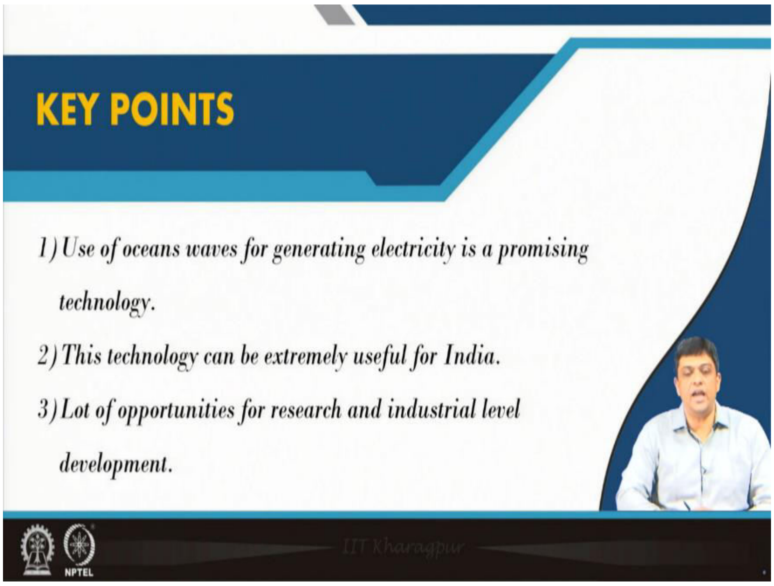
Physics of Renewable Energy Systems
Professor. Amreesh Chandra
Department of Physics
Indian Institute of Technology Kharagpur
Lecture 17
Wave Power and Converters

Hello. Welcome to the lecture of this module and in today's lecture, we will be talking to you about wave power and the converters which are used to extract the power from waves.

(Refer Slide Time: 00:47)

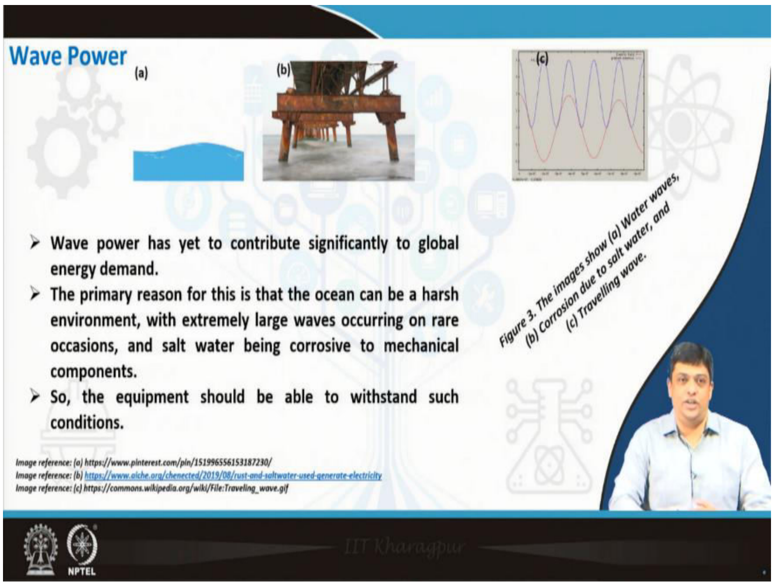
The main concepts which will be covered during the lecture today will be the new technologies based on extracting energy from waves. Once I give you this main concept, we will move to the sub headings which will deal with the types of water converters and the advantages and disadvantages associated with each of them, just the way we have been moving in the previous lectures.

(Refer Slide Time: 01:27)



And by the time this lecture is over you will clearly understand that the use of ocean waves for generating electricity is a promising technology. This technology can actually become extremely useful for us, as we have a long seashore and coastal line. This technology is evolving technology and therefore, lot of opportunities for research and industrial level developments exist. So, both at the basic research and then at the scale up or industrial level you can enter and contribute in the development of this technology.

(Refer Slide Time: 02:20)

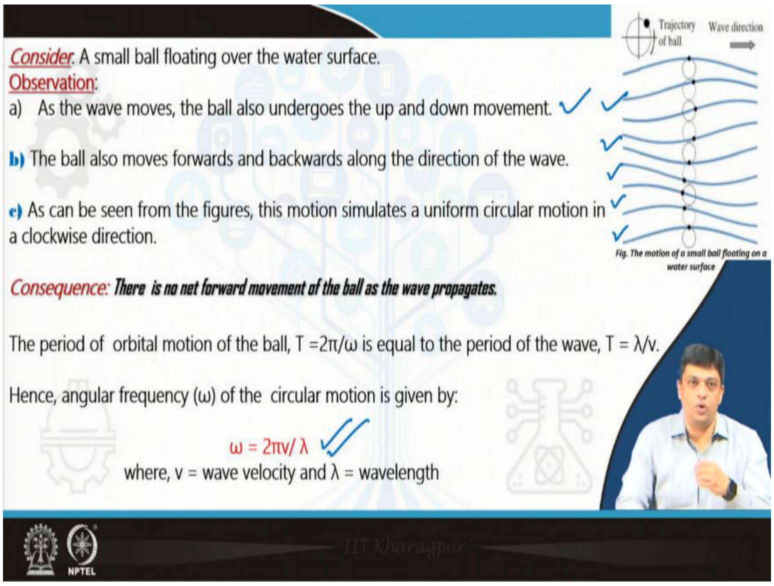


This is where I had stopped in the previous lecture that we will be talking to you about wave power. Wave power is yet to actually become a major player in the overall energy landscape in any country, but it has lot of promise and if we are able to counter the problems such as of harsh environment under which these converters have to operate can if we are able to make technologies which can withstand such harsh environments, then this technology is actually a very interesting and highly efficient technologies. So, we will start with this topic today.

(Refer Slide Time: 03:20)

So, let us before we start taking the real examples of setting up the converters near the ocean or the sea shores, let us try to quickly revise one of the topics of physics which will be used in this lecture today and that is water waves. You should very clearly understand that the nature of water waves which we are going to deal with that is the ocean waves have both the transverse as well as longitudinal components or motion and therefore, their analysis is bit more involved and you must try to understand it clearly.

(Refer Slide Time: 04:14)



To understand this concept, let us take a water surface. On this water surface, you just have a small floating ball. So, I have put a small floating ball on top of this water surface and what are we doing? We are actually examining or monitoring the way this ball will move as a function of travelling water f.

So, you all have seen this when you have gone near to sea that if you throw a small water bottle of plastic or a small ball like that of table tennis ball or anything it oscillates up and down, but if you remember while it is having a motion up and down it also moves in the x axis or the y axis while it is having an up and down movement.

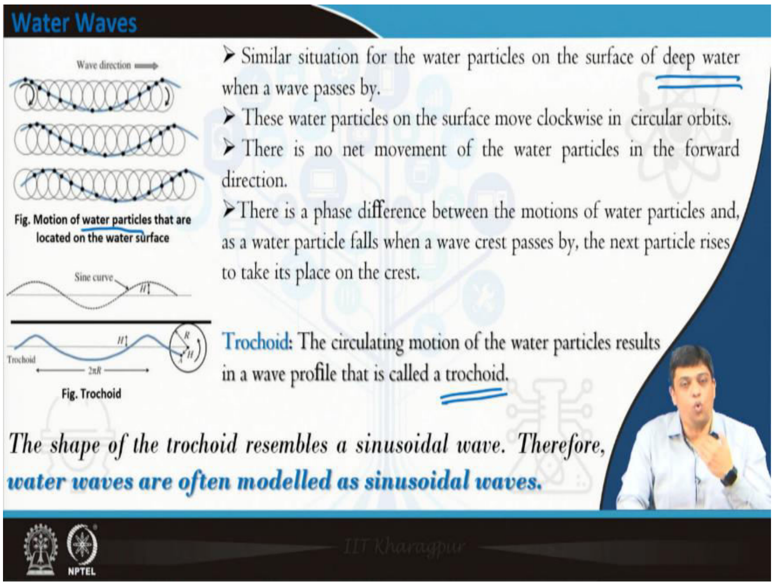
So, this is what we are trying to understand. So, what happens the first thing which we know that as the wave moves, the ball undergoes the up and down movement. So, this is what we have seen and we can clearly imagine. Along with that the ball also has a backwards and forwards movement.

So, what you have both up and down movement and the backwards and forward movement and if you, this is what you actually see as a function of travelling wave. So, from this figure it is clearly visible that if I try to plot this motion, this motion simulates a uniform circular motion in a clockwise direction. What is the immediate consequence? The immediate consequence is that there is no net forward movement of the wall as the wave propagates.

So, there is no net movement as a function of moving wave. Let us consider the period of orbital motion of this ball to be equal to 2 pi by omega. This will be equal to what? This will be equal to the period of the wave. What is period of the wave? T is equal to lambda by v.

Hence the angular frequency omega of the circular motion is given by omega 2 pi v by lambda, where v is the wave velocity and lambda is the wavelength. So, I have immediately been able to estimate the angular frequency of this motion.

(Refer Slide Time: 07:38)



Similar situation actually is observed if you are monitoring water particles on the surface of deep water when a wave passes by. Deep water, you will understand what we mean by these terms in subsequent slides. So again, if I monitor the motion of water particles, the motion of water particles that are located on the surface of the water.

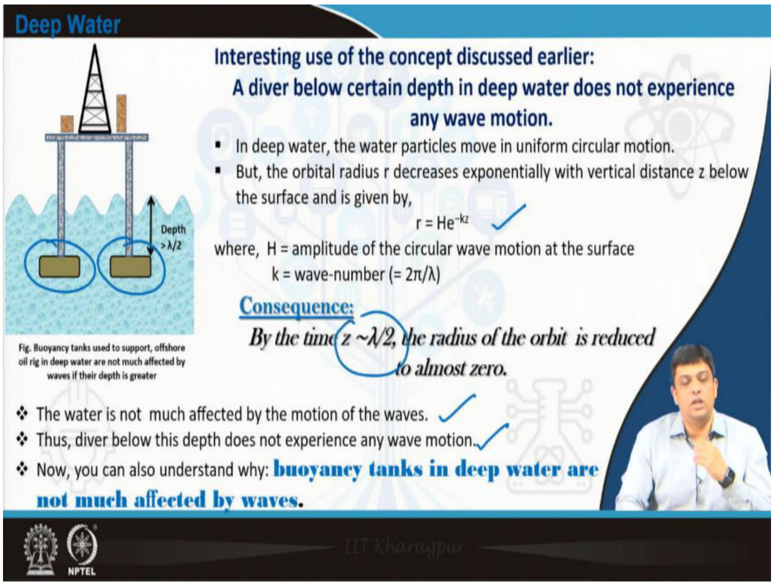
So, on the surface of the water when you have the crest then the particle is here and slowly when the wave goes down the particles are then at the bottom then you have the trough and then you have the crest once again. So, this is what you are seeing. These water particles on the surface will move like what as shown in the earlier slide, they will move in a clockwise manner and have a circular orbit of this motion.

There will be no net movement of the water particles in the forward direction. So, there is no net movement it is the wave which is moving forward. But there is a phase difference between the motion of the water particles and the water particles fall when the wave crest passes by. So, when the crest is obtained then you have the particles which actually are on the top of the crest and trough is here crest is here.

So, when the crest passes by the water particles come down and the next particle rises to take its place. So, when you are moving from crest towards the trough, then what happens you will be moving towards the next particle which will take its position. The circulating motion of the particles result in a wave profile that is called as trochoid.

So, this motion is called as trochoid and if you plot this circular motion, then the shape of the trochoids resembles a sinusoidal wave and that is the reason why water waves are mostly modelled using a sinusoidal wave characteristic. It is because of the motion that results in the nature and that nature can be modelled using a sinusoidal wave and so whenever you talk about the motion of a water wave, you can take it to have it a sinusoidal nature.

(Refer Slide Time: 10:53)



As soon as we have seen this wave, now you have let us say a depth. The wave nature is observed at the top. What is happening at the seabed? Do you also see the wave nature of similar amplitude, wavelengths or the nature of disturbance which is at the depth of much below the surface of the sea? What is happening there? And this is always discussed as an example which is stated as what happens when a diver below a certain depth in deep water is swimming. Does that swimmer experience any wave motion or the sea is quite calm at that depth?

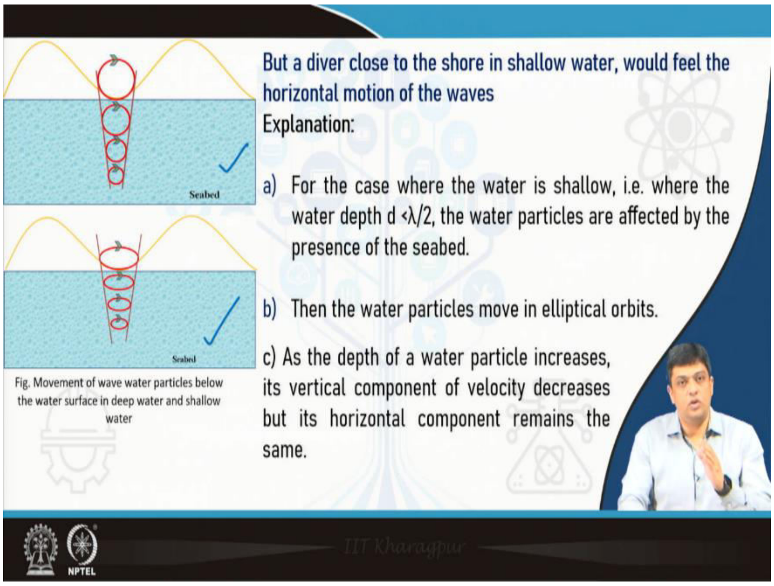
In deep water, the water particles move in uniform circular motion that is okay, but as the orbital radius r decreases exponentially with the vertical distance z below the surface. So, what happens this orbital radius is reducing when you go below this surface and it decreases exponentially and this is given by a typical relation which is r is equal to He raised to the power of minus kz, where H is the amplitude of the circular wave motion at the surface and k is the wave number.

And you are talking about the depth, so height so I talk in terms of the coordinate set. Now because of this what happens? The immediate consequence is that by the time I reach a position of z approximately equal to lambda by 2 or you are below this term or depth, the radius of the orbit is reduced to almost 0.

Now you are actually seeing very little change at these depths and what happens if I am at that level, the water is not affected by the motion of the wave at the surface. Thus, if the water is not affected what will happen? The diver below this depth does not experience any wave motion and that is the reason why you have the buoyancy tanks which support the oil rigs, they are placed at depths below the range of lambda by 2, so that they do not feel the variation in waves at the surface.

And if that is not felt by them, the rigs will be much more stable, otherwise, you will always ask this question the rigs should actually just follow the motion of the waves and then it would be impossible to work on this rigs but the rigs are much more stable and the reason is that you have put this tanks at much more depth to ensure that you are in the region of z approximately lambda by 2 or below that.

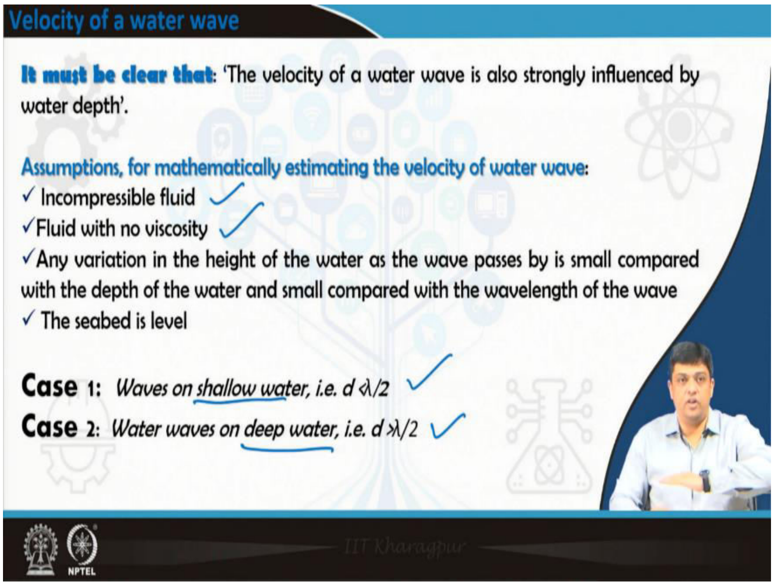
(Refer Slide Time: 15:15)



But the case is slightly different when you are at shallow waters. So, the water depth is less than lambda by 2 and here, the water particles are affected by the presence of the sea bed and if that happens that you are actually not able to reach this condition of nearly 0 amplitudes or radius going to nearly 0 value, the water particles move in elliptical orbits as you see from this picture.

And the depth of the water particles increases its vertical component of velocity decreases but its horizontal component remains the same and that is the reason why you are seeing this elliptical orbits and these two concepts are extensively used when you are designing water converters which are placed on the surface of the water and then how can you extract energy from these water converters, you try to understand what will happen there. So, the usefulness of this information will become clear by the time we end this lecture.

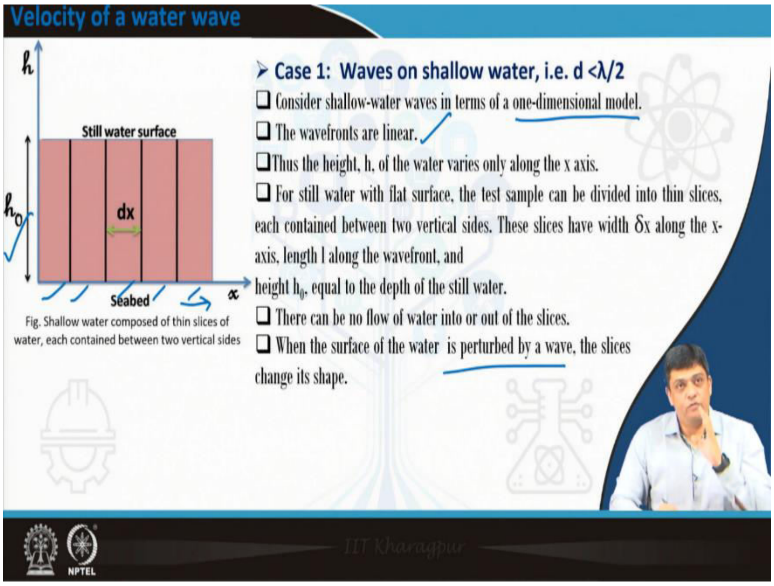
(Refer Slide Time: 16:53)



So, it is clear that if I am at depths more than lambda by 2, then the nature is very different then what I experience at depths which are less than lambda by 2 and if that so, what is the velocity of these water waves at these two depths. Case 1, d less than lambda by 2. Case 2, d more than lambda by 2. So, deep water case 2, shallow water case 1. Let us try to mathematically give you some formulations which will be useful. For mathematically estimating the velocity of the water wave just like we had done in previous classes, we have certain assumptions.

Assumptions are very similar, for example we will consider an incompressible fluid. A fluid which has no viscosity and any variation in the height of the water as the wave passes by is small compared to the depth of the water and small compared with the wavelength of the wave also. So, the variation is in the height is considered to be small in terms of the depth of the water and in terms of the wavelength of the wave which is passing by and the seabed level is considered to be plane or it is a level seabed.

(Refer Slide Time: 18:59)

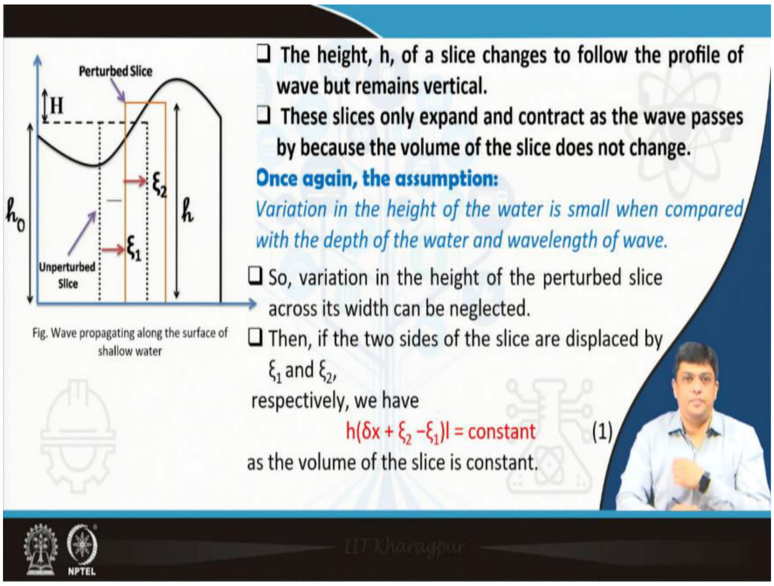


For this, let us try to start with case number 1, that is we are in the shallow water. So, consider shallow water waves and to simplify the model in terms of one-dimensional model just to simplify the picture. The wave fronts which are moving forward are considered to be linear. So, the wave fronts are moving in one direction and they are considered to be linear. Thus, what happens, the height h of the water varies only in the x direction for still water.

So, now we make the life even more simpler we say the water is still and we have a flat surface. This kind of a test sample that means what we are taking as a model test sample this can be then divided into thin slices. Each of these slices are contained between two vertical sides and these slices have a width of delta x along the x axis, length l along the wave front and height h_0 equal to the depth of the still water.

As we have seen, there can be no flow of water into or out of the slices. Now what are we trying to simulate? We are trying to have a condition that if this surface of the water is perturbed by a wave, the slices may or may not change its shape. If it changes what happens? If it does not change what happens? We clearly know that when we are in the shallow water when the surface of the water is perturbed by a wave the sizes change their shape. So, with these basic assumptions we continue.

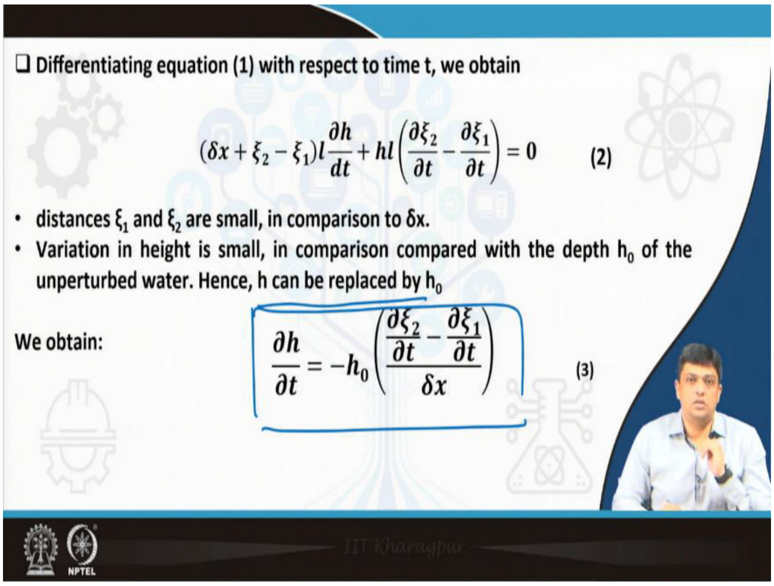
(Refer Slide Time: 21:41)



And then try to find out what is the value of velocity we can obtain. Now the height h_0 of a slice changes to follow the profile of the wave but remains vertical. So, as the wave changes when I am at the bottom then the height changes, when I am at the top the height changes and that is why the height changes. These slices only expand and contract as the wave passes by because the volume of the slice does not change. So, once again what would be the assumption?

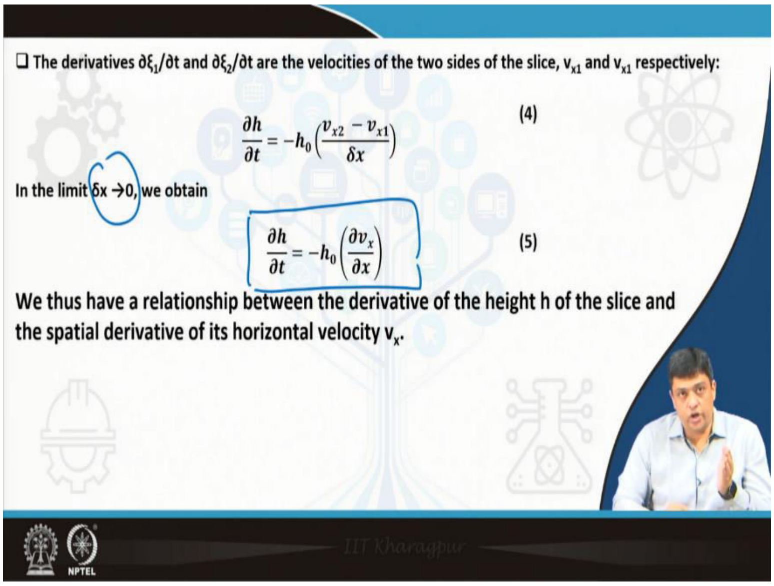
The assumption would be that variation in the height of the water is small when compared to the depth of the water and wavelength of the wave. So, immediately variations in the height of the perturbed slice across its width can be neglected. What happens? If we have two sides of the slice which are displaced by xi 1 and xi 2 respectively, we have h delta x plus xi 2 minus xi 1 which will into l is equal to constant as the volume of this slice is constant.

(Refer Slide Time: 23:21)



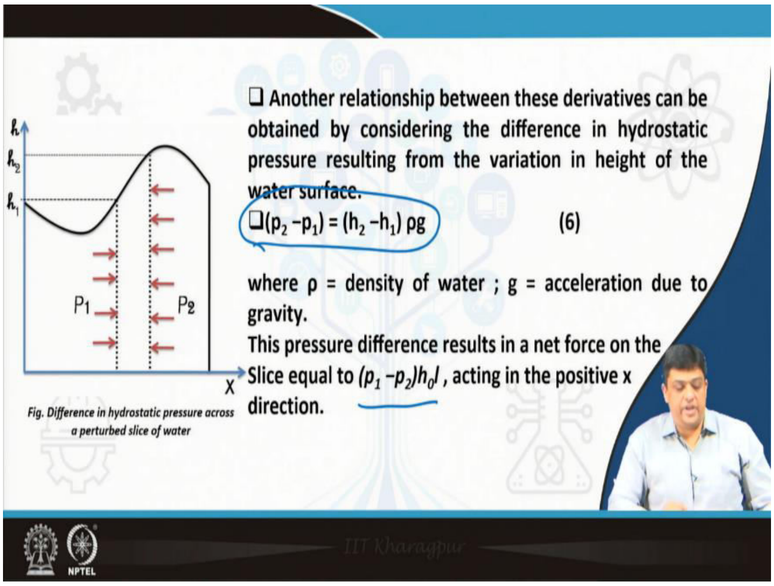
Differentiate that equation with respect to time and if you have the distances xi 1 and xi 2 which are small in comparison to delta x and you also know that the height changes which you observe are small, then you can replace h by h_0 and what you will obtain that the change in height as a function of time can be written as delta h by delta t is equal to minus of h_0 there xi 2 upon delta t minus t bar xi 1 by delta t by table delta x.

(Refer Slide Time: 24:18)



And in the limit, delta x tends to 0 we have a condition which will give us that delta h by delta t is equal to h_0 delta v x by delta x. We thus have a relationship between the derivative of the height h of the slice and spatial derivative of its horizontal velocity that is v_x.

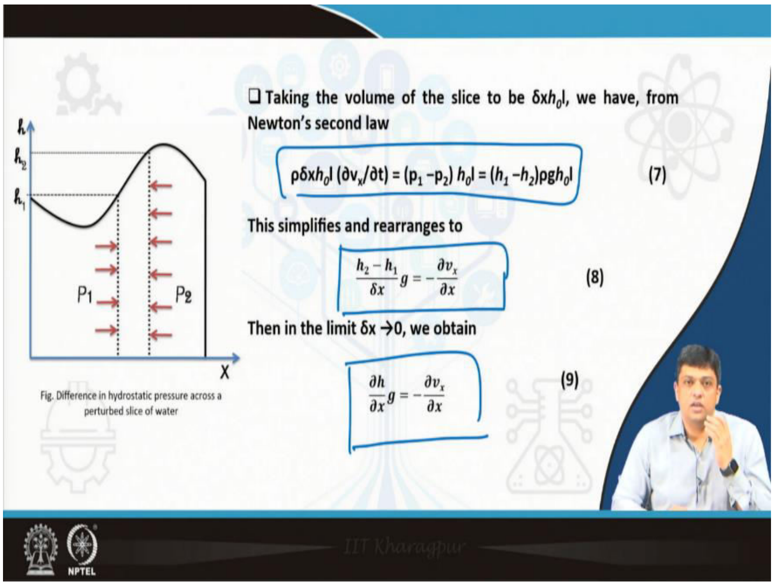
(Refer Slide Time: 24:54)



Similarly, you can derive another relation by considering the difference in the hydrostatic pressure that results because of the change in the height of the slices and for taking that example, let us consider the relation that what will be the condition you will find that p_2 minus p_1 will be equal to h_2 minus h_1 rho g, where rho is the density of water, g is the acceleration due to gravity.

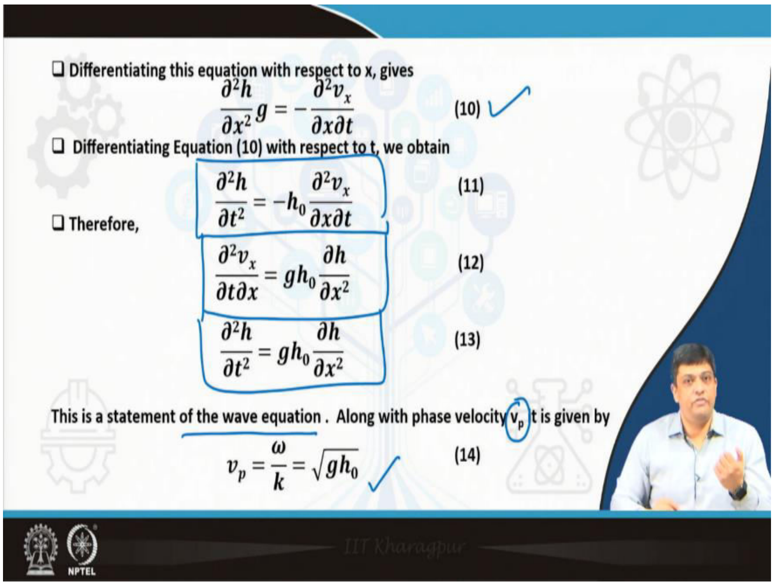
This pressure difference, so when you move from on the wave nature from top then to the bottom there is a change in the height and there is a pressure difference at 2 points. This pressure difference results in a net force on the slice which is equal to p_1 minus p_2 h_0 l which is acting in the positive x direction.

(Refer Slide Time: 26:09)



Now taking the volume of the slice to be del x h_0 l, using Newton's second law we have the relationship which is mentioned in equation number 7. If you rearrange this equation, you will immediately obtain the condition which states that h_2 minus h_1 upon del x into g is equal to del v_x by del x. Then for the condition we are simulating that delta x tends to 0. What do we obtain? We obtain that del h by del x into g is equal to minus del v_x by del x.

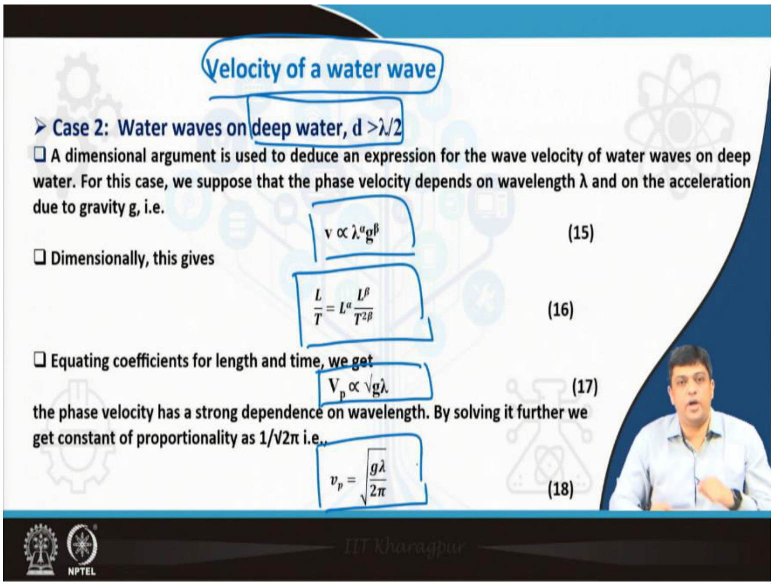
(Refer Slide Time: 27:09)



Again, differentiating with respect to x, you obtain another relation and if you differentiate equation 10 with respect to time, you can immediately write the terms such as del 2h upon del t square is equal to minus h_0 del 2 v_x by del x del t. We know the values in the earlier slide substitute them and you will get del 2 v_x by del t del x is actually equal to g h_0 del h by del x square.

And finally, you have the relation which is giving you del 2 h by del t square is equal to g h_0 del h by del x square. This is a wave equation along with the phase velocity given by g h_0. So, you have actually reached to a condition of a wave equation with the knowledge of phase velocity in it.

(Refer Slide Time: 28:46)

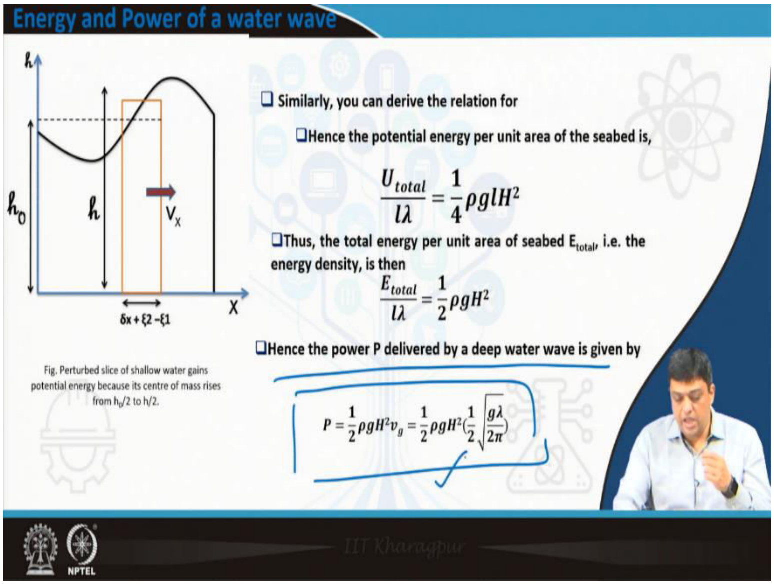


Similar relations can be drawn and you can have the values for velocity of water wave in deep water and all these cases are now discussed in the following few slides. In this case, we suppose that the phase velocity depends on the wavelength and on the acceleration due to gravity that is g.

So, v is proportional to lambda raised to the power alpha and g raised to the power of beta. Dimensionality conditions will come in and both the sides should have the same dimension and then only the you have a consistent equation and using this condition, you have the point that if I write dimensionally, then what you will write L by T is equal to L alpha into L beta by T 2 beta.

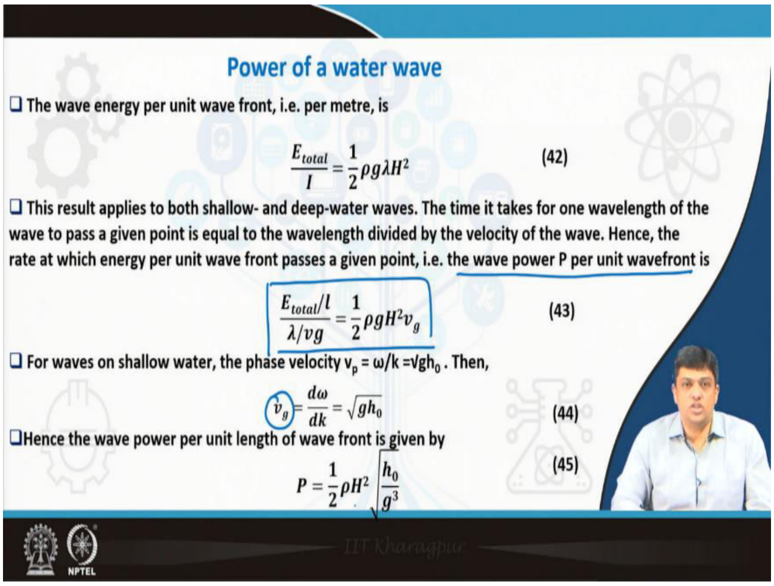
So, then you have the terms which are having the, which are dimensionally correct. Equating the coefficients of length and time, we get again that the phase velocity is proportional to under root g lambda. That means when we are talking about the case in deep water, the phase velocity has a strong dependence on wavelength and by solving this equation further, we get the constant of professionality as 1 by under root 2 pi and you get the phase velocity as V_p is equal to under root g lambda by 2 pi.

(Refer Slide Time: 30:52)



So, we have written the wave equation and as discussed in the previous classes, once we know about the wave equation then we can extract the information about the energy and power of a wave. So, using the same formulations you can clearly show that the power delivered by a deep water wave is actually given by the relation P is equal to half rho g H square v_g and if you replace the terms of which are calculated earlier let us say vg you know that power delivered would be equal to half rho g H square into half under root g lambda by 2 pi.

(Refer Slide Time: 31:53)

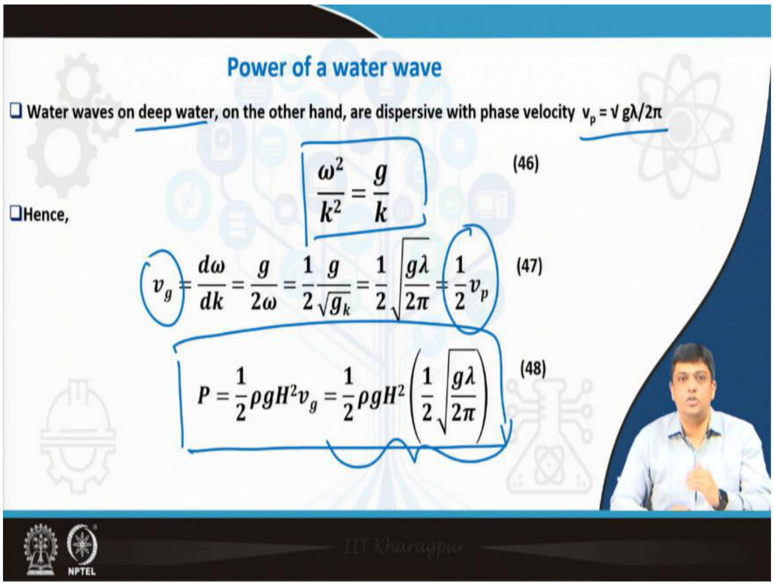


Now the wave energy per unit wave front that is per meter is what you have E total by l is equal to half rho g lambda H square. This result applies to both shallow and deep water.

Using this relation, the rate at which energy per unit wave front passing through a point is what? That is the wave power P per unit wave front and that is given by the relation E total by l divided by lambda by v g is equal to half rho g h square v g.

When you are in shallow water, the phase velocity v_p is omega by k that is equal to under root g h_0 and for the group velocity what I will do I will have d omega by d k and therefore your group velocity will be equal to the phase velocity in shallow waters. Hence, the wave power per unit length of wave front is given by half rho H square under root h_0 by g cube.

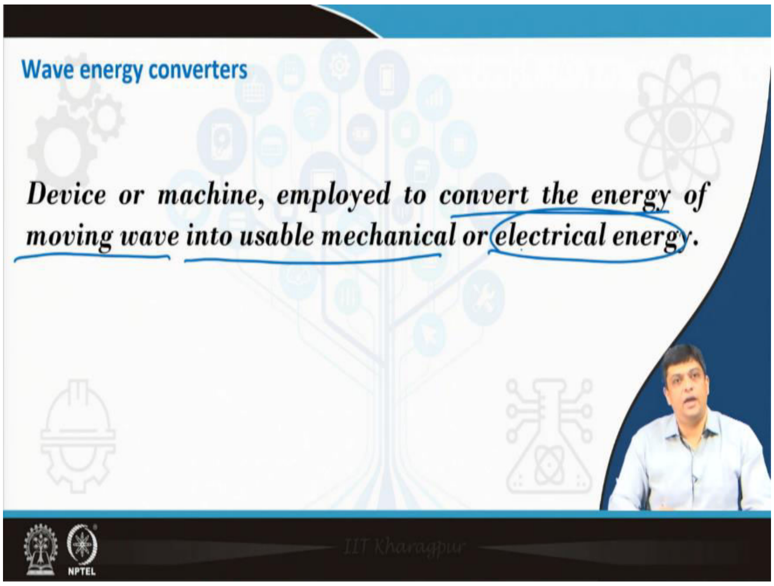
(Refer Slide Time: 33:34)



The next topic would be what? We have talked about shallow waters, now we will talk about the deep water and when we are in deep water, what is the condition we know that the phase velocity is under root g lambda by 2 pi and you have a relation omega square by k square is equal to g by k.

And therefore, what I will get? I will get v_g equal to half of v_p. Knowing this relation, we can immediately extract the information of the power which is there in the deep water and that comes out to be equal to half rho g H square into half under root g lambda by 2 pi.

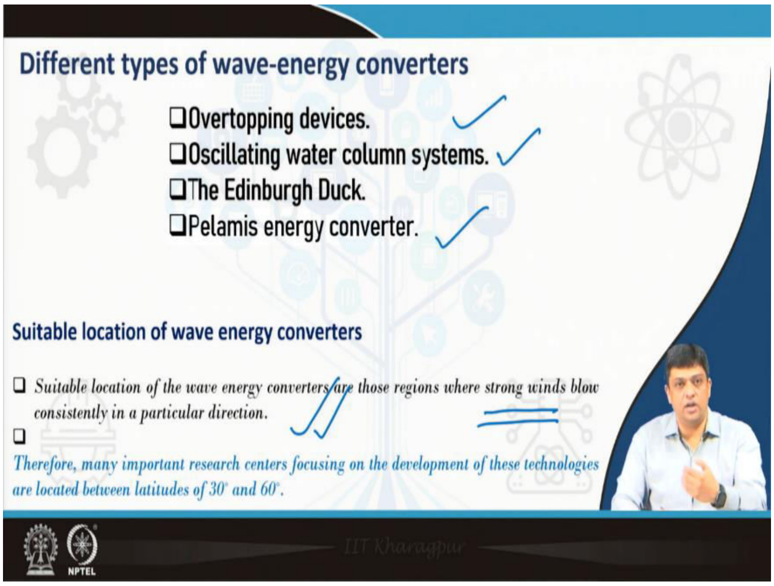
(Refer Slide Time: 34:37)



It is clear that if I am in shallow water or if I am in deep water, there is power associated with the travelling wave and if there is power associated with this travelling wave, if I am able to extract this power I have a strategy to use ocean waves as the source which will be delivering power to us and if we want to convert this power to electricity, then you will be talking about converters of ocean power to electrical power.

And such kind of converters are now being designed and are being installed in various places and they are called as wave energy converters. Very simple, what we had done till now was that we have proved that no matter where you are in the ocean, if you are in the shallow region or you are in the deep-water region, there is a power associated with the moving wave. Now our aim is to extract this power and what are we going to do? We are going to talk about the converters which allow you to convert the energy of moving waves into usable mechanical or electrical energy.

(Refer Slide Time: 36:31)

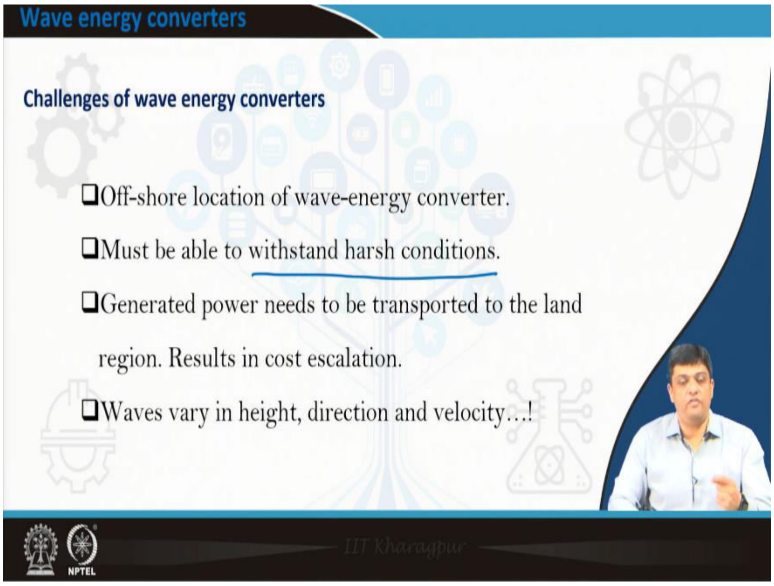


And there are different types of wave energy converters that are being installed and investigated. Some of them are listed in this slide, you can have overtopping devices, you can have oscillating water column systems, you can have Edinburgh Duck type structures which try to extract power from the moving wave or you can have Pelamis type energy converters.

You have to be careful that because you are installing these converters at places, where you are believing that you will be having waves and where do you have waves which are moving and that means you have slightly rough ocean and you have strong waves that is the place where you have actually strong winds blowing over the sea surface.

So, mostly these kinds of structures are located in regions where strong winds are blowing and you will find that most of the research centres which are trying and developing such kind of technologies are located between the latitudes of 30 degrees to 60 degrees and you are having strong winds between these two latitudes and therefore, you have the research centres installing the developed or fabricated systems in this area.

(Refer Slide Time: 38:28)

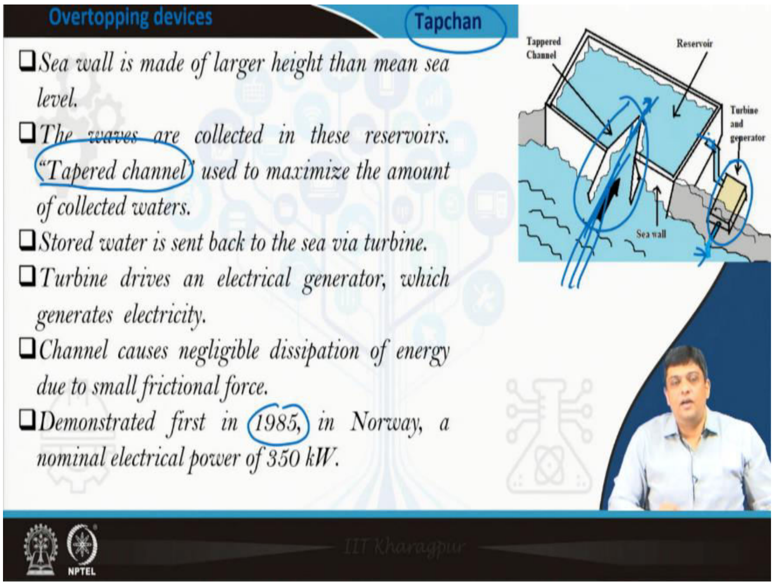


The major challenges of the way energy converters are that they have to be installed at offshore locations. So, they are maybe somewhere inside the ocean or they are just at the place where your sea is meeting the land. As they are exposed to water continuously and that too salty water and it is a very harsh environment that they encounter, these converters have to withstand the harsh conditions.

Now suppose you have installed energy converter in the middle of the ocean. Now how do you want to extract this energy may be electrical energy which has been generated? So, then you need to have the transport from the generation unit to the land region and if you then have these long wires cables then you result in a condition which is termed as and related to cost escalation.

Now as all of us know that waves vary in height, direction, velocity and with changing directional velocity the power of the moving waves are continuously varying. So, it is a very unstable and unpredictable source, so you must have the idea, how to channel the power out of this unpredictable source.

(Refer Slide Time: 40:34)



Let us talk about the first topic that is the overtopping devices. It is a very simple design, very similar to water dam. What were you doing in water dam? You had river flowing down, you had reservoir or you had a reservoir which was collecting rain water but that reservoir was at a much height which was much above the place where you were installing the turbine and because of this flow of the water in the penstock and then to the turbine was resulting in the conversion of potential energy to kinetic energy and that this kinetic energy was driving your turbine blades.

This is what you were doing in dam. So, in these devices which are also called as Tapchan devices, because they use tapered channel designs I will just tell you what that is. This Tapchan based devices are very similar, so what you do at the seashore you build walls, you are making a reservoir. So, you can make let us say a 10 meter or a 20 meter or 30-meter wall and a reservoir, a big tank. Waves are coming in, now you force these waves to enter this reservoir.

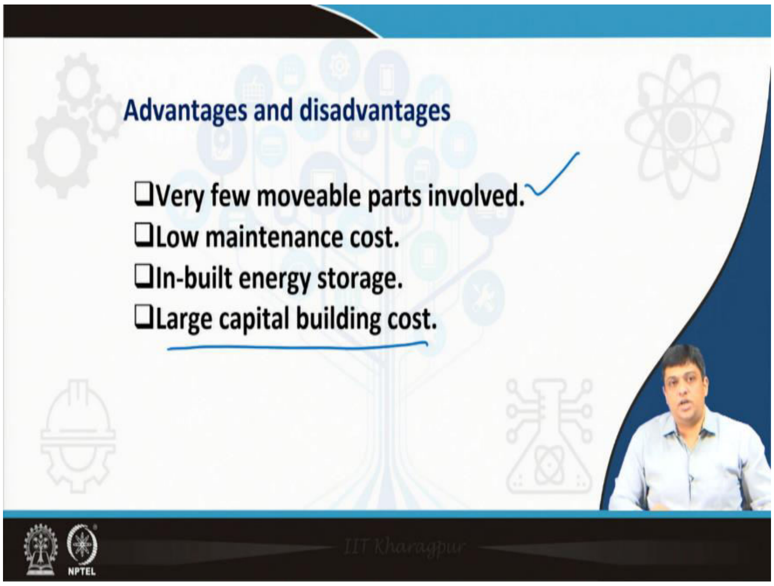
Now because of this tapered channel, because of this tapered channel, you are increasing the velocity of the water which is going to come out of this let us say the end nozzle of the tapered channel and then the water will move in and because the water is continuously flowing in, the water which are getting inside this reservoir do not have the chance to come out from this tapered channel.

What happens? Slowly water level rises in this reservoir. Now I have filled this reservoir up to 20 meters height and now suppose I install a turbine and a generator at a much different height which is much lower than the place where we are having the channel let us say similar to penstock which will send the water down.

Because of this difference in height, the potential energy stored in this water will then be converted to kinetic energy this and will go and hit the turbine blades in the generators and you will have the generation of electricity. Once you have done the job that is the turbine blades have been set into rotation the water can flow back into the sea.

And the channels are believed to cause negligible dissipation of energy as they have very small frictional forces. This was first demonstrated in 1985 in Norway with a nominal electrical power being obtained of approximately 350 kilowatts. So, the design is very simple, but there are associated problems to it.

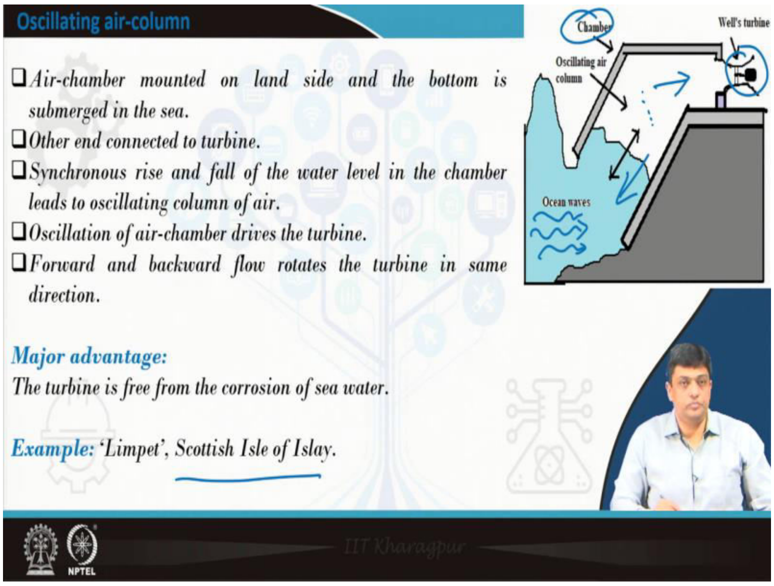
(Refer Slide Time: 44:36)



For example, you have large capital building cost. The advantages, it has very few movable parts, low maintenance and it has an inbuilt characteristic of energy storage. Why I have sent in water stored in reservoir. Now the energy is already stored in this water. The time I need energy, I will switch on the turbine and let the water flow down the penstock or the tube which is sending down the water to the turbines.

So, it has the inbuilt characteristic of energy storage, but yes it changes the landscape. It can lead to various other social issues if built very near to human habitats. So, advantages and disadvantages are again associated with Tapchan technology.

(Refer Slide Time: 45:57)



The second technology which is being developed is the oscillating air column devices. So, what happens? There you were sending in water inside, collecting it in a reservoir and then sending the water down to run the turbines. Here, the design is slightly different. You have the ocean waves which are moving in and in this, you install a structure which is similar to an air chamber mounted from the land side.

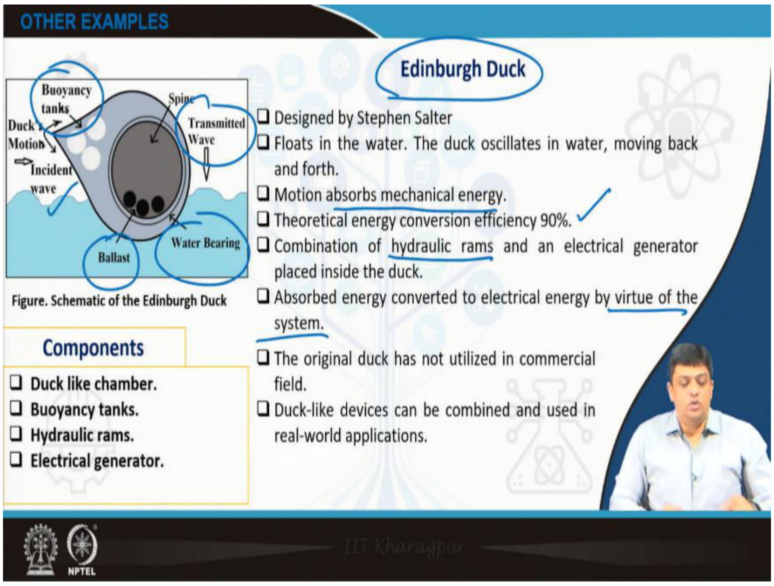
So, there is an air chamber which is mounted from the land side and submerged into the sea. Now what is there in this air chamber? You have air. When the water recedes, the air will be filled in this chamber, when the water rises the air will be sent out of this chamber. So, when water recedes more air is filled in the chamber. When water is rising the chamber throws out the air. So, you have the oscillating air column and this synchronous rise and fall of water level in the chamber leads to an oscillating column of air.

At the mouth of this chamber which is towards the land side, you install a Well's turbine. Well's turbine why? Because it moves in the same direction irrespective of the condition where the air is actually moving from its back side to the front side or vice versa the motion would be in the one direction, the turbine will always move in one direction irrespective of the flow direction of the air.

And now I have a turbine which is moving, if I have a turbine which is moving what is the output you get? You have the electrical power if the turbine is connected to the generators. The major advantage is the turbine is free from corrosion of sea water because the turbines are much further away from the harsh water which is flowing in the ocean. This was first tried in Scottish Isle of Islay.

There are certain issues which are associated, you have to ensure that the water column does not get damaged, you have you will have noise pollution because of this movement of such amount of air gushing in and gushing out or gushing in to the chamber you can have serious noise pollutions and that has to be very carefully checked, so that the local habitat do not suffer from noise pollution. So, although a very simple design, it also has certain limitations.

(Refer Slide Time: 49:42)

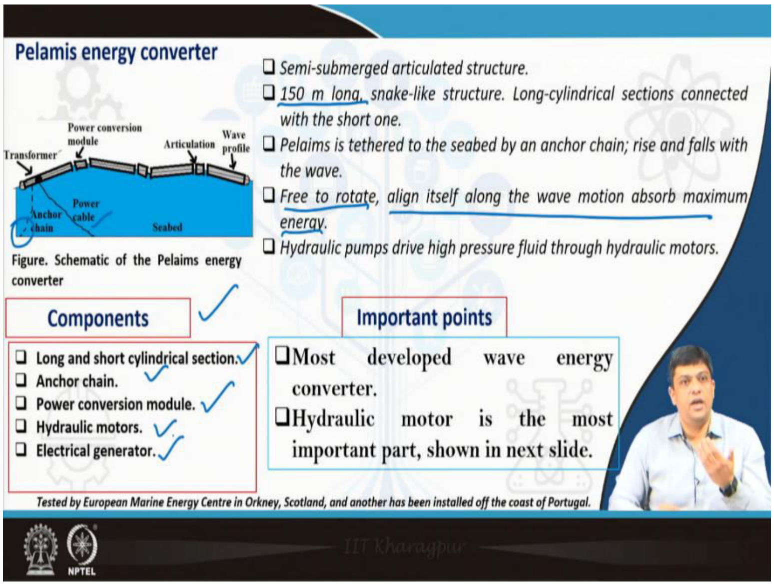


One of the earliest designs which were made by Stephen Salter to extract power, but a design which has not gone into commercial use is the Edinburgh Duck and this Duck has the design given in the left-hand side picture. So, you have the buoyancy tanks which are preventing this Duck to sink.

So, what happens this Duck is actually as the wave passes through this Duck moves up and down, up and down and that results in the generation of electrical energy. If this Duck is able to absorb the mechanical energy and the hydraulic rams which are inserted they are also moving as the Duck is moving back and forth, the absorbed energy gets converted to electrical energy by the virtue of this system.

The original Duck was not utilized in commercial way but it has a very high efficiency. Slightly more sophisticated design is discussed bit later. Here you see that one of the major problems with this is that you are leaving this Duck on an open sea with no way to stop it from floating away from the place it is installed.

(Refer Slide Time: 51:49)

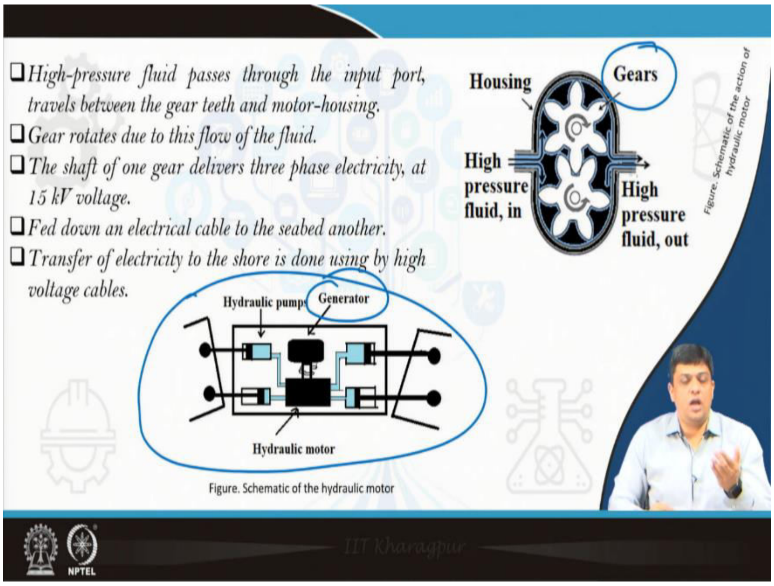


So, to counter these kinds of factors you have a new design which came into picture such as the Pelamis energy converters which are actually anchored. So, now you have the similar design but you have these structures are anchored, so that they do not flow away from the place they are installed.

And then the motion of the wave results in the extraction of mechanical energy and then if you can convert this mechanical energy to electrical energy then you can use the power cables to transfer the electricity to land. They are actually free to rotate align itself along the wave motion and therefore, are able to absorb the maximum energy. Typically, they are of 100 meters, 150 meters long and they simulate a snake-like structure.

They are not actually fully submerged but they are semi-submerged structures and the typical components of these Pelamis energy converters are the cylindrical sections, the anchor chain, the power conversion modules, the hydraulic modules which are actually connecting or they are ensuring the stability of the whole structure and obviously the electrical generators

(Refer Slide Time: 53:37)

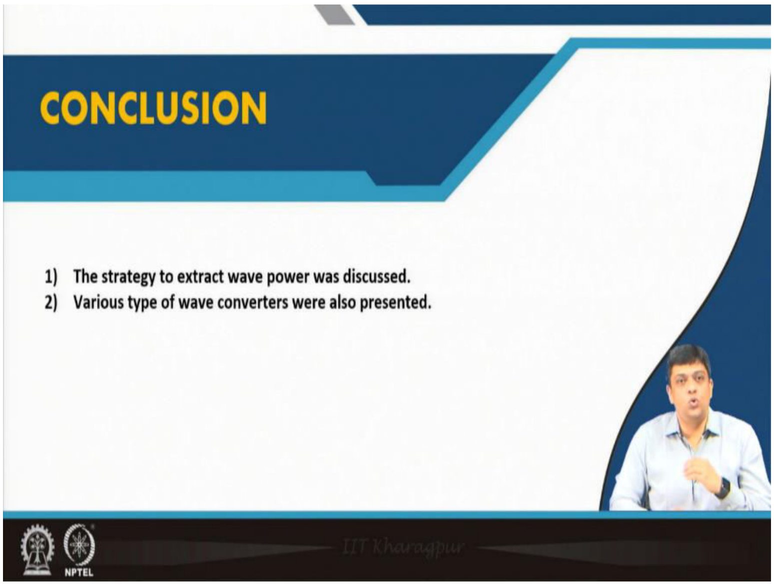


If you look into what I said, the hydraulic motors they are the typical structures which are shown here. So, you have the hydraulic pumps will take the water, through the water that will result in a hydraulic motor and you will have the generators. Once that is obtained the water will then come out and go to the next.

So, you have hydraulic pumps driving the hydraulic motors and you will see that the action of the hydraulic motor is such that they are controlled with gears. So, for example, I am showing 2 gears and you will see that both the gears are moving independent to each other. So, you have the high-pressure fluid coming in and driving these gears and then going out.

So, this high-pressure fluid passes through the input port, travels between the gear tip and the motor housing and then comes out. Gear rotates due to this flow of the fluid and the shaft of one gear is able to deliver a three-phase electricity let us say at 15 kilowatts. Once you have the electrical output, you can then transfer the electricity to the shore.

(Refer Slide Time: 55:18)



So, these were the main water converters which are being investigated and are being used in various places. So, I hope that in this lecture it is clear that there is a novel strategy which is coming into forefront, which is allowing you to extract wave power and there are many wave converters that have been proposed and I am sure that you will find that many more will come in future and there is a lot of scope of research and development in this topic.

(Refer Slide Time: 56:05)

This is the major reference book which has been followed to prepare this lecture and I hope you enjoyed this lecture today and from the next lecture, we will move to the next module of this course. I thank you for attending this lecture have a nice day.