POWER PLANT SYSTEM ENGINEERING

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Module 4

Lec 6: Energy From Oceans: Part-II

Dear learners greetings from IIT, Guwahati. We are in the MOOCs course Power Plant System Engineering module 4 that is Hydro and Renewable Energy Generation Systems. So, in our last lecture we are covering the energy harness mechanisms from oceans. So, part 1 we have covered where it was emphasized that ocean temperature difference from the ground and the deep water will give the significant impact for harnessing energy through heat engine principle. Now, in those context it was the ground water and the deep water that gives the necessary temperature difference through the concept of heat engines. Now, in this lecture we will be focusing on waves because in earth around 70% of space is being occupied by oceans and seas and almost everywhere or in most of the geographical sites we will find waves and tides. So, both are actually governed by the gravitational forces of sun and earth on the surface. So, because of this reason since there are some waves, those waves have significant potential to harness energy or power. So, in this lecture today we will be focusing on harnessing energy from oceans. We will mainly focus on ocean waves, energy and power from the waves and wave machines and also we will focus on tidal energy. This tidal energy comes by virtue of lunar cycle or effect of lunar cycles on water surface of sea and ocean.

So, just to give insight in our previous discussions, the solar energy is the main source behind this formation of various renewable form of energy on earth. So, if you say solar energy as renewable source of energy, first type of energy that we get in passive manner is due to uneven solar heating on earth surface. So, we call this as a wind energy. And when the solar energy is absorbed by the seas or ocean surfaces then it creates currents within the sea and ocean. And due to this current, there is a circulation of water from the surface to the deep water. However, in most of the cases, the deep water does not feel the impact of ground surface water when you see beyond the depth of 1 km. So, for that reason, there is a definite potential of the temperature difference that is available from the deep water and the surface water and that difference is close to about 15℃. So, when you harness energy or power output through this temperature difference we call this as ocean temperature energy conversion.

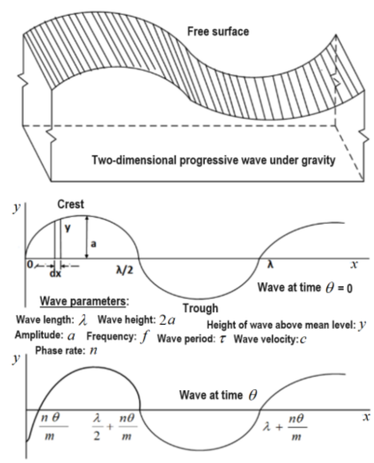
The next part of solar energy as a passive impact is rain. So, when the solar radiation comes on the surface of sea or ocean, water gets evaporated and moves up and they form cloud at high altitudes and eventually it comes as a rain. Now, when this rain comes, we collect this rain water in dams or hills or high altitude area and from this we get the hydraulic energy. And this hydraulic energy is by virtue of potential energy of water which is stored in a dam.

And next part is the tidal energy and this tidal energy mainly occurs due to the gravitational effects of solar and lunar cycles on the ocean surface. So, our main intention in this lecture is about the tidal energy. And also when we have sea or ocean waves in the coastal area, there is a possibility to harness the energy through some machines what you call as a wave machines. So, the focal point of our main attention on today's lecture will be the tidal energy and ocean waves.

So, I mentioned some of the most significant impact of renewable energy and on top of that wave energy also falls under that category in renewable form. Although this infrastructure cost is very high, but they have a good potential because they are available free, but we need to have particular geographical site to harness those energy and we call this as a wave energy. So, there are some advantages because they are alternative form of energy and they are freely available and they do not require large land masses because the coastal areas can be considered by default as the area in which we need to install our device.

But main disadvantage is that these wave energy instruments or devices are to be kept in the site itself. So, at the time of large wave activity or in case of unforeseen circumstances that like storms & cyclones those machines has to be taken care about their sustainability. So, mechanical strength to withstand that enormous power in stormy sea areas is a big issue. Another is capital investment; maintenance cost is very high and sometimes it is not known to us. So, this makes some kind of a negative impact on wave energy, but still in technical viewpoint, it has a great deal of capacity because almost in earth 70% of the area is occupied by seas and oceans and we can have coastal area belt as the main basins to get the tides or waves.

Now, before you go further let us try to understand ocean waves and for that we need to know something about this wave motion. So, what happens in this coastal areas is that you will find a kind of a progressive wave that comes to this coastal areas and these waves take the sinusoidal pattern and what we have taken one particular segment in which a wave is defined and this wave has some specific characteristics. If you take a sine wave like this, there is the topmost part of this wave, we call this as a crest and height from this mean line to this topmost position is known as amplitude of the wave. And when this waves comes to the bottom part then there is a trough that means, it also gets negative peak in terms of ‘a’. So, through this process we get a wave height of ‘2a’ and of course, for a given wave we also define a length, what we call as wavelength.



So, the periodic fashion continues in certain time and that is called as wave period and once this wave period completes, again same trend of the wave continues. So, this is a sequential wave that starts at this point shown in the diagram. And if you look at phase rate that means, it is the same wave, but it does not start at y = 0 or x = 0, but it start at some other location. So, there is a phase rate in terms of its horizontal axis. So, that way the waves are characterized. Now this may be the wave at time $\theta = 0$, but at a different time the waves may take a different phase. So, these are the significant ways we characterize this wave.

Another important parameter is the frequency of the wave and that is nothing, but 1 by time period, $1/\tau$. We also defined the wave velocity *c* and this tells us how the wave progresses in x-direction. Now, after characterizing this wave and taking the statistical data in standard sea and ocean, it has been found that there is a definite relation in terms of water depth. That means, if you are going deep into the sea water or ocean water, starting with 0.3 m to let us say 3 km depth, you visualize for each particular wavelength λ, we find that there is a specific wave period. Now, for another type of wavelength there is also a specific time period. Now, if you keep on doing it and a peculiar characteristics follows from this data. That means, if you draw an inclined line in the table shown, then we can see that with water depth below 3m or 30m or 300m, will find the wave period and the characteristics feature of this wavelength is almost remains same.

Wave Period (s)					
Water depth (m)	**Wave length (m)**				
	0.3	3	30	300	3000
0.3	0.442	1.873	17.645	176.3	1763.3
3	0.442	1.398	5.923	55.80	557.62
30	0.442	1.398	4.420	18.73	176.45
300	0.442	1.398	4.420	13.98	59.23
3000	0.442	1.398	4.420	13.98	44.20

Now, looking at this, one can find a relationship between wavelength and period and that we are going to emphasize here. So, to characterize this wave, one standard way to write this expression of the wave is y. If you take the mean line at any point on this wave, this vertical line we say it is y and that point we can frame this equations for y.

Expression for wave: $y = a\sin\left(\frac{2\pi}{\lambda}x - \frac{2\pi}{\tau}\theta\right) = a\sin(mx - n\theta)$

Now, when this m and n are defined in the following manner and of course, we have the expression for wave velocity c.

Wave propagation velocity, $c = \frac{\lambda}{\tau}$; $m = \frac{2\pi}{\lambda}$; $n = \frac{2\pi}{\tau}$

Now, from this data one typical relationship is obtained, which is as follows.

Relationship between wave length and wave period, $\lambda = 1.56\tau^2$(m)

y:Height above mean level (m); θ:Time(s); λ: Wave length(m)

a:Amplitude(m); τ:Wave period(s);

So, that means, if you look at a water depth of 3 km or more we will find the wavelength relations in terms of wave period. So, at any geographical location and at a particular depth, this is the characteristics feature of wavelength and wave period. And of course, we have definition of frequency and phase rate. And all these things can be defined for a particular wave.

Frequency, $f = \frac{1}{\tau}(s^{-1})$; n: Phase rate(s^{-1}); $(mx - n\theta) = 2\pi\left(\frac{x}{\lambda} - \frac{\theta}{\tau}\right)$:Phase angle

So, you we look at this way this two dimensional waves mostly in the coastal area. Now, the way we see the wave that means, it does not replicate the water motion, it is the wave which is the characteristics features of the pattern that is followed by slug of mass of water. But each water particle does not follow the sinusoidal pattern. So, this is the characteristics features that the motion of the water is not in the sinusoidal pattern. So, in reality what happens is that a given particle of water rotates in an elliptical path in the plane of wave propagation with specified horizontal and vertical axis. Now, when you say ellipse, it has a major axis and a minor axis. So, we define this elliptical path as horizontal semi axis of the ellipse and vertical semi axis of the ellipse. Now, we see this wave is not exactly on the surface, there is a depth. So, you take a particular bottom of the surface as depth and measure the height to the mean level of the surface wave, and we say it as h and the height to any location is η.

So, basically entire height is covered with sinusoidal wave, but the motion of the water particle is mostly elliptical. So, when you look at the wave on the surface it has an elliptical path, and its major axis α and minor axis β. This elliptical path is seen at the mean level from the depth. Now, if you keep coming down towards the depth from the surface then slowly we will find that the elliptical pattern changes to circular. So, that means, at the bottom of the wave the pattern is mostly circular, because we will find that the horizontal semi axis and vertical semi axis that is α & β become closely equal that means $\alpha \approx \beta = a$. Here ‘a’ stands as amplitude of the wave.

Horizontal semi-axis of the ellipse, $\alpha = a\frac{\cosh(m\eta)}{\sinh(mh)}$

Vertical semi-axis of the ellipse, $\beta = a\frac{\sinh(m\eta)}{\sinh(mh)}$

β varies from 0 at bottom; η varies from 0 to a

At surface, $\eta = h$; At large depths, $\alpha = \beta = a$

a:Amplitude; h: Depth of water η: Distance from bottom

So, this relation makes the conclusion that when you look at the same wave at the surface it is elliptical and the same wave in the bottom is circular. So, that is the pattern, the waves follow. Now, we are interested in harnessing energy from the wave, and looking at this wave parameters, the energy numbers has to be calculated. For that there are two types of energy one wave possesses; one is potential energy that arises from the elevation of water from the mean level. Another one is the kinetic energy of the wave which is between two vertical planes perpendicular to the direction of the wave propagation placed one wavelength apart.

So, if you look at one particular wavelength that means, start of the wave & end of the wave, then within that wavelength we see that whatever energy, the water particles or slug of water possesses is by virtue of its velocity. And we know this velocity of the wave is *c* and that also can be related with respect to amplitude and wavelength. So, we are not going deep into this theory. So, there is a hydrodynamic theory that tells us about the kinetic energy and potential energy possessed by the wave. Now, here we are looking at an arbitrary length L in a two-dimensional plane, but along that arbitrary width we are looking at a wave having wavelength λ.

So, basically if you say the wavelength is λ, and this height or this width is normally called as L. So, within that area, λL is your wave area and we are looking for the energy which is being possessed by that particular slug of water mass. So, that way we can find out the kinetic energy and potential energy per unit area and it happens to be the fact that both are equal.

Potential energy and Kinetic energy, $PE = \left(\frac{1}{4}\right)\rho a^2(\lambda L)g; KE = \left(\frac{1}{4}\right)\rho a^2(\lambda L); A = \lambda L$

Potential energy and Kinetic energy per unit area, $\frac{PE}{A} = \left(\frac{1}{4}\right)\rho a^2 g; \frac{KE}{A} = \left(\frac{1}{4}\right)\rho a^2 g$

ρ:Density of liquid; a: Amplitude; λ:Wavelength; f: Frequency of the wave

L:Arbitrary width of two-dimensional wave perpendicular to the direction of wave propagation

So, by adding these two terms we get the total energy per unit area

Total energy per unit area, $\frac{E}{A} = \left(\frac{1}{2}\right)\rho a^2 g$

If you know the frequency of the wave or what causes the waves comes into pictures, so time also gets included here. So, the energy term can be converted to power term. So, power density per unit area can also be found out by multiplying the total energy with frequency and this in fact gives the total power density of the wave.

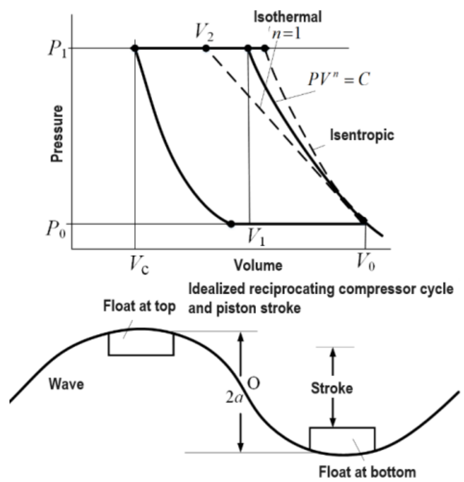
Power density, $\frac{P}{A} = \left(\frac{1}{2}\right)\rho a^2 f g$

So, once you have estimated this we can say that at a typical location we can estimate this number to be 840 W/m^2. And that is the power density of the wave in a particular geographical locations. But same thing if you compare with the solar power, at a particular location it is 240 W/m^2. So, here you can see a significant difference. Although the ocean waves get generated due to solar radiation, but intensity or power density of the wave energy is much higher than the intensity due to solar energy. So, it gives a significant impact that density of wave power is about 3.5 times higher than that of solar power.

Now, once you know the estimates of the kinetic and potential energy wave let us see the technology to harness this energy. So, for that one simple device is used that is called as flow type wave power machine. So, essentially it is a wave machine that harness wave power by storing air in a tank, which is called as air storage tank. This air storage tank is further connected to an air turbine that means, this compressed air gets expanded in a turbine to generate electricity. So, whenever the wave energy is available, you store them and this stored air or high pressure air gets released for the power generation in the subsequent method by expanding in a turbine. Now, to store this energy in a tank, we have is a device, which is simply a kind of a piston cylinder device or you can say it is a compressor and this is put on a float. Float is like a device which normally floats on water. And here this float means it is floats in the wave.

So, wave has a series of sinusoidal pattern and during one case we can say it is a compression & other case you can say it is expansion. When the float is there, in one period of the wave, the piston gets compressed and whatever slug of air is there in this cylinder is then compressed and it enters in this path and finally, enters to the storage tank. So, this is what we say piston compression stroke. Now when the piston is in expansion stroke, the air from the atmosphere is sucked through this inlet valve and this happens in the other cycle or other part of the wave. That means one is crest part, other is trough part.

So, during crest part, the piston sees compression and in the trough part, the piston looks at expansion. When it is an expansion the atmospheric air enters into the cylinder and during the compression part the stored energy gets into this air storage tank. And finally, this air storage tanks are integrated to an air turbine. So, this is the mechanism by which we get power from the wave.



Since it is a kind of a simple reciprocating device, one can frame the pressure volume diagram. If you see this particular wave and this is the float position and we have the wave height '2a'. Instead of '2a' the stroke length will be little less than that because the float has certain width or height. So, effectively we have the stroke of the piston. So, initially we have atmospheric air conditions at p_0& V_0. So, atmospheric air gets compressed during the compression stroke of the piston and the final volume becomes V_1. Now, this compression is called as a polytropic compression, so $pV^n = C$.

Now during the compression obviously, the temperature gets increased. So, effectively we need to bring down these temperatures in an isothermal process. So, from this point you go along an isothermal line and finally, we have the final volume as V_2. So, basically keeping pressure $p_2 = p_1$, we arrive at the new volume because we are cooling down from state 1 to state 2. So, finally we arrive at the expressions when you get the work done by the turbine that means after this compression the air gets expanded in the turbine. So, work done by the turbines is a function of some non-dimensional number that is r_c, the pressure ratio in the compressor, r_e the expansion ratio. Then we have p_3 that is the exhaust pressure from the turbine.

Work done by air turbine, $\frac{W}{m} = c_p T_0 \left[1 - \left(\frac{r_c}{r_e}\right)^{\frac{k-1}{k}} r_c^{\frac{(1-k)}{k}}\right]$

$$\left(\frac{r_c}{r_e}\right) \approx 1.1; p_2 = p_1; r_c = \frac{p_1}{p_0}; r_e = \frac{p_2}{p_3}; V_2 = \frac{V_0 p_0}{p_1}$$

Compressor inlet condition: p_0, V_0 & T_0 (atmospheric)

After compression: p_1, V_1 & T_1; p_3: Exhaust pressure in turbine

r_c: Pressure ratio in compressor; r_e: Expansion ratio in turbine m: Mass of air;

c_p: Specific heat of air; k: Ratio of specific heats

So, these are the realistic number that we get. So, we are not going deep into this calculations here, but in the end result, we ultimately get the power that we can harness from a wave.

So, in our previous discussion I told that there is a flow type wave power machines. In a flow type wave power machines, we are using the power of the wave or energy of the wave to compress the air in a storage tank. So, basically water power gets converted into gas power in terms of air. But there are some wave machines or devices, instead of storing air they store water itself in a very compressed form. So, high pressure water gets compressed. And those machines are called as hydraulic accumulator wave machines, high level reservoir wave machines. That means, you take that wave and store that water at certain level of height. There is a dolphin type wave generator, dam atoll wave machines. So there are variety of machines that takes care about the storing water instead of air. And one typical example I can cite is for a float size of 3m $\times$ 1m $\times$ 0.5 m. And of course, it is an experimental evidence that at a given location if you say that a: Wave amplitude (m); τ: Wave period (s) for this wave machine which normally run through storing water, then we can get the power per unit length perpendicular to the wave as per the below relation

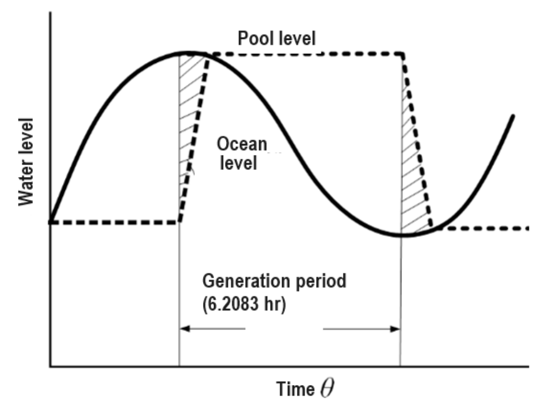
Power per unit length perpendicular to wave, $\frac{P}{L} = 1.74a^2\tau \left(\frac{\text{kW}}{\text{m}}\right)$

So, this is the expression is an experimental correlation for a given geographical location. And this can be more or less an estimate for how much power we can tap.

Then next segment of our discussion is the tidal energy. So, basically when you say wave energy, it is a continuous process that means it is throughout the year. And it is mainly with the combined effect of solar and moon cycle. But there are some situations when you have tides. Tides are mainly governed by a lunar cycle. And these tides are very frequent at some particular geographical sites and these tides have very significant impact. In some period of moon cycle, the tides are very high. So, if you look at particular lunar cycle which falls as a 29.5 days period, we can see very high tides and low tides and they have significant difference in their height. So, if you draw a mean line, we can say that the difference between the high tides and low tides is called as a tidal range. And occurrence of the tide happens to be in a periodic manner governed by this lunar cycle. And what happens if you take 29.5 days period and one wave period will be about 12 hour 25 minutes. So, this is pre calculated or effect of moon position from the earth surface. So, lets start with a new moon, go to the first quarter, so we have a low tide. When you have a new moon it is a high tide. High tide is called a spring tide and when we say low tide we say it as Neap period. Again during spring period tides, we say full moon and that means, tides are very high and the cycle pattern continues in 29.5 days periods. So, this picture gives relative tides during a lunar month. Now why these tides occur? This is mainly due to the gravitational force the moon and sun acting together on earth centrifugal force on water due to the earth's rotation. And the net result of this rise and fall of water is not constant. So, they are characterized by a schedule and range which is defined in this manner. Range means it is a height, schedule means it is a time period. So, thereby we have the virtue of having very large tides which is close to 20m high which means this tide can have a significant impact for energy harness.

Now let us see how we can tap this tidal energy. So, to tap this tidal energy, we need to think about a single-pool tidal systems. So, at a given geographical site location, you create a dam and we also know that when you create a dam, we will see that in some period, this side will have high tide & other side will have low tide and in some other period we will have in reverse also. So, basically that means high tide and low tides can be reversible on both sides of the dam. When you say it is a dam, essentially speaking, during the high tide period that means one side will have a high elevation of water and that elevation of water can go up to 20m height.

So, during the other side of the period it is a low tide. So, you can introduce a reversible turbine which can operate in either side or it is like a water turbine to produce power. Now this is something like, integrating a hydroelectric dam in a particular site locations for tide. Of course, this potential height is not that much high, what we normally see in the hydro power plant, but it is quite effective to harness the tide power. Now time stands as the schedule. So, for water level positions, there are two parts, one is the pattern that the tides follow & other is the pool level or ocean level.



There are two sides of the dam. So, that means there is only one side, we store the water & other side, the water is less. So, difference between these two is your range. So, that range could be as high as 20m. So, effectively this 20m height potential energy can be harnessed. Since it is a cyclic process, we cannot have a continuous power because water level keeps on changing with time and a simplified model can be a triangular pattern. That means power vs. time curve will be in a triangular pattern, so it is continuously up and down. But we can have a minimum kind of average power that can be calculated for this range *R*. A typical mathematical expression can be given from this graph. So, we have pool level, we have ocean level and we have this generation period 6.2083 hour. So, how it comes? We see that the power generated during one tidal period is 12 hour 25 minutes. So, it occurs once that means this is 6 hour 12.5 minutes. So, it is close to this 6 hr 12.5mins (22350s). So, simplified expressions for work done from the water is as per the below expression.

Differential work done by the water, $dW = (gh)dm = -g\rho Ahdh$

For sea water ρ is a constant. Relatively height is same, height does not change because we know for a given location and the lunar cycle, the typical height of the tides. So, what changes is the mass, because the change in the mass is frequent here. So, this mass we can write it as a dm. So, dm we can write it as ρgh. So, the density term comes into picture. So, we get a differential work and that differential work can be integrated for this entire height range and this turns out to be

Theoretical work obtained during full emptying(or filling) in a single pool tidal system,

$$W = \int_R^0 dW = -g(\rho A)\int_R^0 hdh = \frac{1}{2}g\rho AR^2;$$ Total time period: 6hr 12.5mins (22350s)

ρ:Density of sea/ocean water $\left(1025\,\frac{\text{kg}}{\text{m}^3}\right)$; A:Surface area of the pool(constant)

m:Mass of sea/ocean water flowing through turbine; h: Head; R: Tidal range

g: Acceleration due to gravity $\left(9.81\,\frac{\text{m}}{\text{s}^2}\right)$

Now, we know this time period that is 6 hour 12.5 minutes. So, from this work and time we can calculate the average power.

Average power delivered by water, $P_{av} = \frac{W}{22350} = \left(\frac{1}{44770}\right)g\rho AR^2$

Average power density for a single pool tidal system, $\frac{P_{av}}{A} = \left(\frac{1}{44770}\right)g\rho R^2 = 0.225R^2$

So, this is a very significant observation that we get. That means, we can say this is the capability of tidal power at a given geographical locations. And there are some other important inferences like although we get the capability of tides in a given location, yet the average efficiency is in the range of 25%- 30%.

So, a simplified analysis can lead to the fact that if you take an average area of 13000 km^2 that means, you take a coastal area which spreads about 13000 km^2 and there the tidal range availability is 8m, then for this area and this range, the capacity of tidal power could be 50 GW and this is again with an efficiency of 27%. So, you can imagine that how much large power is possible or capability of tide power from the sea or ocean resources. This number is huge, but the infrastructure or harnessing technology is more challenging.

So, with this we come to the end of this lecture. So, we will try to look into some of the numerical problems that we covered in this lecture.

Q1. An oceanic wave with 2 m long and wave period of 6 s, occurs at the surface water with depth 100 m. Find the wavelength, wave velocity, horizontal and vertical semi-axes for water motion at the surface. (a) Estimate the energy and power density of the wave; (b) Considering a float type wave machine, estimate the power per unit length perpendicular to the wave.

So, the first problem is on an oceanic wave which is of 2 m long and it has wave period of 6s and it occurs at a surface water depth of 100 m. So, you take a particular two dimensional progressive wave and the characteristics feature of the wave is given to us.

So $2a = 2$ m; where $2a =$ crest to trough distance

$\Rightarrow a = 1\text{m}$

$\tau = 6$ s; Depth of water, $h = 100$ m

We need to calculate the other features like wavelength, wave velocity, horizontal and vertical axis of water motion.

So, we can recall our expression for wave length relation with time period

$$\lambda = 1.56\tau^2 = 56.2 \text{ m}$$

Wave velocity, $c = \frac{\lambda}{\tau} = 9.4$ m/s

Frequency, $f = \frac{1}{\tau} = \frac{1}{6}$ Hz $= 0.16$ Hz

This is about wave.

Now, about water motion, we can see the water motion is mainly elliptical at the surface and it is circular at the bottom. Bottom means this height is given to us as 100 m. So, from our analysis, we need to recall

Major axis of the ellipse, $\alpha = a\dfrac{\cosh(m\eta)}{\sinh(mh)}$; η is the distance from the bottom; $m = \dfrac{2\pi}{\lambda}$

$$\Rightarrow \alpha = 1\frac{\cosh\left(\frac{2\pi}{56.2}\times 100\right)}{\sinh\left(\frac{2\pi}{56.2}\times 100\right)} = 1$$

And similarly for minor axis,

Minor axis of the ellipse, $\beta = a\dfrac{\sinh(m\eta)}{\sinh(mh)} = 1$

What it demonstrate is that $\alpha = \beta = a$ which means it is a circular wave at bottom and in this case $h = 100$m. This is what exactly a standard ocean wave follows. Then we can find out the energy and power density.

Energy Density, $\dfrac{E}{A} = \left(\dfrac{1}{2}\right)\rho a^2 g$; Take density of saline water, $\rho = 1025\ \text{kg/m}^3$

$$\Rightarrow \frac{E}{A} = \left(\frac{1}{2}\right)1025 \times (1)^2 \times 9.81 = 5027.6\, J/m^2$$

Similarly, Power density, $\dfrac{P}{A} = \left(\dfrac{E}{A}\right)f = 5027.6 \times \dfrac{1}{6} = 837.9\ \text{W/m}^2$

So, this is the power density for that wave. And from this wave if you want to harness power using a float type wave machine, then you need to find the power per unit length perpendicular to the wave.

So, Power per unit length perpendicular to wave, $\dfrac{P}{L} = 1.74a^2\tau = 1.74 \times (1)^2 \times 6$

$$= 10.4\,\frac{\text{kW}}{\text{m}}$$

This for this relations holds good for power in kW and ‘a’ in meter & τ in second. So, for this wave machine we can get this much power.

Q2. Calculate the total energy and average power for a simple single-pool tidal system for a tidal range of 12 m and pool area of 10000 km^2. If the efficiency of the tidal system is 28%, then what will be the average power density?

Then we have this next problem that is on tidal energy. So, in tidal energy, we look for a single pool tidal system, for which range is given as 12 m and pool area is 10000 km^2. So, for that things we recall our expressions this theoretical work for a single pool tidal system.

Theoretical work for a single pool tidal system, $W = \frac{1}{2} g\rho A R^2$; R is Tidal range $= 12\text{m}$;

$\rho = 1025 \frac{\text{kg}}{\text{m}^3}$; $A = 10000\ \text{km}^2$; Tidal period $= 6\text{hr}\ 12.5\text{min} = 22350\text{s}$

But we are requiring average power density.

$$\frac{P_{avg}}{A} = \left(\frac{1}{2 \times 22350}\right) \times g\rho R^2 = 32.4 \frac{\text{W}}{\text{m}^2} = 32.4 \frac{\text{MW}}{\text{km}^2}$$

$$\Rightarrow P_{avg} = 324000\ \text{MW}$$

So, the average power which is available in the tide is 324000 MW, but even if you tap 27% efficiency then $P_{actual} = 90720$ MW. That means, just multiply P_{avg} with 0.27, will arrive at this power. So, effectively we say that in a large area, the power density for the tide is quite high and if it can be harnessed suitably, then it can sustain the energy or power requirement for big cities. So, this is all about my discussion today on ocean energy and tidal energy. With this lecture I conclude. Thank you for your attention.