

Free Surface Flow
Dr. Mohammad Saud Afzal
Department of Civil Engineering
Indian Institute of Technology Kharagpur

Lecture 1

Welcome everyone. My name is Mohammad Saud Afzal. I am an Associate Professor at Department of Civil Engineering at Indian Institute of Technology, Kharagpur. So in this course, which is on free surface flow, I am going to teach you about the core concepts involved in free surface flow. This course is primarily meant for the advanced undergraduate level courses and also for the Masters and PhD level courses.

So now starting the free surface flows the first module and the first lecture. So what we are going to do we are going to start with the basic concepts. There are several important basic concepts from the course hydraulics which is sort of a pre you know this particular course hydraulics is a prerequisite for this course. It would be very nice if somebody has already studied that course and it is one of the compulsory courses. during your undergraduate in civil engineering.

And but nevertheless, to make the course complete, we will start with the introduction to basic concepts. The first question comes to our mind is what is a free surface flow? So as everybody knows, and I know you would be knowing from your bachelor's days or your hydraulics course, that liquids are transported from one location to another using natural or constructed conveyance structures. That structures could be anything, right. Natural could be canals, the manmade could be pipes, and there are different other things.

So the cross section of these structures, may be open or closed at the top. So, the structures which have a closed top, so that means that is not exposed to the atmosphere are referred to as closed conduits and those with the top open are called open channel. So that means open channel exposed to the atmosphere. For example, here tunnels and pipes are closed conduits, whereas rivers, streams, estuaries, even the open canal, they are open channels.

So, the flow in an open channel or in a closed conduit having a free surface is referred to as free surface flow or open channel flow. So, the prerequisite of free surface flow, it should be in an open channel. It could be also in a closed conduit, but the important condition is that there should be a free surface. For example, a pipe with having water half filled. and open it both side.

So, these type of flow could be referred as free surface flow or open channel flow. Now let us see some of the interesting cases which are given below. You see there are four figures, one to the left, then to the right, then the left at the bottom and right. You see one is ocean, one is river flowing, there is one. stepped spillways There are dams, there are canals.

So, these are the different figures that I am showing. Now, what is the observation that can be made from these images? So, there is one common observation is that all of these figures have a free surface. Free surface that means they are subjected to the atmospheric pressure. So, in case of ocean, as you would see, ocean, although there are waves and other things, but again, the top of the ocean is exposed to the atmospheric pressure.

So, if you measure the pressure at the top, it will be atmospheric pressure. Same is with the rivers, canals, basically big, so water at the, you know, the water that is near the dams and also in the stepped spillway. So, the free surface, what is a free surface? It is an interface between the moving liquid and an overlying fluid medium and will have a constant pressure. So, in Civil Engineering applications water is the most common liquid with air at the atmospheric pressure as the overlying fluid.

So, in case of Mechanical Engineering another field there we could have you know different fluids, but in Civil Engineering 95 percent of the cases we deal with the flow of water in hydraulics and water resources. In that cases, the first liquid is the water and above it is the air. Air is also a fluid, right? So, the below is water and the top is air at atmospheric pressure as the overlying fluid. Now, what is the motivating force or what is the driving force for an open channel flow?

So, the primary motivating force for an open channel flow is gravity. However, there could be other forces as well that does not mean that we cannot classify that as open

channel flow, but primarily in 95 percent of the cases that is the main you will find conditions where you will have both pressure gradient and gravity acting and that flow would be called as pipe flow or open channel flow. There will be cases, but in general that is the most important definition. Now, that being said, we should see some of the examples of open channels.

So, examples could be the flow in natural rivers. So, the rivers that is near your you know wherever you encounter them in near the big cities or you know in your even in your village. Streams and rivers that is very common near the villages. Also, the flows in artificial you know channels that is the manmade canals and what is the use of those canals that transmits water from a source. Source means that source could be river as well to a place of need such as for irrigation that is so a canal is generally built to transport water from a big source to the place where it is needed most.

In our Indian scenario we mostly use it for irrigation channels. Also, this can also help us in water supply for example, in IIT system the water is supplied from our source to the campus through may be a canal or even some case the pipe. So, that case also that is also an artificially manmade structure. Also, one of the examples of open channel flow can be found in hydropower generations. And one of the other examples are the sewers, sewers that carry domestic or industrial waste waters.

And the last, but it is not an exhaustive list, you can find many other examples, but navigation channels. Navigation channels are the channel where the ship moves or the boat moves for the sake of the navigation. So, some good examples of these are open channel. Now, it is evident that the size, shape and roughness of open channel would vary across a sizable range and covering a few orders of magnitude. So, depending if you are in the river or in the canal or in a very, you know, maybe even if you are in a lab in open channel flow. So, these sizes, shape and also the roughness, roughness of the bed element would vary. In some cases, the length would be like in meters, sometimes the canals could be in kilometers, sometimes in 100 of meters. So, the point of saying here is that it can be few orders of magnitude. So, basically,

One common thing is that all the open channel will have a bottom slope and a mechanism of flow is akin to the movement of the mass down an inclined plane due to gravity. So, important thing is for open channel there should be a bottom slope and because of which due to gravity an inclined plane motion happens and the water moves. This, I mean the component of weight of the liquid along the slope act as a driving force. So, that is basically gravity " mg " if you see the angle if one of the components of the weight among the " $mg \cos \theta$ " would be the driving force. So, basically instead of saying the weight we say gravity.

So, if you see this is how the profile peak view of basic open channel flow looks like. You see there is a water surface at the top and just for the sake of showing the our bottom we have given this angle. However, this slope is very very small. So, maybe 1 in 20 would be even too much, 1 in 40, 1 in 80, 1 in 100 actually that is the normal. But even that component of 1 in 100 is enough to give us weight or gravity component so that the open channel will flow.

So, we see from the datum up till the distance z is the level of the bottom and from there the depth is y that is parallel to the channel bottom. and the water is flowing with the velocity v and the angle is θ and the x is in the, there is a positive x direction. So, as I said earlier, this figure presents a longitudinal view of flow in an open channel and the figure shows many of the basic quantities that govern which I have already described just now. And the flow depth y is the most important quantity when approaching problems in open channel flow. One thing you should remember this course open channel flow apart from being you know theoretical 50 percent of the time we are going to dedicate in problem solving.

So, when we approach the problem solving in open channel flow the most one of the most important parameter is the flow depth and depth is measured in the vertical plane from the channel bottom to the water surface. So, it is the depth is measured from the channel bottom all the time. So, again, so the flow velocity v is also of primary importance by for solving the open channel flow problems. So, in reality, what will happen is the velocity will vary in the vertical from essentially 0 at the channel bottom to

generally a maximum value at or near the water surface. So, this is what the velocity v we have showed is an average velocity that we have shown.

In reality what is going to happen that due to the no slip condition the velocity will be 0 at the bed and maximum at the free surface and therefore we will have the average velocity if we do the area averaging. We will see some problems also in that regards later. So, not just the vertical velocity also varies across the width of the channel in potentially very complex ways depending upon the channel shape. So, velocity could vary in x direction, it could vary in y direction, it could vary in z direction as well. Now, this figure shows the cross sectional view of the basic open channel flow in all then showing all the quantities.

For example, like the velocity, the channel cross section is potentially quite complex in shape. It should be apparent that the cross sectional area of the channel that is this area A , this area A is dependent on the flow depth y . More than anything else, this observation is what distinguishes channel flow from flow in a closed conduit. So, the quantities like discharge Q , the area A , the Y and the Z and datum just to tell you that apart from the longitudinal view, the one of the most important view or you know the way that we are going to solve the problem or tackle the problem at hand will also to consider the cross sectional view of the basic open channel. So, in a closed conduit what happens is like one of the examples of closed conduit is pipes.

So, as so, when a pipe is flowing full the cross sectional area is fixed and constant right. Thus the physics of the flow are constrained largely to understanding the flow velocity issues of friction and of total energy possessed by the flow. This is what happens in closed conduits and this is not this is also partially true for open channel as well, but in closed conduit since it is full the cross sectional area is constant right, but in open channel flow it would vary depending upon the depth of the water. So, things will largely depend on the cross sectional view of the basic open channel flow and that is the main content of this particular slide. So, again showing the cross sectional view.

So, in open channel flow the depth plays a dual role. What are the dual roles? Firstly, it controls the energy possessed by the flow right and secondly it determines the cross

sectional area of the flowing volume and this is the challenge of solving open channel flow problems. First energy which is dependent on the water depth, also the cross sectional area. We will see that in more detail when we go ahead and also solve the problems related to the open channel flow.

So, I have been you know talking a lot about open channel flow, correct, but I have also mentioned several times about pipe flow. So, as a student of free surface flow or even previously hydraulics one of the important concepts to understand and revise beforehand going to the advanced topics of free surface flows to understand the difference between open channel flow and pipe flow. So, you see there are two figures here to the left we are showing the pipe flow right and this the right hand side we are showing the open channel flow and we have drawn different energy line hydraulic grade line center of center line of pipe, but in open channel flow we show the energy line water surface channel bottom. So, the flow in conduit may be either open channel flow or pipe flow. The two kinds of flow are similar in many ways, but different in one important aspect that we are going to see.

So, the open channel flow must have a free surface, that is important, whereas pipe flow has none. So, pipe flow has no free surface, open channel flow must have a free surface. Since in pipe, the water must fill the whole conduit, otherwise it will be referred to as open channel flow. Now, another thing is a free surface is subject to atmospheric pressure. However, pipe flow being confined in a closed conduit exerts no direct atmospheric pressure but hydraulic pressure.

I mean, so the flow in a pipe flow is guided mainly by the pressure gradient. So, the total energy in the flow of the section with reference to the datum line is the sum of elevation. Z of the pipe center line. So, when we consider the pipe flow, we use the Bernoulli's equation and try to estimate. One is, it is the sum of the elevation Z of the pipe center, the piezometric height y and also the velocity head $\frac{v^2}{2g}$, where v is the mean velocity of flow.

and the energy is represented by what is called the energy grade line or simply the energy line. You see in the this diagram on the left hand side pipe flow, we have called the

energy line, energy grade line or simply energy line. And you can also see that this the z_2 , y_2 and $\frac{v_2^2}{2g}$ in the left hand side that is the pipe flow. So, the loss of energy that results when water flows from section 1 to 2. So, you again consider this particular figure on the left hand side that is the pipe flow, between 1 and 2, 1 is one cross section and second is the another cross section and the water is flowing from this one to the other. So, it is obvious and that there will be energy loss when water flows from one point to the other. And, this loss is represented by h_f , f refers to frictional loss. So, h_f and hf signifies the energy loss due to friction when water flows from one point to the other. So, as of now you see in the left hand side pipe flow z_2 is the datum, y_2 is the hydraulic grade line $\frac{v_2^2}{2g}$ is the velocity head and this is the energy line. However, we also try to demonstrate h_f which is the energy loss. Now, we have a similar diagram for open channel flow on the right hand side. For simplicity, it is assumed that the flow is parallel and has a uniform velocity distribution and that has a slope of the channel is very small. So, to make things easier, we are just assuming that it is a simple flow and it is a simple parallel flow and the uniform velocity.

In reality, the velocity might not be uniform. That means the velocity might be varying at different points and in different times. However, just for assumption of this particular case, we assume that the velocity is uniform. So, when we assume when we have this assumption, the water surface is the hydraulic grade line and the depth of the water corresponds to the piezometric height. That being said, we saw the difference between open channel flow and pipe flow.

Now, since we are going to study open channel flow, we are going to see what are the different types of channels that we are going to cover in this particular course. So, when we talk about channels, two terms comes to our mind. One is prismatic and the other is non-prismatic channels. What is the difference? So, a channel in which the cross-sectional shape and size and also the bottom slope are constant is termed as prismatic channels.

Basically, a constant size, bottom slope and shape will be termed as prismatic channel. And what will be a non-prismatic channel is opposite of that. However, before going to that, we see some examples. So, most of the manmade, that is the artificial channels are prismatic because that has been created by us. So, we try to make it prismatic with constant slope, with constant shape and size.

And these channels are over a longer stretch, several kilometers. The rectangle, trapezoidal, triangle and circle are some of the commonly used shapes in man-made channels. All natural channels generally have a varying cross sectional area and consequently are non prismatic. So, as I said the opposite of prismatic is non prismatic. So, any cross section or you know, any type of channel that have either one or all of these shape as not constant will become will be termed as non prismatic.

Rigid and Mobile boundary channels. Another classification apart from prismatic and non-prismatic are rigid and mobile boundary channels. What are rigid channels? Rigid channels are those in which the boundary is not deformable. So, the bed is not deformable, the walls are not deformable.

And, in which sense is that that the shape plan form and roughness magnitudes are not function of flow parameters when we talk about maths and physics. So, the you know shape is not going to change roughness magnitude they will never not depend on how slow or fast the water is flowing. Or any other parameter even the turbulence and some of the examples are lined canals because that is also manmade, right, sewers and non-erodible unlined channels. So mobile boundary channel. So, in mobile boundary channels the boundaries undergo deformation that is important and what is the reason that is due to the continuous process of erosion and deposition due to the flow.

So, you might have studied in hydraulics then when the water flows on the sediment bed or any type of bed. Because of the velocity, it exerts shear stress on the bed. And if that shear stress is strong enough to dislodge that particular particle or the grains from the bed, it will and this will cause the process of erosion. And a little bit further when the velocity slows down that particular sediment grain or set of sediment grains will deposit further downstream and that process will call deposition. So, if these mobile boundary

channels they undergo deformation and the reason is erosion and deposition and that happens because of the flow velocity.

So, the boundary of the channel is mobile in such cases and the flow carries considerable amount of sediment through suspension and in contact with bed. What this means is in this mobile boundary channel, there will be majorly two type of sediment loads, one will be the one that is moving along the bed that we will know as bed load transport and the second is when the particles are dislodged from the bed and are in suspension that is the suspension or the suspended load. So, we talked about two types of channels, prismatic, non-prismatic. We talked about rigid bed or channel and also non rigid or mobile boundary beds.

Now, another type of classification that we are going to see is about the classification of flows that the water that is flowing, how those can be classified. You see these open channel flow can be classified in mainly in steady and unsteady flow. And among steady you see the flow can be we are going to see more details about each of these uniform what is gradually varied, what is rapidly varied and what is spatially varied when it comes to steady flow. In unsteady flow, there will be nothing called uniform unsteady flow that cannot happen. So, we have three, gradually varied flow, rapidly varied flow and spatially varied flow.

So, in this particular course, this is what we are going to see in lot and lot of detail, spread over these 12 weeks. So, now coming to each type of classification is steady and unsteady flows. So, what is a steady flow? A steady flow occurs when the flow properties such as the depth or discharge at a section do not change with time or very simply being put said that if the flow properties are not changing with time.

Then this that type of flow is called steady flow. These flow properties can be anything, velocity, flow depth and other things, right? So, at time t is equal to 0, if the velocity was 1 meters per second and at time t is equal to 10 second, And on further times, it is still 10 meters per second, the depth has not changed or any of these properties have not changed. Then that is steady flow.

It is important that none of these properties should change for steady flow. It is not that the depth is allowed to change and velocity not, no. That will not be steady flow. So, with respect to time, no property is allowed to change in steady flow. And then the opposite is if the depth or discharge changes with time, the flow is termed as unsteady.

In nature, most of the flows are unsteady in nature, right? So this is one of the classification. The other classification is, so this is with regards to time. So, now we are going to see classification of flows based on the space and that that gives us 2 types of flows: uniform flows and non uniform flows. So, what is the uniform flow if the flow properties.

The flow properties are, for example, the depth of the flow, the velocity of the flow, as I talked before, if these flow properties remain constant along the length of the channel. So the velocity, depth and other flow parameters, if they do not change with space, for example, if there is a canal. and 5 kilo let us say that is 1 kilometer long and at let us say 200 meter from the beginning, we do measurement and at let us say 400 meter we do measurement and at 600. If the velocities and water depth and other parameters are same at all these locations, then that means that type of flow is said to be uniform flow. So, just repeating when the flow properties do not change with space that is called uniform flow and opposite if the flow properties would change if either one or all of the properties are changing with space that is called non-uniform flow or varied flow that is an important difference and most of the courses based on these distinctions.

One question to you as one of the potential students and also you know that the student that are undergoing this course is, is unsteady uniform flow practically possible in natural open channels? Unsteady uniform flow, right? What would be the answer? have a thought about like 2 seconds. So, what is going to happen?

The answer is a big no. And the reason is unsteady means first of all that the velocity is or the another flow parameters are changing in time. So, that means it is changing. So, it would it is obviously implied that for a uniform flow For uniform flow, none of these property should change in space, but since it is changing in time, it will definitely change in space.

And therefore, unsteady uniform flow is practically not possible. And therefore, you see when I did the classification two slides back. I did not include in among the unsteady flow as a non-uniform unsteady flow. So, in among steady there were four classifications uniform, gradually varied GVF, rapidly varied RVF and spatially varied SVF. And in unsteady only three that is gradually varied, rapidly varied and spatially varied.

So, let me go back. So, I think this is a nice point to stop for this 30 minutes lecture and in the lecture number 2, we are going to start our gradually varied flow. Thank you.