Hydraulic Engineering
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Lecture-28
Introduction to Open Channel Flow and Uniform Flow

Welcome. This week we are going to start this topic called open channel flow and this will be continued for the next week as well. So, this is a big topic start I will start with some of the most basic fundamentals of open channel flow.

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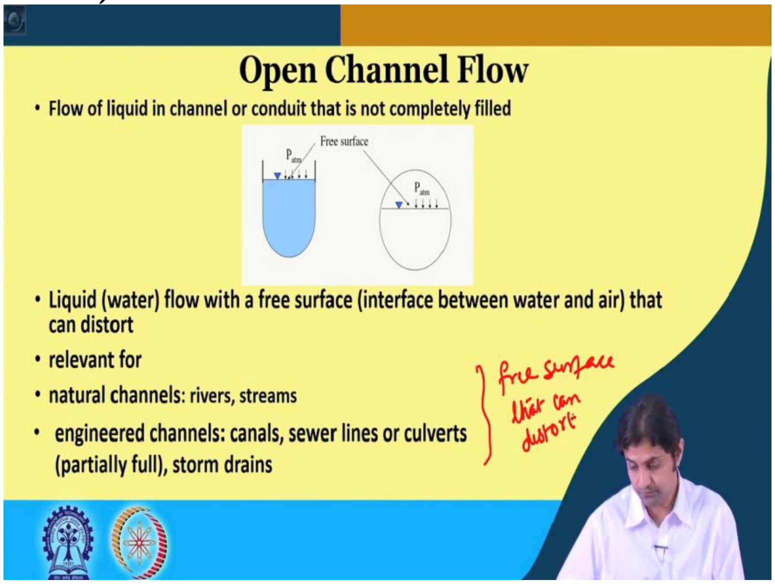

So, open channel flow. So, the first question that comes to my mind and of course, it would be coming to your mind as well. What is open channel flow? So, the most basic definition of open channel flow is, it is the flow of fluid in a channel or a conduit that is not completely filled with water. So, this is illustration, where you see, there is this tube in which some water is filled, but the free surface is exposed to atmospheric pressure. So, P atmosphere means atmospheric pressure.

So, this is another look, where you can see, if this is a circular in shape if the water is filled up till this, you know, up till this level and it is exposed to the atmospheric pressure. This is also called open channel flow. We will come to this, you know, definition and you would see there is another type of flow which is called pipe flow that we would come from, I mean, that we would see from 2 weeks from now on. So, the difference between open channel flow and the pipe flow.

So, one of the most important difference is exposure to atmospheric pressure or it will have a free surface in open channel flow. As I said, the liquid in this case which is water, the flow with a free surface. So, that is the interface between water and air is called free surface. And the important property is that this interface or this resurface can distort. So, distort means it will not always remain horizontal. It could be that it can take any other shape as well. And the study for or study of open channel flow is relevant for, you know, natural channels.

So, this is one of the important areas and the flow in rivers and streams. These are all a sort of an open channel flow. Also it is relevant not for only the natural channels but engineered channels like canals, sewer lines or culverts, whether the culverts are partially full, if it is totally full then not but partially full and storm drains. So, if you see one of the important feature here of all these channels, you know, is that it has a free surface that can distort, that is very important.

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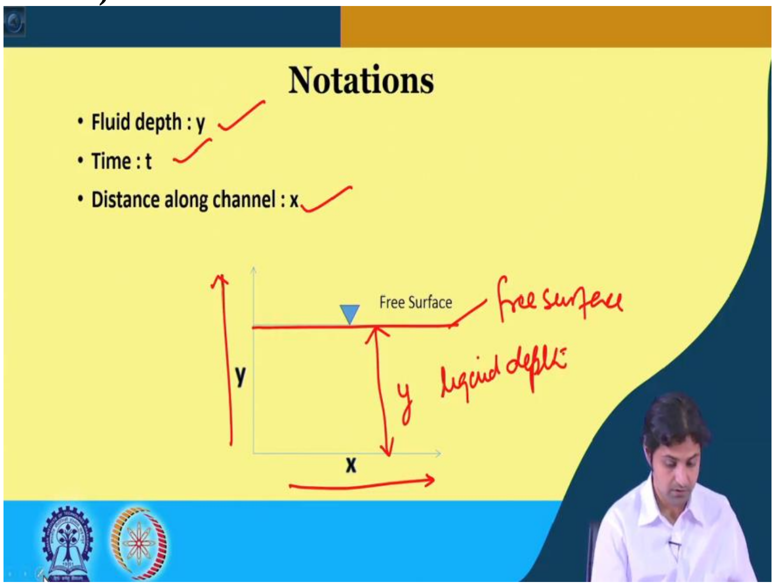

So, notations. So, the notations that we are going to see, so, this is if we plot this open channel in x and y direction, this is the x axis, this is the y axis, fluid will be something like this, here I have plotted horizontal line and this is the free surface. And this fluid depth y, will have liquid in it or here, in this case, water so or liquid depth or fluid depth. The notations that we are going to use is fluid depth is indicated by y, time is indicated with t and distance along the channel is indicated as x. So, this is a notation that we are going to use entirely, I mean, in the entire module of this open channel flow.

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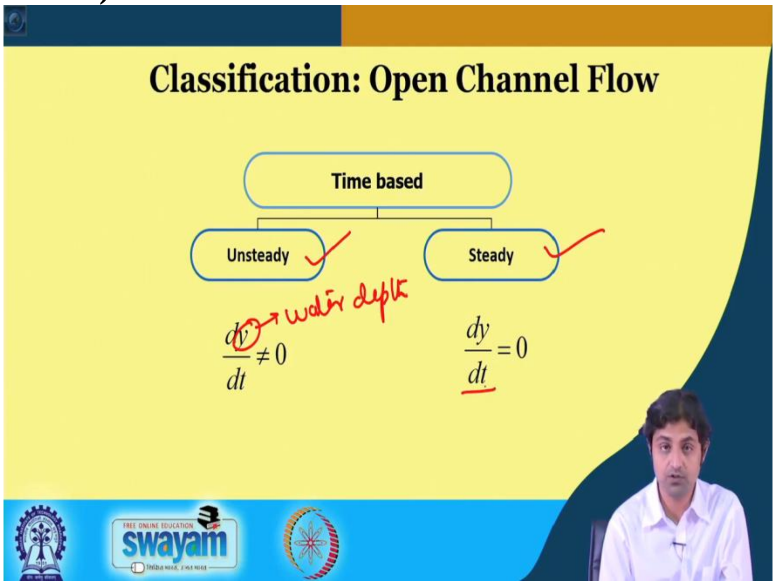

So, the classification of open channel flow, these open channel flow can be classified in different ways. The first is time based. So, one of the definitions is unsteady flow and steady flow. So, I will like any other flow this open channel flow can also be classified. We have seen these terms in fluid kinematics in our basics of fluid mechanics two module. So, what is unsteady? So, unsteady means dy / dt.

So, y as we said, is the water depth. So, for basic definition, we see the change of water depth with respect to time if it is not equal to 0 then that is unsteady flow. And for steady flow, the change of water depth at any point with respect to time if it is 0 then it is called steady flow.

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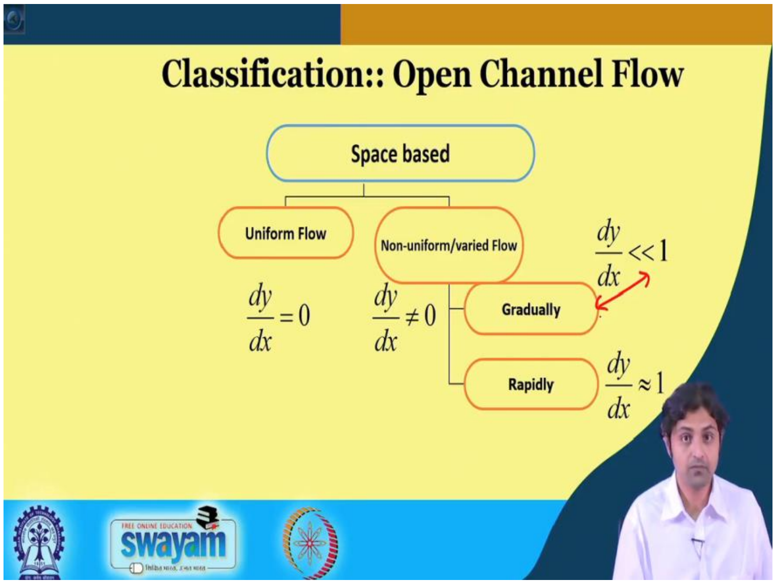

One of the other classifications is, so, the last one if you go and see was time based. So, the other classification by, you know, instinct we can, I mean, we can imagine will be space based. Space based, there are 2 major type, one is uniform flow, I will tell you what that is, and the other is non uniform flow or varied flow. In non uniform or varied flow there are 2 types. One is gradually varied and other is rapidly varied flow.

And this is very important because many lectures will be dedicated to the gradually and the rapidly varied flows and many lectures will also be dedicated to the uniform flow in open channels. So, for uniform flow the rate of change of depth, with respect to x axis will be 0. So, dy / dx is going to be 0, for uniform flow. So, I mean, for non uniform flow, varied flow, it is very easy to imagine, when dy / dx is not equal to 0 it is non-uniform or variedly flow, as it is written here.

Very simple definition, dy / dx is equal to 0 means uniform flow, dy / dx not equal to 0 indicates non uniform or varied flow. One question that would come to your mind is now, how do we know which one is gradually varied flow and which is rapidly varied flow. So, to get that definition, it is the same value of dy / dx that determines if the flow is gradually varied or rapidly varied. So, if it is a gradually varied flow then dy / dx will be a very, very small quantity much, much less than 1.

So, dy / dx is like depth and this is the stream direction. So, if the river is flowing in x direction, dy / dx is less than 1 is gradually varied flow. And for rapidly varied flow, this dy / dx is of the order of 1. So, it is not insignificant. I mean it is not less than 1.

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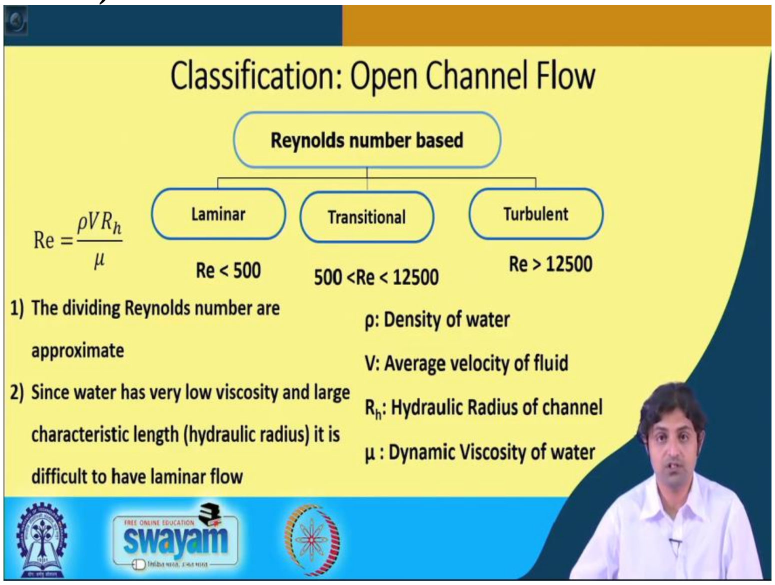

So, on one of the, you know, other classification of open channel depends upon a quantity that is called Reynolds number. So, in a open channel flow, Reynolds number is given by $\frac{\rho V R_h}{\mu}$. Here, ρ is the density of water, V is the average velocity of the fluid, R_h is hydraulic radius of the channel and μ is the dynamic viscosity of water. We have already seen what the density of water is, we already know what the average velocity of the fluid is, we already have seen many times what the dynamic viscosity of water is.

So, the thing that is we are hearing for the first time is called hydraulic radius of the channel. So, this we are going to learn in this module. What is the hydraulic radius of the channel? So, depending upon this, the variation of a Reynolds number, the flow can also be classified as so laminar, transitional and turbulent. As the normal classification, this is same type of classification that we have seen in basics of fluid mechanics two, but specific to open channel flow. So, these values of Reynolds number will be a little bit different.

But the core concept that higher Reynolds number indicate turbulent flow and lower Reynolds number indicate laminar flow will still hold true. So, in case of open channel flow based on

Reynolds number it has been found out that, when the Reynolds number is less than 500, the flow is laminar, if the flow is in between Reynolds number of 500 and 12,500 the flow is going to be in the transitional regime and if the Reynolds number is greater than 12,500 the flow is going to be fully turbulent.

These values are something that you can remember. It will be very helpful in your future fluid mechanics, I mean, in future courses related to hydraulics or, you know, water. These dividing the Reynolds number, that is, 500, 12,500, they are approximate, not exact, it changes from situation to situation, but what we have given you today is an approximate or an, you know, approximate value.

One important thing to note is, since water has very low viscosity and large characteristic length, it is difficult to have laminar flow. I will just try to show you, I mean, see Reynolds number is given as rho V Rh / mu. So, water densities of the order of 10 to the power 3. Hydraulic radius for any open channel, I mean, you will see, but let us say it is of the order of meter, for example. Let us say, I mean, it will be much more the hydraulic radius could be, let us say it is the order of 1.

Velocity, let us say, whatever smallest velocity if you can give will be like 0.1 meters per second something of that order, mu is 10 to the power - 5, or 10 to the even, you know, 10 to the power - 5 Pascal Second. If I am not, I mean, it varies from 10 to the power – 3 to 10 to the power - 5. In any case, this is much greater than, you know, 10 to the power 6 or something. I mean, and 12,500, this limit is of the order of 10 to the power 4. So, basically however small velocity you have.

Because of the very low viscosity and large characteristic length, you know, it is almost impossible to have laminar flow in open channel. So, this value I am not pretty sure about, but it could be of even if it is of the order of 10 to the power - 3, then also we will have, you know, this will be greater than 10 to the power, let us say, 5 also, could be, so easily turbulent flow. So, this was the classification based on Reynolds number.

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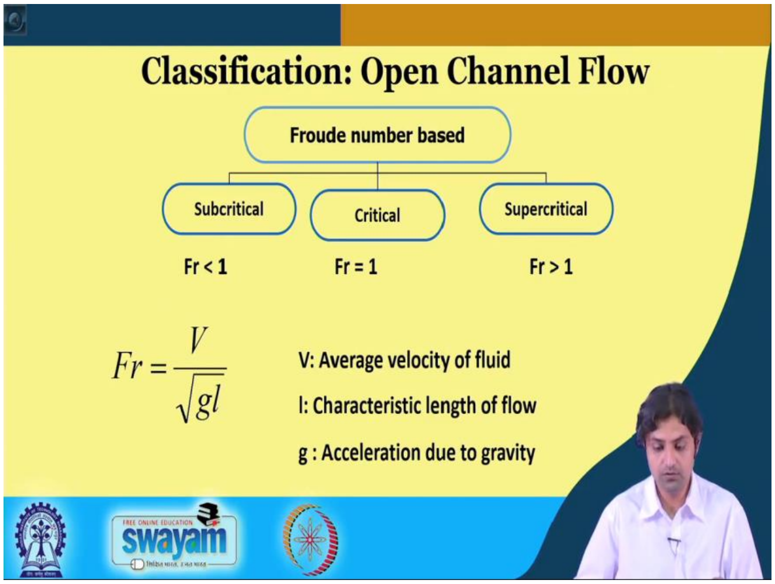

Now, there is another classification that depends on Froude number. This Froude number we have seen in the last week's lecture, where we were dealing with a topic called dimensional analysis. This Froude number normally is given by $\frac{V}{\sqrt{gl}}$. And this Froude number based classification has 3 regimes, one is subcritical flow, the other is critical flow, the third one is supercritical flow.

This is going to be V under root g h, where h is the depth of the water, in this case. So, if Froude number is less than 1, this means, the flow is going to be subcritical. If the Froude number is equal to 1, this flow will be called critical open channel flow and very obvious to you, if the Froude number is more than 1, this is called supercritical flow. Quite easy to understand this one. So, a Froude number is given by $\frac{V}{\sqrt{gl}}$.

So, V here is the average velocity of the fluid that you already know. You already know g acceleration due to gravity and l is characteristic length of the flow. Most of the cases, it is the water depth, but it could be different as well. We will solve some questions and then you will see what this length is going to be. So, after the classification, we are going to take our attention to a topic which is related to, you know, open channel.

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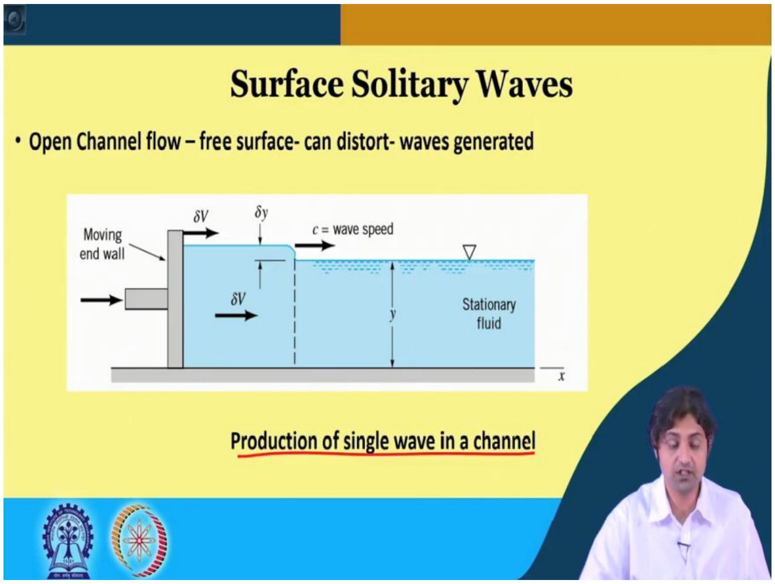

And that is called surface solitary waves. And the prelude to this is, in the definition we had clearly specified that in open channel flow, the free surface can distort. And the smallest distortion can produce waves and that is what we are going to see. As I said, in open channel flow, free surface can distort and therefore, waves can be generated. So, this is the free surface, if we push it with something, you know, something like this can be formed and this pattern is called waves.

You have you can actually bring, you know, water, I mean, bring some water in a pan or, you know, in a maybe a big kettle and where the or it is exposed to the free surface and you try to push it with one hand, you will see a disturbance at the surface will be there and it will travel. One of the other things that you can see, if you throw something on the free surface then also waves are formed in a, you know, pond. As a child, you might have thrown stones in the pond then also you would have seen the waves were formed.

That is because of the distortion of the free surface caused by the force of, the force with which the stone falls on the pond or the river. So, this is one of the waves where the surface solitary waves will be generated. How? Suppose there is, you know, a water, water enclosed in this area and we have a moving end wall. So, I mean, supporting this water is a moving end wall. So, moving end, because if we can move this wall the disturbance can be produced and the waves can be generated. We will derive something in our upcoming slides for that.

So, in the beginning as I said, that the water depth will is demonstrated by y. So, I will explain you what these each term indicates. So, water depth is given by y. Initially this is a stationary fluid so no motion, x is given in this direction. So, now so what we assume I will just explain, we have, we will come back to it again, but delta V is the velocity with which the wall is moving and because of the movement if we suppose that the water in this area goes up by distance delta y.

So, this is as I said, it is production of a single wave in a channel. This is one of the ways in which a single wave can be produced in a channel. And the channel is supported by the moving end wall on one side.

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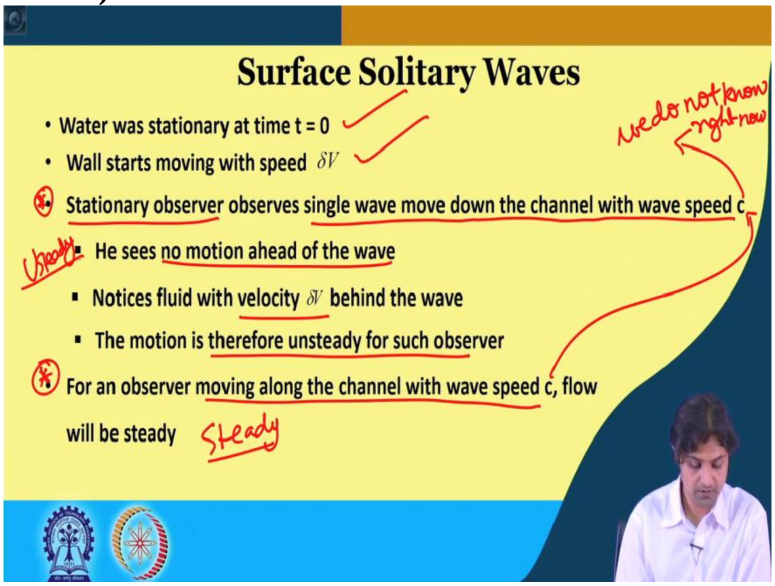

So, there are some assumptions, as I told. Water was stationary at a time, at time t is equal to 0. The wall starts moving with the speed the delta V, as we have already seen in that figure. Now, if there is any stationary observer, so, as u as any stationary observer, what are you going to observe, you will observe single wave that moves down the channel with a wave speed c, which we do not know now. So, we call this speed c which we do not know right now. The observer will also see no motion ahead of the wave.

So, ahead of the wave there will be no motion because the fluid was stationary. The observer will also notice the fluid with velocity delta V behind the wave. Behind the way he will observe the fluid velocity because the wall is being pushed with velocity delta V. So, for such an observer the motion is unsteady. The motion is therefore, unsteady for such an observer, who is basically stationary and observing from a distant point.

So, for an observer, if there is any observer that is moving along the channel with a wave speed c, the same wave speed c, the flow is going to be steady. So, this, you know, this is there are 2 different ways of observing. One is observing as any stationary observer, one is moving with the wave and then observing the flow. And in this case, this is going to be unsteady flow, U steady. U stands for un and this is steady.

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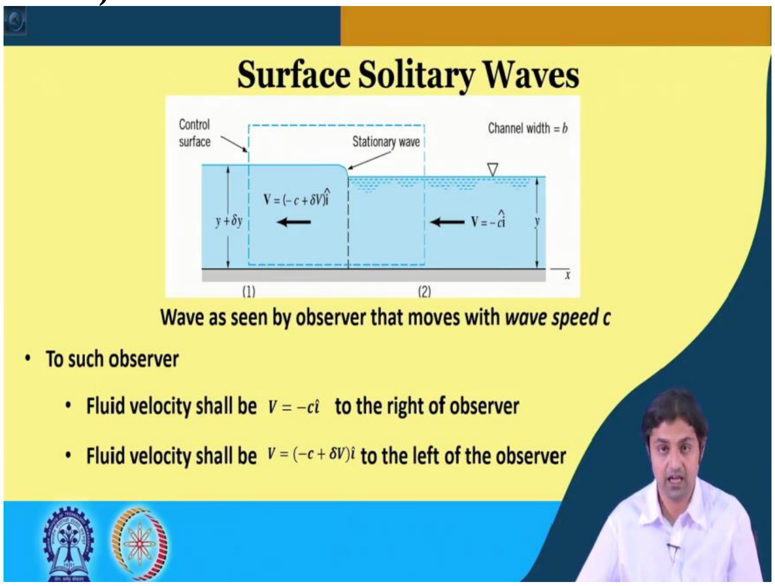

So, again we come back to the same figure. Now, we have much more, you know, science included in this, what we have done, we say that the channel width is b. And we draw the control surface as indicated by this. I am going to rub this off, but just to show you. This is the control surface because the water surface was elevated by distance delta y, the total height here is going to be y + delta y. Here, it will still remain y. So I will come to this velocity, here and here, in a short while.

So, this is the figure that will be observed by an observer that is moving with wave speed c. So, for this derivation we are using the another approach, where the flow was steady. So, it is with an observer that is moving with wave speed c. And for such an observer, what happens? The fluid velocity shall be - ci to the right of the observer because he is moving with the wave. So, this is to the right of the observer, and this is the left of the observer. So, to him the fluid velocity will be, because this is stationary.

This part in reality is a stationary, this part is stationary part and the he himself is moving in x direction with speed c, so to him the fluid velocity shall be – c i cap, i indicates the unit vector in x direction. Now, to him the fluid velocity here, you know, outside, you know, to the left, this as I indicated, this one will be, because in reality what is happening is this side is moving with delta V and he himself is moving with this speed c here.

So, the total speed is going to be - c + delta V in this direction because he is traveling with the wave. So, - c + delta V in i direction, to the left of the observer. We are using the vector notation that is why we are saying that it is - c + delta V into i cap.

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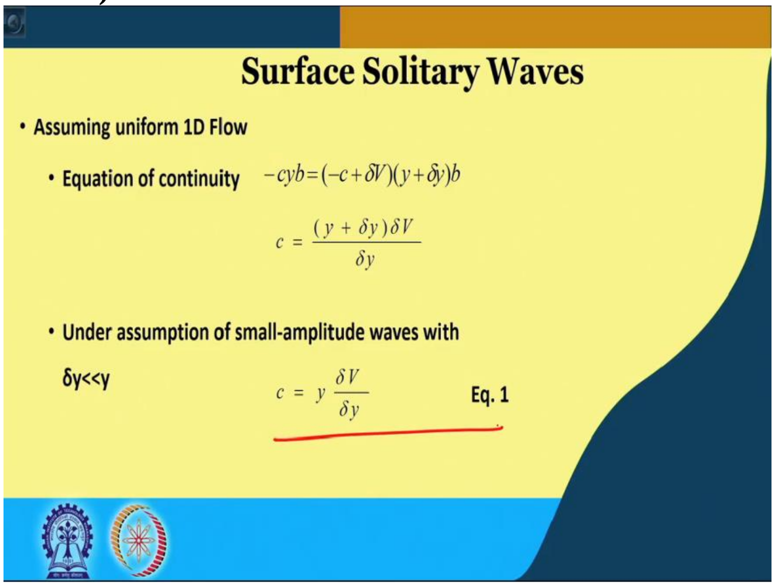

So, if we assume, uniform 1 d flow, 1 dimensional flow, the equation of continuity is going to give us, because the width of the channel is, you know, we have seen here is b, channel width. So, - c a1 v1, so this is v1 into y b, that is, this section here, if we were assuming 2 control surfaces, and on the left side the velocity to the observer is - c + delta V and the area is going to be on this side is y + delta y into b and here it is going to be y into b. So, we have used the same notation, I will just take away the ink.

So - cyb is equal to $(-c+\delta V)(y+\delta y)b$. So, what happens? So, b and b should get canceled out. And this c on this side, so, if we try to solve this, so I will, you know, so - cyb, can be written as, so we keep this as one term, b, b gets cancelled from each side. So, I will take away b, - c y and this whole multiplied by - c, + delta V multiplied by y + delta y. So, - c y is equal to - c y - c delta y + delta V into y + delta y.

So, this gets cancelled because same and this will come here and it will be c delta y is going to be y + delta y multiplied by delta V and c can be written as $c=\frac{(y+\delta y)\delta V}{\delta y}$, same as it is shown here. So, to make the presentation clean, I will just take away this small derivation. So, c becomes y + delta y into delta V / delta y. Now, there is one assumption that we have we will we are going to assume that this is a small amplitude waves.

A small amplitude waves means the height of the wave or in this case, delta y that is the elevation with the water surface goes up or the wave, you know, some parameter that is related to the wave height is much, much less than the water depth. So, the if we say a small amplitude wave this means delta y should be much less than the water depth. This is assumption in all the wave mechanics or, you know, wave theory. So, if we will assume that then we can simply write.

So, y + delta y if we add delta y to y that means it will remain y and that is how it becomes y. So, c is equal to $y\frac{\delta V}{\delta y}$ will remain same because here we have applied this theory. So, that is called equation number 1. So, I think I will take a break and, you know, stop this lecture at this point in time and we will continue from this equation number 1, I mean, this particular point from our, in our next lecture. See you next class. Thank you.