Free Surface Flow

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Lecture 2

Welcome students to this second lecture of the first module of introduction to basic concepts. So we are going to continue from where we left off in the last lecture. And we are going to start the introduction of this gradually varied flow. So, if you see if the change of depth in a varied flow is gradual, so you see we talked about uniform flow, we talked about non-uniform flow. So, gradually varied flow is one of the classifications of non-uniform flow.

Non-uniform flow that the flow properties such as water depth are changing in space. Now, the question is how fast not fast how you know over how long or how short distance this flow depth is changing and depending on that we have different different classifications. So, for gradually varied flow if the change of depth in a varied flow is gradual that means very small. So, a small change is happening over a very long distance. And, because the consequence of that is that the curvature of the stream line is not excessive.

That type of flow is called gradually varied flow or more commonly referred to as GVF. So, you see this gradually varied flow GVF. So, in other words, GVF can also be so dy/dx. This is water depth and this is stream wise distance. This dy/dx is very, very, very less than 1 or tending to 0. This is the important thing about basic definition of gradually varied flow. So, example is the backing up of water in a stream due to a dam that is a very, very small you know slope of the water and therefore, that is the Gradually Varied flow So, opposed to gradually varied flow there is rapidly varied flow and by the name itself you will get a good idea what a rapidly varied flow is right. So, what happens in rapidly varied flow is that the curvature in a varied flow if that is large.

Or in other words, if the depth is changing very rapidly over a shorter distance, so that the curvature is large. That type of flow is called the rapidly varied flow or more commonly referred to as RVF, very common word RVF. Again, in terms of $\frac{dy}{dx}$, the terms I have already explained to you before, this is greater, it is very large. This is water depth Wd and this is the stream wise direction.

Right. And one of the examples is a hydraulic jump, a very, very common topic and very, very famous topic that is occurs below a spillway. So, you see suddenly you know the y here is so much and after the hydraulic jump. So, this is less water level this side and larger. So, you see the difference and it happens over this much distance that is one of the examples of the rapidly varied flow.

Now, a third classification is spatially varied flow. So, varied flow is class generally classified as gradually varied flow and rapidly varied flow and both of these assume that there is no external flow added or taken out of the system. So, whatever happens is natural right, but you see there will be conditions like you know in let us say let us say water supply system right. So, when the water is flowing in an open channel flow there will be people who will be drawing out water. from the canal right that means, water is being taken out if you consider sewers.

So, even the there is a sewer line right. So, people so, there will be channels from the houses to the main sewer line where water is being added to that channel. So, in that cases we have another term called spatially varied flow. And normally RVF and GF, GVF have no flow that is externally added or taken out of the system. So, if what basically means is if some flow is added to or subtracted from the system or abstracted from the system, the resulting varied flow is known as spatially varied flow.

What it means is spatially varied flow is also a varied flow, it is not a uniform flow. depending if the flow is being added or subtracted that term is called spatially varied flow, very different from gradually varied flow and rapidly varied flow. spatiially varied flow (SVF). So, this was the term that was not covered in detail or you know in your course hydraulics, but at this is the specialized course. So, this part will be taken very well care this time.

So, now and one of the examples is the flow over a side weir is an example of SVF. So, this is you see. So, this is the channel water that is flowing and if you have a weir the water is coming down here in the flood plain. So, you see the water is being extracted out and therefore, it is a spatially varied flow.

So, side weir through which the flow is abstracted from the main channel all right. So, I am just going to give you some of these diagrams, some of the examples of the different type of flow. For uniform flow, important thing is constant depth. Unsteady uniform flow, it never happens. There is no point in saying or very rarely it happens.

Therefore, there is So, third type is varied flow, uniform flow. Unsteady uniform flow, then we have varied flow. Varied flow can be rapidly varied flow, gradually varied flow. And then we also have SVF, which we have not shown here right now.

But the idea is you see in gradually varied flow more importantly, very low slope. Whereas, in rapidly varied flow you see large gradient. This is basically summary of what I have covered when it comes to classification of flows. So, hydraulic drop is also one of the example of rapidly varied flow. Flow over a weir is also an example of rapidly varied flow.

This hydraulic jump you know less depth before and more depth after is example of hydraulic jump that is an example of rapidly varied flow. And gradually varied flow, this is rapidly varied flow, these are all examples, this is example of unsteady flow. So, unsteady gradually varied flow in example is flood wave. So, if I ask you during your you know examination to tick what is an example of unsteady gradually varied flow, so flood wave is one of the examples. Whereas unsteady rapidly varied flow that is bore is one of the examples, these are the diagrams.

So, now, another classification of flows we were talking about flows we said steady and unsteady flow. Now, another is laminar and turbulent flow. A very very important classification based on so many research topics and since this is an advanced course or that is that which means a third or fourth year bachelor's course or a master's level course or PhD course and therefore, this to understand this particular topic is crucial to understanding the open channel flow. So, this flow is called laminar flow if the liquid particle appears to move in a definite smooth path. and the flow appears to be as a movement of thin layers on top of each other.

So, this is important to move in a definite smooth path. but in I mean compared to laminar flow in turbulent flow the liquid particles move an irregular path this is an important keyword here which is not fixed unlike the laminar flow with respect to each I mean. So, when it so, whether it is respect to time or space in turbulent flow the movement will always be irregular whereas, in laminar irrespective of space things can change, but it should be you know a smooth path. the relative magnitude of viscous and inertial forces determines.

So, what determines if the flow is laminar or turbulent? So, there are two type of forces, one is viscous force that is the frictional force, the other is inertial force that is the body forces. So, how strong are these forces compared to each other? will determine if the flow is going to be either laminar or turbulent. Now, the flow is laminar if the viscous forces dominate that is important and the flow is turbulent if the inertial force dominate very clear cut definition.

In laminar, viscous forces are much more larger in magnitude. And in case of turbulent, the inertial forces are much more larger in magnitude than the viscous force. So, the magnitude is not important. It is the relative magnitude with each other that determines if the flow is laminar or turbulent. Now, one of the most famous and arguably are the most important parameters of fluid mechanics, not just for the water guys, but also mechanical engineering anywhere, where you have the flow, fluid flow, aerospace, mechanical, in some cases, you know, coastal engineering, ocean engineering, hydraulics, water resources is Reynolds number.

So, in the last slide, we were talking about the relative magnitude of viscous and inertial forces. So, based on that there is a number called Reynolds number and that the formula for Reynolds number is $\frac{VL}{\upsilon}$. So, Reynolds number is the ratio of , let me just write inertial force divided by viscous force. So, what is going to happen is viscous force is much larger than the inertial force Reynolds number will be small right what happens in the inertial force Reynolds number will be high very simple.

So, among in this one Re is Reynolds number V is the mean flow velocity L is the characteristic length, it could be anything characteristic length could be let us say for a pipe flow it could be the diameter, for an open channel flow it could be the depth or in some cases in some cases it could be width as well, but mostly it is the depth and use the kinematic viscosity of the fluid. This viscosity things is very analogous to friction. So, unlike pipe flow in which the pipe diameter is usually used for characteristic length either hydraulic depth or hydraulic radius may be used as the characteristic length in free surface flow. So, as I told you just now pipe flow in pipe flow L mostly is the diameter of the pipe right.

However, in open channel flow This length is either hydraulic radius R which we will see later what is hydraulic radius or hydraulic depth. hydraulic radius or hydraulic depth. I am pretty sure you have studied that in your hydraulics course what hydraulic radius and hydraulic depth are. Now, the transition from laminar to turbulent flow in free surface flow occurs for Reynolds number of about 600.

So, I was talking just now that the Reynolds number is high. that means, the flow is turbulent if it is low that is laminar. So, basically the point in saying this is if the Reynolds number is less than 600 it has been observed that the flow is laminar and the transition to turbulent flow will occur if the Reynolds number starts increasing to 600. What is the way of increasing the Reynolds number?

One way is increasing the velocity very straight right. So, if you keep on increasing the discharge the Reynolds number is going to go higher and therefore, the velocity the flow will slowly turn from laminar to turbulent. In real life applications, laminar free surface flows are extremely rare. Like unsteady uniform flow was rare, here laminar free surface flows are also very, very rare. A smooth and glassy flow surface may be due to the surface velocity being less than the required to form the capillary waves and may not necessarily be due to the fact that the flow is laminar.

So, you need a very, very ideal lab conditions. for what laminar flow. So, you see laminar Reynolds number is $\frac{\rho VD}{\mu}$ Reynolds number should be less right. So, either the one of the ways is either the velocity should be low or the diameter is also low or the characteristic length. One of the real life examples where you will find the flow to be laminar is the flow in the blood vessels.

You see the capillaries, the arteries and the veins and those things you know very small capillaries, they are so thin that the number is obviously very small. Care should be taken while selecting geometrical scales for the hydraulic model studies so that the flow depth on the model is not very small. Very small depth may produce laminar flow on the model even though the prototype flow mass that the prototype flow to be modeled is turbulent. The results of such model are not reliable because energy losses are not simulated properly. That is one of the just and as I said that the laminar free surface flow or open channel flow is very rare.

So, what is more common is turbulent regime for open channel. And that means when the flow regime is turbulent there will be negligible surface tension effect. This is quite an important. So, we finished one these classifications. Now, another classifications is subcritical, supercritical and critical flows.

What are those? So, before actually really in reality starting this in your hydraulics you have heard about a term called Froude number. So, this particular classification is based on the Froude number So, flow is called critical if the flow velocity is equal to the velocity of the gravity wave having small amplitude. So, flow velocity everybody knows and gravity wave what is gravity wave you remember from hydraulics $\frac{V}{\sqrt{gD}}$.

So, that means So, if the ratio of flow velocity $\frac{V}{\sqrt{gD}}$, if those two are equal V and $\sqrt{gD}$, then this is called a critical flow and when v or $\sqrt{gD}$ then this is called ratio is 1. That means Froude number is equal to 1 means a critical flow. A flow is called supercritical subcritical flow if the flow velocity is less than the critical velocity.

Let me just you know I will write it down again. So, Froude number is $\frac{V}{\sqrt{gD}}$. So, subcritical what is subcritical if this flow velocity is less than $\sqrt{gD}$. or the critical velocity. That means for Froude number less than 1, the flow is called subcritical flow.

And what is supercritical? The flow velocity is greater than the critical velocity. That means Froude number will be greater than 1. So, is equal to 1 means critical, less than 1 means sub, greater than 1 means super. So, the Froude number Fr as I have told just now is the prime non dimensionless parameter governing the flow phenomenon open channel.

So, Reynolds number was the first one and the second one is Froude number. Now, when we have talked about Froude number, we should see the definition as we saw for the Reynolds number. What is a Froude number? Froude number is equal to the ratio of the inertial and gravitational forces and it is defined as $\frac{V}{\sqrt{gD}}$ is very important I have defined in the previous slide as well. It is the ratio of the inertial and gravitational forces.

What was the Reynolds number if you recall what was the ratio about Reynolds number was the ratio of the inertial forces and viscous forces. So, in the denominator was viscous forces numerator was common that was inertial forces. is ratio of inertial to viscous that was Reynolds number classification between laminar and turbulent. For critical, subcritical, supercritical the ratio is in between the inertial and the gravitational forces and it is defined as $\frac{V}{\sqrt{gD}}$. So, Fr is equal to 1 is critical flow, Fr less than 1 is supercritical flow, Fr greater than 1 is supercritical flow, Fr = 1 is critical flow, Fr less than 1 subcritical flow, I might have said it wrongly and Fr greater than 1 is supercritical flow.

Now we have been talking a lot about flow parameters. So, some of the flow parameters have already talked about flow, depth, velocity, but let us look at some of the important flow parameters which will include these two as well. What is the top width T? The width of the channel section at the free surface. So, wherever there is a free surface, this is the cross section and this is the free

So, this width is called the top width referred to as T , wetted area. So, the cross sectional area of the flow normal to the flow direction right. So, cross section. So, what will be the wetted area here right. this entire area, this is the wetted area.

Now, wetted parameter the parameter that so, the parameter that is wet. So, this so, basically this free surface is nothing right, but mean this free surface not a part of the channel right. So, this length plus this length plus this length this is the wetted, this is P wetted parameter. Anyways, the length of the line of the intersection of the channel wetted surface with the cross section normal to the direction of the plane.

So, let us see this figure. So, what is hydraulic radius? So, the hydraulic radius is the ratio of the wetted area to the wetted parameter very simple R = A/P, straight and simple A we have seen here in the last slide this area and this is the P, R is A/P. What is hydraulic depth? Ratio of the wetted area to the top width, this is important.

So, see if you determine A, if you determine P and you determine T, rest of the things can be calculated and this hydraulic radius and hydraulic depth could potentially become one of the characteristic lengths when calculating the Reynolds number. So, D is A/T. wetted area to the top width. This will be very very frequently used in the upcoming you know topics or while solving the numericals. So, we have seen the type of you know the different type of flow properties mostly the type of basically the top width, area, cross section, parameter, hydraulic radius.

We have seen the different type of classification now we will see the properties of typical channel cross sections. So, you see, let us see if for example, this is a rectangle, this is a trapezoid and this is a triangle and this is a circular. Of course, we see that the water is filled up till the depth y. So, if you see this is if the width is B and this is the depth y here, the area is Boy, wetted parameter will be B_o plus y plus y that is B_o plus 2y here. Similarly, hydraulic radius you know that is the area divided by wetted parameter that is B_o y by divided by B_o plus 2y. Top width everybody can know this is B_o.

So, this will also be B_o and you can calculate the hydraulic depth D as well. It is the ratio of the area divided by the top width that will give us the hydraulic depth as y. This is very simple case of rectangular. Similarly, you can find for the trapezoid as well just going you see area will be this square plus half of each triangle.

So, it is B_o x y plus this complete triangle that is half in this particular area. So, it is B_o plus sy into y and weighted parameter will be this one. So, B_o and this is y. So, this is $1+\sqrt{1+S^2}$. So, this is $B_o + 2y$. and this will be the top width right that will be $V_o + 2Sy$.

This you have calculated and then rest of the things here hydraulic radius you can calculate from the formula and also the hydraulic depth you can calculate from formula and the same process you can do for triangular use the same process you can do for circular as well. Now, just having a small look about the velocity distribution, you know velocity distribution in open channels. So, this is a natural channel A, this is a rectangular channel and this is typical velocity profile. So, you see this figure you have already seen that at the bed is equal to 0. maximum velocity almost at the free surface, almost.

Of course, there is a maximum velocity is exactly at this point, but yeah. So, the velocity keeps on increasing as you go farther and farther away from bed because of the reduction in the frictional forces. And just to show you how does the you know in the natural channel, rectangular channel, how the velocity profile or distribution looks like. So, the presence of corners and boundaries and open channel causes velocity vectors of the flow to have components not only in the longitudinal and lateral direction, but also in the normal direction to the flow. Basically, what it means is because of the presence of corners and boundaries in open channel flow, the velocity would be 3 dimensional basically what it means.

So, in macro analysis one is concerned only with the major component but what see it could happen that in the y and z directions you know the velocity is you know very little. So, compared to one direction the other two directions it might not be that great. Let us say if the velocity in x direction is 10 meters per one let us say 2 meters per second and in that it is of the order of centimeters in other y and z direction then that means very simple. A simple means that we can neglect the small. So, here we are concerned with the major component that is the longitudinal component V_x.

The other two components being small which is normally the case are we ignore. and V_x is designated as V. The distribution of V in a channel is dependent on the geometry of the channel and the influence of the channel geometry is apparent. The velocity V is 0 at the solids boundaries which I have told you before at the bed for example, and gradually increases with the distance from the boundary. The maximum velocity of the cross section occurs at a certain distance below the free surface. Normally, it should occur in the free surface, but it happens just below the free surface.

This is due to the phenomenon which we will study in this course. This dip of the maximum velocity giving surface velocity which are less than the maximum velocity is due to secondary current. There is some phenomenon called secondary current which we will see and is a function of aspect ratio of the channel. So, this dip that we have seen here. So, you need not worry about this much, but because we will see in the later in the course that this is due to the dip current, the secondary current.

Thus, for a deep narrow channel the location of the maximum velocity point will be much lower from water surface than for a wider channel of the same depth. And this characteristic location of the maximum velocity point below the surface has nothing to do with the wind shear on the free surface, not to worry that much. A typical velocity profile at a section in a plane normal to the direction of the flow is presented in the previous figure. Now if we see the field observation in rivers and canals that has shown that the average velocity at any vertical AV occurs at a level of $0.6y_o$ from the free surface where the so you see there is if you see this right free surface let us say, this is 0, increases at the top, but you know there will be an average velocity.

So, this average velocity which is average is generally at $0.6y_o$, this is what it means. and it is also been found out. See these are observations from the experiments and field that the average velocity is the velocity at 0.2 distance from the free surface that is 20 percent below the free surface and 80 percent below the surface the average of those and which this velocity at the depth of $0.2y_o$ from the free surface and V 0.8 is the velocity at the depth of 0.8 y_o from the free surface. And this property of velocity distribution is commonly used in stream grazing. However, the surface velocity vs is related to the average velocity surface velocity means velocity at the free surface.

Again, these are only observations V average can be given as KVs right now, it is not that much of a concern, but just understand that the velocity average can be written as KVs where K is a constant. and changes for different conditions. So, K a coefficient with a value between 0.8 to 0.95 on what parameters does this K depends on the channel section and has to be determined by the field calibration. So, these are experimental and the field values we know K we can estimate the average velocity in an open channel by using floats and other surface velocity measuring devices. So, I think this is the end of our lecture number 2 for the first module.

I will see you in the lecture number 3. Thank you so much.