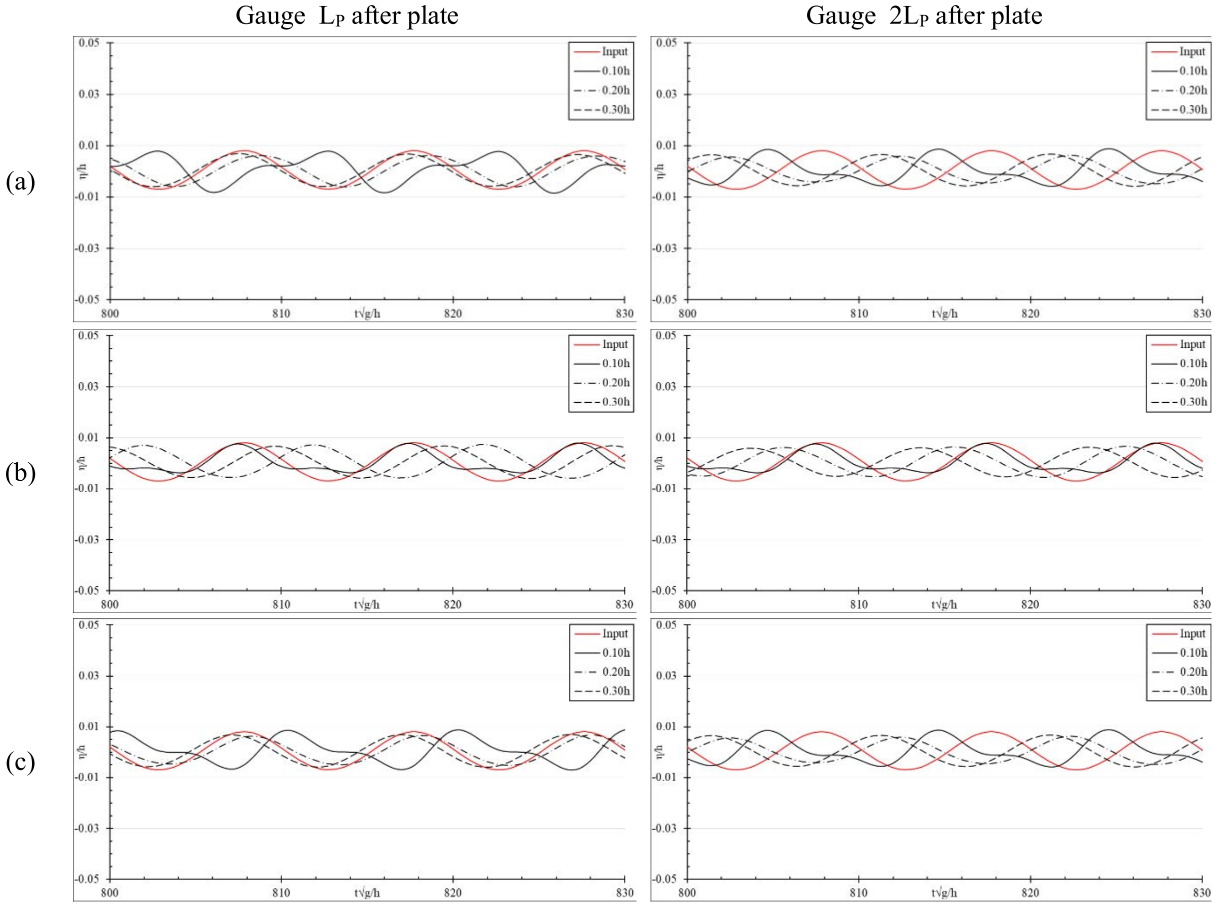


Figure 12 - The Surface elevation of a wave propagating over a submerged plate at depth, (a) L_P =3h (b) L_P =6h (c) L_P =9h, for Intermediate (Linear) water conditions (H/h=0.015, λ/h=9.339, t√g/h=10.00) at points L_P and $2L_P$ after plate.

Case 2 - Intermediate Water

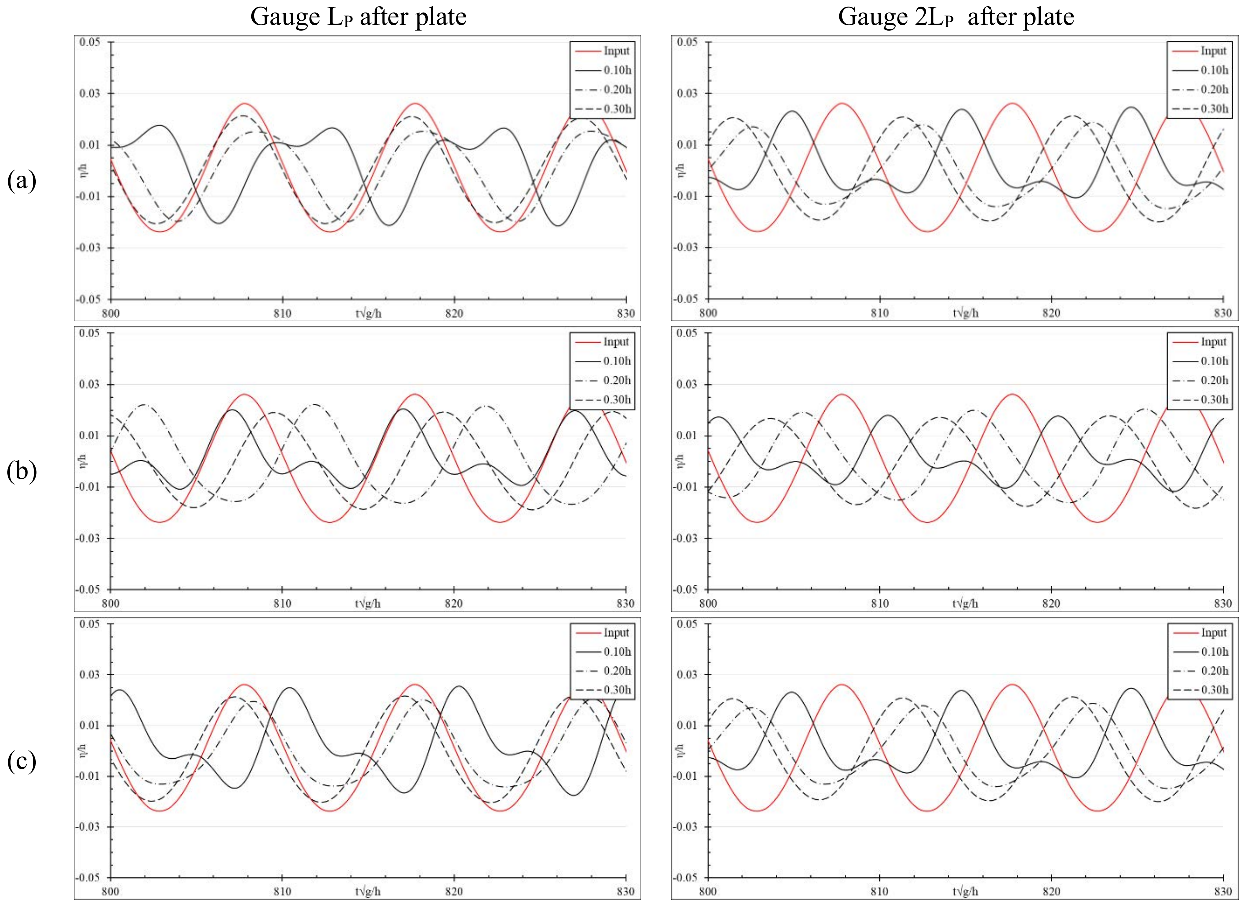


Figure 13 - The Surface elevation of a wave propagating over a submerged plate at depth, (a) L_P=3h (b) L_P=6h (c) L_P=9h, for Intermediate (Linear) water conditions (H/h=0.050, λ/h=9.339, t√g/h=10.00) at points L_P and $2L_P$ after plate.

Case 3 - Cnoidal (Shallow) Water

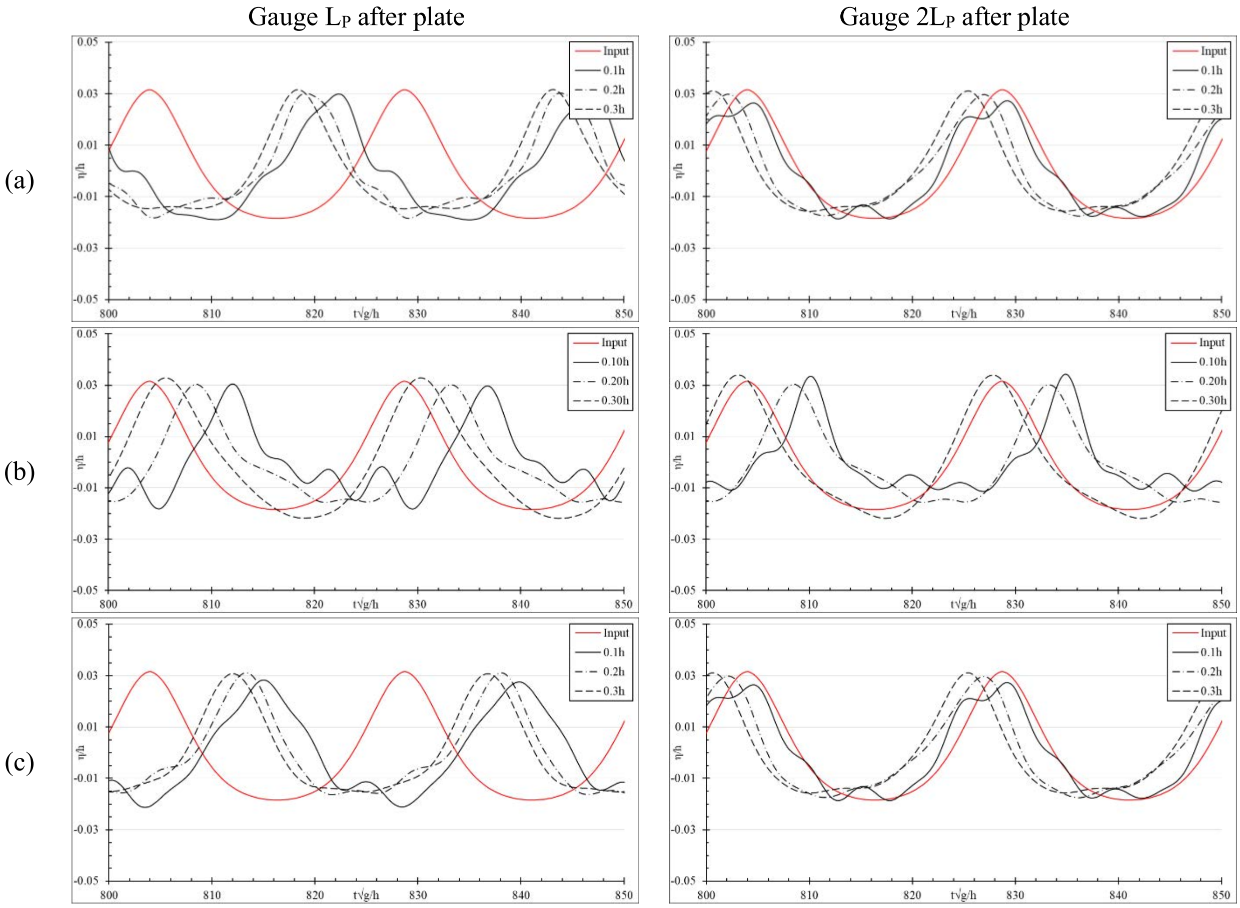


Figure 14 - The Surface elevation of a wave propagating over a submerged plate at depth, (a) L_P=3h (b) L_P=6h (c) L_P=9h, for Intermediate (Linear) water conditions (H/h=0.050, λ/h=24.737, t√g/h=10.00) at points L_P and $2L_P$ after plate.

Discussion of Results After Plate

Within the figures above, the surface elevation is shown at one and two plate lengths downstream of the plate. They show the result of the wave propagating over a plate and being re-introduced to the original water depth. In majority of the cases, at both one and two plate lengths after the plate, the surface elevation of the wave returns to, or decreases below, the original wave height of the input wave. The surface elevation is seen to slowly decrease over the distance $2L_P$ after the plate, this is likely due to the interaction of the wave propagating over the plate and the water volume passing under the plate. This interaction likely dissipates some energy causing the wave to reduce in surface elevation.

This re-introduction of the two fluid volumes also causes a further phase shift which increases as the wave propagates downstream of the plate. This phase shift increases the further the wave is downstream of the plate. This can be assumed to continue the further downstream the wave is from the plate. This Phase shift, like the surface elevation, is due to energy loss as the two fluids are re-introduced.

The variation in plate length shows that the further away the plate length and wavelength ratio was from 1:1, the larger the decrease in surface elevation occurred as the wave propagated downstream of the plate. Therefore, the shorter the plate, the more effective the plate is in decreasing the surface elevation downstream.

It can also be seen that there is a large variation within the submergence depth, particularly in Case 3, where the surface elevation doesn’t follow a purely regular wave path. This oscillation of the surface elevation can be assumed to be caused by reflections of the wave after the wave has propagated over the plate. This being seen most predominantly in Case 3 suggests the amount of influence the reflections have on the wave after propagating over the plate is more exaggerated within shallow water conditions.

5. Conclusion

As the world consumes more electricity, the increasing demand for a clean and efficient energy source has surged. Marine and ocean energy has presented the possibility of offering an abundance of clean energy. Wave energy has been proposed as the most abundant source of energy within the ocean and over the past several decades has been explored as the solution to the growing demand for energy. Various methods have been created to harness the energy held within waves. However, this poses an issue. Waves by nature are random. They range in embodied energy depending on their location and the remoteness of their positioning. Thus, the placement of the Wave Energy Devices influences the effectiveness of its energy generation.

Introducing a fixed flat submerged plate within a Wave Energy Device system allows the focusing of a wave along the plate. Therefore, allows the energy of the wave to be focused at a singular point allowing for the largest amount of energy to be harnessed from the wave. This allows for Wave Energy Devices to be placed closer to the shore where the waves are less destructive and regular. The Wave Energy Device can then focus them in order to concentrate the energy of the wave at a singular point. This closeness to shore offers benefits. For example, when maintenance required and fixing the device and plate to the sea floor.

The numerical study carried out throughout this research paper has presented areas for discussion of what configuration of the plate offered the most effective outcome, with regards to surface elevation of the wave. It was found that the relationship between plate length and wavelength posed the biggest influence over the surface elevation. The harmonics produced as a product of this suggests that the closer the plate length and wavelength become to the ratios, 1:1, 1:2, 1:3…, the more likely for an increase in surface elevation is to occur. It was also shown that the closer the plate length and wavelengths ratio became to 1:1, the larger the increase in surface elevation was.

The submerged depth of a plate can also be seen to affect the surface elevation. The amount the plate was submerged influenced the amount of decrease in surface elevation occurred. Showing the closer to a shallow water condition the case was the less the plates submergence depth effected the surface elevation. The submergence depth did however have a larger influence over the phase shift of the wave. With more phase shift produced the mores submerged the plate became.

The effects were also found after the wave propagated over the plate. The length of the plate played a large factor in the amount the waves surface elevation decreased, with a shorter plate, relative to the wavelength, decreasing the surface elevation more. The surface elevation decreased at a slow rate as the wave propagated further from the plate. The phase shift of the wave was also seen to increase the further the wave was from the aft of the plate.

Reviewing the information within the paper, the effects of a submerged plate for use as a wave focusing device shows promising signs. With the ability to alter the wave both during and after the plate, the devices capabilities for use within a Wave Energy Device and as a breakwater system seem possible. It was also discussed that the regularity of the wave after propagating over the plate decreased as the water conditions became shallower. This suggests the impact of reflections on the wave increase in shallower water conditions.

The increase in surface elevation discussed within this paper, shows that there is a potential to increase energy of a wave at a focal point. Due to this, introducing a submerged plate into the system of a Wave Energy Device will increase the effectiveness of the device, allowing for a greater yield when implemented.

Future work

To further understand the problem, additional tests are required. The testing was carried out using plate lengths of 3h, 6h and 9h. As the amplification of the wave is more influenced by the relationship of the plate length and wavelength, selecting plate lengths closer in comparison to the wavelength of the wave is required. Plate lengths bigger than the wavelength should also be tested. This will show the effects of having the plate length be bigger than the wavelength of the wave, as well as seeing if the same trend applies.

The submergence depths of 0.1h, 0.2h and 0.3h, should also be studied further. As the trend showed, the wave height and lengths relationship with the water depth dictated how much the submergence depth affected the surface elevation of the wave. The submergence depths should also be broadened. This will indicate, if a decrease in surface elevation due to an increase in submergence depth continues along the same trend. Also, the study of an increasing or decreasing submergence depth along the plate length should be conducted, as more gradual decrease of water depth may pose beneficial effects to the surface elevation of the wave. If a relationship could be found to optimise the wave focusing for several wave conditions using a singular plate by implementing multiple submergence depths. A system could be created allowing for the focusing of multiple waves by using a singular plate.

The placement of the gauges could also be explored, as the focal point may not be within the centre of the plate. Thus, looking at the position of the focal point on the wave will allow for a better understanding of the ideal placement of a WED.

The surface elevation of the wave after the plate should also be explored further. As discussed in above sections, the surface elevation begins to decrease as the wave propagates further from the plate. As the measuring gauges were relatively close to the plate, the effects of the wave propagating over the plate further away from the plate could not be explored. If gauges were located further downstream of the plate, the effects of the plate could be determined, seeing if the trend continues as the waves propagate downstream of the plate.

The velocity of the wave as it propagated over and past the wave was discussed but a more in-depth study of what effects the plate has on the velocity of the wave is required. It was seen that there was a delay in the peaks of the wave as it propagated over the plate and to which the delay increased after the plate. The amount of delay that occurred was relative to the difference in plate length and wavelength.

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