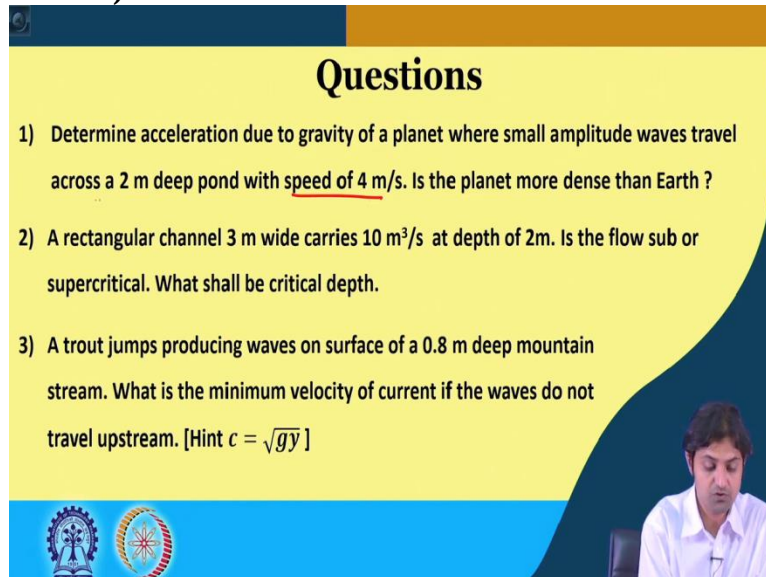


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Lecture-30
Introduction to Open Channel Flow and Uniform Flow (Contd.,)

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Questions

- 1) Determine acceleration due to gravity of a planet where small amplitude waves travel across a 2 m deep pond with speed of 4 m/s. Is the planet more dense than Earth ?
- 2) A rectangular channel 3 m wide carries $10 \text{ m}^3/\text{s}$ at depth of 2m. Is the flow sub or supercritical. What shall be critical depth.
- 3) A trout jumps producing waves on surface of a 0.8 m deep mountain stream. What is the minimum velocity of current if the waves do not travel upstream. [Hint $c = \sqrt{gy}$]

Welcome back. In the last class, we stopped the lecture by looking at the questions. So, there were 3 questions that we have to solve. And we start this lecture by going to solve these questions, you know. So, the first question, again just going back is, determine the acceleration due to gravity of a planet where small amplitude waves travel across a 2 meter deep pond with speed of 4 meters per second. So, you know, so the speed of the wave is given, c is given and we have also been given the depth.

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Answers: 1) $V = \sqrt{gy}$ $V^2 = gy$ $g = \frac{V^2}{y} = \frac{4^2}{2} = \frac{16}{2} = 8 \text{ m/s}^2$

2) $Q = AV$ $V = \frac{Q}{A} = \frac{10}{3 \times 2} = 1.66$ $F_r = \frac{V}{\sqrt{gy}} = \frac{1.66}{\sqrt{9.8 \times 2}} = 0.376$

$F_r < 1$ Flow is sub critical

For critical depth $F_r = \frac{V}{\sqrt{gy}} = 1$ $\frac{1.66}{\sqrt{9.8 \times y}} = 1$ $y = 0.281 \text{ m}$

3) $c = \sqrt{gy} = \sqrt{9.8 \times 0.8} = 2.8 \text{ m/s}$ → Answer

V > 2.8 m/s → flow won't travel upstream



So, the way it is solved is, the first question, we know, V or c is equal to under root gy. So, V square can be written as g into y, squaring both side. Therefore, if we want to find out g, it will be V square / y, V or c. So, V was given as 4 meters per second and y was given as 2. So, this gives us an acceleration of 8 meters per second squared. Of course, the density, there are many other things that the density depends upon but if they say the acceleration due to gravity is less than 10 it should be less dense than the earth, I mean, very crude approximation.

This is not a very clear answer, but more importantly finding out this acceleration due to gravity was important. Second question, it has told us to ask, it has asked us to find out the flow regime. So, we know that Q is given by area into velocity. Therefore, the we have been given the discharge; we have been given the area. So, area is 3 into 2 and the Q was given as 10. If you go and look, go back and look at the problem, it says that the rectangular 3 meter wide, so this was the width, carries 10 meter cube, so this was discharge, at the depth of 2 meter, this was d.

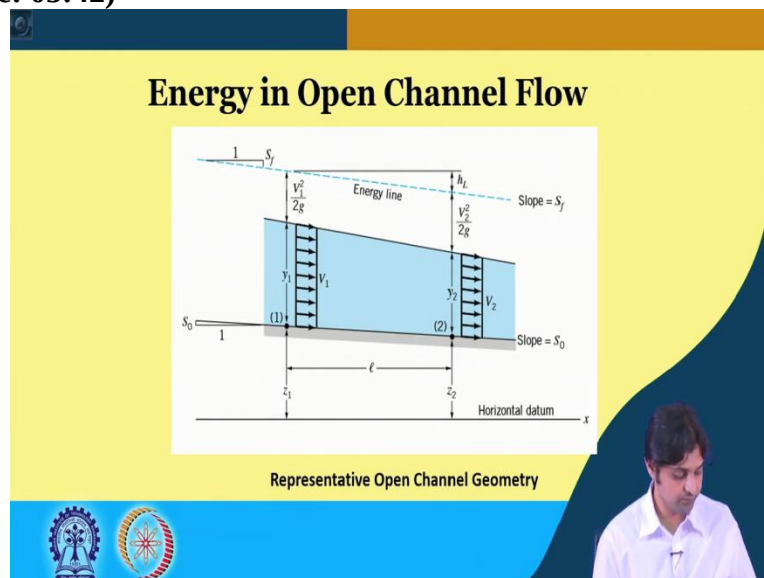
Now, if this is asking if the flow is subcritical, supercritical. So, Froude number is given by V under root gy. So, V we have already found out using the discharge, it was 1.66 from here, g is 9.8 and depth is given as 2 in the question itself. So, this comes out to be 0.376, which means Froude number is less than 1 and therefore, the flow is subcritical, very simple to solve. Now, going, so and the second part was it we have to find out critical depth for the same flow condition.

So, see the same flow conditions is there V is not going to change. The only thing that we can change is y . And for the critical depth Froude number has changed from 0.376 to 1, therefore y will change. So, if we use this equation, $V / \sqrt{gy}$ is equal to 1, therefore substituting V will remain same 1.66, g is 9.8 and y we have to find out. Using this equation we can find out y is 0.281 meter so it has to be less shallow. Earlier the depth was 2 meter, here we have to make it 0.28 meters.

So, before starting the third question we should now revise. I mean just relook what the third question is. It says that the trout jumps producing waves on surface of a 0.8 meter deep mountain stream. What is the minimum velocity of current if the waves do not travels upstream? So, just going back, so what I am going to do, so basically, there is a velocity V of a stream and there is speed c of wave.

So, we have to find V , such that, it is greater than c . So, first half I will find out the speed of the wave which is dependent only on depth. Depth is given 0.8 meter. So, this comes out to be 2.8 meters per second. So, if the stream speed is greater than 2.8 meters per second, this means the trout would not travel upstream. So, that is the answer.

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So, now, starting with a brand new sub topic here. What is the total energy in open channel flow? So, coming back from classification of open channel flow to the development of surface solitary waves due to a disturbance because free surface can distort, we are going to see what the energy

in open channel flow is. Here, we have assumed, I am going to go into more detail but first try to explain you a figure.

So, this is the horizontal datum, this is any level and our channel is like this, you know, and the bed slope. So, all the surfaces in the world might not be horizontal, it could be at a very small angle to the horizontal and let us say that small angle slope of the channel is let us say S not will be a very small value but anyways to be able to consider there is a slope S not. If at cross section 1, the depth of the flow is y_1 and the velocity here is V_1 and at section 2, the depth is y_2 and the velocity is V_2 .

We have indicated what the, you know, because of speed V_1 , this is the energy line and other stuff, you know, $V_1^2 / 2g$, $V_2^2 / 2g$, you know. And this is the total head and if going from one point to the other point, the head loss is at h_L . We will come to these terms again and this is something S_f that we will come back to again what this slope S_f is. S_f is generally the slope of the energy that is lost. But that we are going to come very soon now. So, this is actually a representative open channel geometry.

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Energy in Open Channel Flow

- 1) The slope of the channel Bottom $S_0 = (z_1 - z_2) / l$ is assumed constant over length l .
Quite small
- 2) Fluid depths at two cross section are y_1 and y_2
- 3) Fluid velocities are V_1 and V_2 at two cross sections
- 4) Under assumption of uniform velocity profile across any cross section, 1 D energy equation for this flow is

$$\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1 = \frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2 + h_L$$

Handwritten red annotations: "Energy at section 1" with an arrow pointing to the first term of the left side, and "Energy at section 2" with an arrow pointing to the first two terms of the right side.

So, going back again, I was saying that all the channel will have a small slope. So, the slope of the channel bottom S_0 can be actually found out. How? If the height of this particular point is z_2 and this is z_1 , then S_0 will be $z_1 - z_2$ and if this is the length of the channel that we have considered, it will be $z_1 - z_2 / l$. And we assume that the slope of this channel S_0 is assumed

constant over this entire length and this actually is very small S_0 . As I said the fluid depth at 2 cross sections are y_1 and y_2 . The fluid velocities are V_1 and V_2 at 2 cross sections.

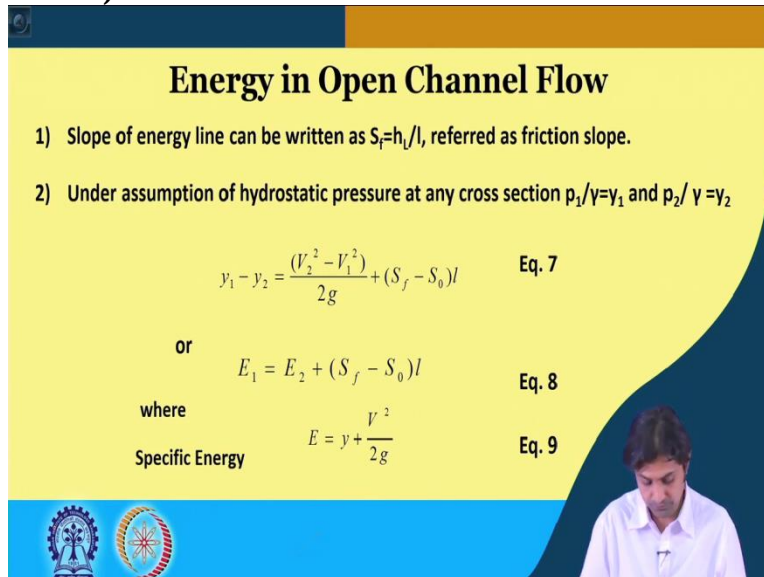
Under the assumption of uniform velocity profile across any cross section, we assume that the velocity profile is uniform and not like the boundary layer that we have seen in our previous week's lectures. So, under the assumption of uniform velocity profile across any section one

dimensional energy equation for the flow is we say that $\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1$, this is energy at section 1

is equal to $\frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2 + h_L$.

So, if we assume, if there is a head loss h_L , then this is if we account for energy loss then our energy should be conserved. If we know how much energy has been lost and we add it to the system, so this is energy at section 2.

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Energy in Open Channel Flow

- 1) Slope of energy line can be written as $S_f = h_L / l$, referred as friction slope.
- 2) Under assumption of hydrostatic pressure at any cross section $p_1 / \gamma = y_1$ and $p_2 / \gamma = y_2$

$$y_1 - y_2 = \frac{(V_2^2 - V_1^2)}{2g} + (S_f - S_0)l \quad \text{Eq. 7}$$

or

$$E_1 = E_2 + (S_f - S_0)l \quad \text{Eq. 8}$$

where

Specific Energy $E = y + \frac{V^2}{2g} \quad \text{Eq. 9}$

Actually, this is another way of writing, we can also write the slope of energy line. So, we had said that if h_L is the head loss or energy loss, from going from point 1 to point 2, and if we divide it by length L , we can also write is, write it in terms of slope. So, if we say, S_f is the slope of then we say it as h_L / L . where L is the length of the channel in the consideration and this is called friction slope. So, under the assumption of hydrostatic pressure at any cross section, if we assume hydrostatic pressure, p_1 / γ can be written as y_1 , under hydrostatic.

And $\frac{p_2}{\gamma}$ is written as y_2 . So, under this one and this one our energy equation from this changes to, so $\frac{p_1}{\gamma}$, this is $\frac{p_1}{\gamma}$, this is $\frac{p_2}{\gamma}$, V_1 was on this side on the left hand side while going it becomes negative on the right hand side and same, the same about S_0 . Because, okay, I think I should go back here and try to do this on the slide. It would be much more easier. So, p_1 / γ was y_1 . This is y_2 . So, $\frac{p_1}{\gamma}$, see I am writing the left hand side, it is becoming y_1 .

And we bring this one on this side, the $p \frac{p_2}{\gamma}$ on the other side becomes $y_1 - y_2$. Let us concentrate, we also write $(V_2^2 - V_1^2)$. So, V_1 we have brought on this side $+ z_2 - z_1 + h_L$. So, I am writing $y_1 - y_2$ is equal to $(V_2^2 - V_1^2) / 2g$, $z_2 - z_1$. So, you remember what this is, $z_1 - z_2$ was S_0 . So, it becomes minus of $S_0 l$ and h_L is S_f into L . So, it becomes $y_1 - y_2$ is equal to $\frac{(V_2^2 - V_1^2)}{2g} + (S_f - S_0)l$, same as given in the next slide. This is the equation, simplified equation that we get.

And this we call as equation number 7 or in other words we can say, so at energy at 1, energy grade line at 1 is E_1 , which is $y_1 + V_1^2 / 2g$ and on the right hand side E_2 , so if we say E_1 is equal to $y_1 + V_1^2 / 2g$ and E_2 is $y_2 + V_2^2 / 2g$, then we get E_1 is equal to $E_2 + S_f - S_0$ into L . Equation at where E is a specific energy. What is this E ? We call E as specific energy, which is given by $y + V^2 / 2g$ at any point. You know, at any point where the specific energy is given by $y + V^2 / 2g$.

So, this is a new concept called specific energy to which you have been introduced now. It is the sum of the depth. So, the depth and the kinetic energy head. And this is equation number 9 that we are talking about.

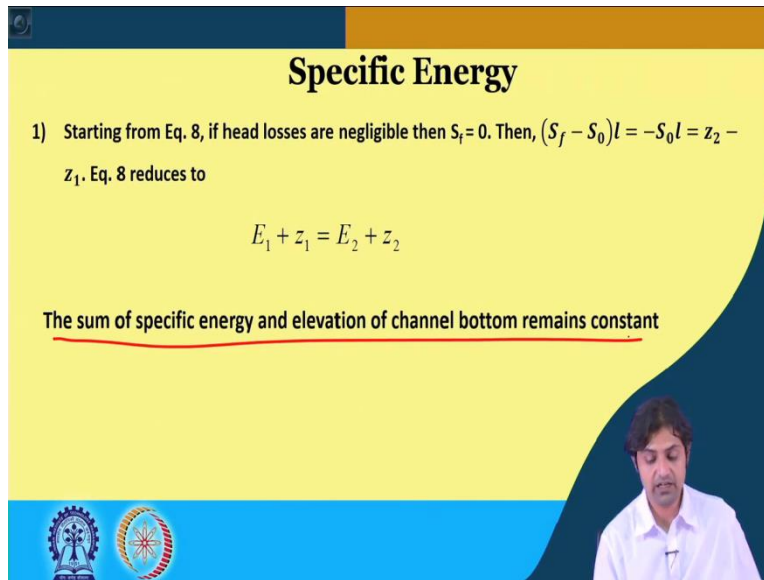
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Specific Energy

1) Starting from Eq. 8, if head losses are negligible then $S_f = 0$. Then, $(S_f - S_0)L = -S_0L = z_2 - z_1$. Eq. 8 reduces to

$$E_1 + z_1 = E_2 + z_2$$

The sum of specific energy and elevation of channel bottom remains constant



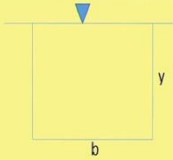
So, going to, I mean, more detail into specific energy if we start from equation number 8. What was equation number 8? It is E_1 is equal to $E_2 + S_f - S_0$ into L . If head losses are negligible, then S_f is equal to 0 that is true, then $S_f - S_0$ in that will become minus S_0 into L or $z_2 - z_1$ c. Then equation 8 can be written as $E_1 + z_1 = E_2 + z_2$. How? We are we I will just show you, it is better to show. So, equation number 8, if S_f is 0, and S_0 is given as z_2 minus, $z_1 - z_2 / L$.

So, E_1 is equal to $E_2 + - S_0$ into L and S_0 is given as $z_1 - z_2 / L$. So, $S_0 L$, so E_1 is equal to $E_2 +$ minus of $z_1 - z_2$. So, E_1 is equal to $E_2 - z_1 + z_2$ and if you bring z_1 on this side, it becomes $E_1 + z_1$ is equal to $E_2 + z_2$. So, this is the result that we have got, which indicates that the sum of specific energy and the elevation of the channel bottom remains constant, if the head losses are negligible in a frictionless case.

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Specific Energy

1) Consider a rectangular channel with constant width b



$$q = Q/b = Vy b/b = Vy$$

- Eq. 9 can be written as

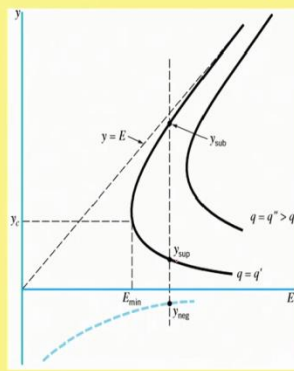
$$E = y + \frac{q^2}{2gy^2} \quad \text{Eq. 10}$$

Now, for the specific energy, we consider a rectangular channel with a constant width of b , something like this and having height y . So, q is going to be Q/b discharge per unit width, Q is given by velocity into y into b . So, q is going to be V is the velocity into the depth. Now, using this equation 9. What was equation 9? So, equation 9 was E is equal to $y + V^2 / 2g$. And if we use this thing in equation number 9, y will remain y and instead of V we write q/y . So, we can write $q^2 / 2gy^2$.

So, in terms of y and q , we have written E is equal to $y + q^2 / 2gy^2$. If you see, this is a cubic equation in y , anyways, we will come to it and this is written as equation number 10.

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Specific Energy



- For a given q and E , Eq. 10 is a cubic equation
- 3 Solutions: y_{sup} , y_{sub} , y_{neg}
- y_{neg} has no physical meaning
- y_{sup} and y_{sub} are termed alternate depths

MCQ

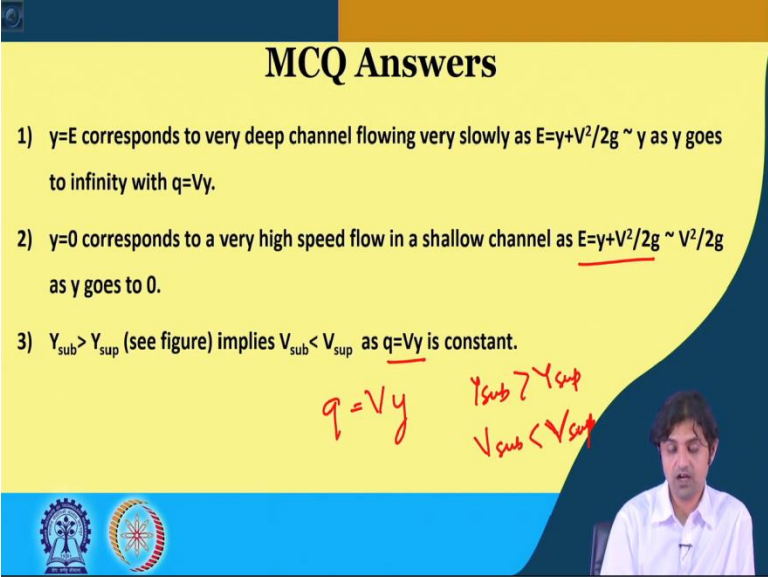
- What does $Y=E$ represent ?
- What does $y=0$ represent ?
- Prove $y_{sup} < y_{sub}$

So, for this particular case, if our equation number 10, if we plot equation number 10, this is the type of curve that we get. Where, E specific energy has been plotted against y, for specific q. So, we have fixed the q and try to plot E as a function of y, and this is what we get, we are going to go on it one by one. So, for a given Q and E, so if we choose a q and E equation 10 is a cubic equation in y, so for that there are going to be 3 solutions. y super, y sup, y sub and y negative.

So, if you take on one curve, there is will be 3 y. This will be 1, this will be 2 and this will be 3. So, actually y negative because this is negative y, this will have no physical meaning, y negative will have no physical meaning, y sup and y sub are termed as alternate depth. So, this one and this one are actually called alternate depths. Because it is cubic equation we get 3. One is not possible and the 2 are called the alternate depth.

Do not worry about sup and sub and negative for now. Now, my question to you is, I have some question. What does this line represent, y is equal to E? Secondly, what does y is equal to 0 represent? Where is y is equal to 0? y remains 0 all the time, so this is the line on E axis and we also have to prove that y sub is greater than y sup. Of course, we can see this, but we have to show.

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MCQ Answers

- 1) $y=E$ corresponds to very deep channel flowing very slowly as $E=y+V^2/2g \sim y$ as y goes to infinity with $q=Vy$.
- 2) $y=0$ corresponds to a very high speed flow in a shallow channel as $E=y+V^2/2g \sim V^2/2g$ as y goes to 0.
- 3) $y_{sub} > y_{sup}$ (see figure) implies $V_{sub} < V_{sup}$ as $q=Vy$ is constant.

Handwritten notes on the slide:

- $q = Vy$
- $y_{sub} > y_{sup}$
- $V_{sub} < V_{sup}$

So, the answer is y is equal to E corresponds to a very deep channel flowing very slowly. Why? Because E is written as $y + V^2 / 2g$ and this will go to y, as y goes to infinity, because, you know, in a deep channel y is very deep. Secondly, y is equal to 0 corresponds to a very high

speed flow in a shallow channel, because if you see, E is given as $y + V^2 / 2g$, because in a shallow channel this term will turn out to be $V^2 / 2g$, as y goes to 0.

And the third is y_{sub} is greater than $y_{supercritical}$, see the figure, because this implies that velocity of supercritical is greater than velocity or subcritical as q is equal to Vy is constant. So, q is given as V into y . So, from the figure, we can see that y_{sub} , if y_{sub} is greater than y_{sup} , you know, then V_{sub} has to be less than, because q is equal to Vy is constant, I mean, it is constant.

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Class Question

➤ In Specific Energy diagram

- Determine y_c in terms of q
- Determine E_{min} in terms of y_c
- Determine V_c
- Determine Fr_c

* Note: subscript c denotes critical condition (at E_{min})

Now, the class question is, in specific energy diagram, determine y_c in terms of q , also determine E_{min} in terms of y_c and determine V_c , determine Froude number. So, we are let us go and see what E_{min} and those things on the diagram is. So, this is the diagram this is energy minimum. This is y_c critical, so this should correspond to critical flow depth, this is y is equal to E and things like that.

So, we are going to solve this question. Look at the question once again. So, determine y_c in terms of q , determine E_{min} in terms of y_c , determine V_c , determine Froude number at critical depth, so everything is about critical depth.

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Answer

$$E = y + \frac{q^2}{2gy^2} \quad \text{Eq. P1}$$

- To obtain $E_{\min}$, set $dE/dy=0$

$$\frac{dE}{dy} = 1 - \frac{q^2}{gy^3} = 0 \quad \text{Eq. P2}$$

$$y_c = \left(\frac{q^2}{g}\right)^{\frac{1}{3}}$$

- subscript c denotes conditions at $E_{\min}$



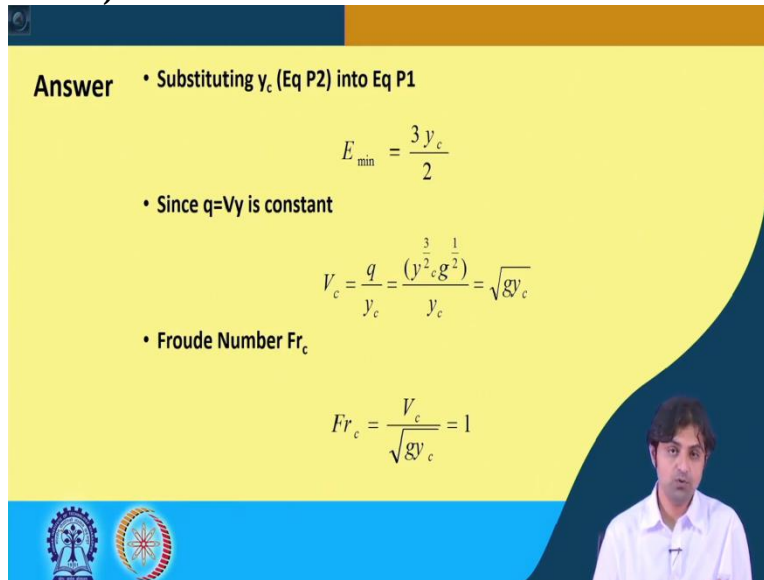
So, then we start with the equation that we already know. So, we know this equation, E is equal to $y + q^2$ divided by $2gy^2$. This is equation number 1. Now, if we want to obtain $E_{\min}$ we have to set dE/dy is equal to 0. And if we set dE/dy is equal to 0 then it becomes $1 - q^2 / 2gy^3$, something like that, or $1 - q^2 / gy^3$ is equal to 0. I will take down this. So, dE/dy is $1 - q^2 / gy^3$ is equal to 0.

So, to solve this, and this will give the corresponding y that is going to come from this equation is going to give us y_{critical} . So, we can write q^2 is equal gy^3 . So, that means, y^3 is g , sorry, y^3 can be written as q^2 / g . That means y is given as q^2 / g to the power $1/3$ and because it is critical, we write at critical. So, that is y_c . So, that is the first thing that we obtain, y_c in terms of q , this is equation 2.

Subscript c here, denotes conditions at $E_{\min}$. At $E_{\min}$ we say critical condition. Now, if you substitute y_c into equation number 2, so if you substitute y_c in equation number 2. Sorry, y_c in equation number 1. So, E will be $y_c + q^2 / 2g$ and now, y_c we have got q to the power $2/3$ into g to the power $1/3$. No, we can actually use the value of q^2 . Sorry, erase all ink.

So, we can use E is equal to $y_c + q^2$ can be written as gy_c^3 divided by $2gy_c^2$. So, g and g will get cancelled, y_c^3 will get cancelled with square. So, E will be $y_c + y_c / 2$. That is $3y_c / 2$ and let us see our solution at the back, $3y_c / 2$.

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Answer

- Substituting y_c (Eq P2) into Eq P1

$$E_{\min} = \frac{3y_c}{2}$$

- Since $q=Vy$ is constant

$$V_c = \frac{q}{y_c} = \frac{(y_c^{\frac{3}{2}} g^{\frac{1}{2}})}{y_c} = \sqrt{gy_c}$$

- Froude Number Fr_c

$$Fr_c = \frac{V_c}{\sqrt{gy_c}} = 1$$

So, $E_{\min}$ is going to be $3y_c / 2$ and since q is equal to Vy is constant we can obtain V_c . So, this is going to be q , we already know in terms of y_c and g . So, we are going to get at critical under root gy_c , which we already know at Froude number is equal to 1, Fr_c is equal to, now Froude number is $V_c / \text{under root } gy_c$, so that is going to be 1, but anyways, we will calculate. So, Froude numbers it is coming to be 1. So, actually we have only looking at the curve without assuming that it was already a critical flow, you know, we have derived this.

So, Froude number at this particular point came out to be 1. So, this is the point where the flow regimes are separated, I will just go back to this. So, we have calculated this just looking at by plotting the figure, you know, that is why this was subcritical and this was super critical. There will be a similar curve like this here as well, there will be a negative here, there will be a sub here, sup and $E_{\min}$. So, for each q this is a different case.

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Class Question

A rectangular channel has a width of 2 m and carries a discharge of $6 \text{ m}^3/\text{s}$ at a depth of 0.20 m. Calculate critical depth and Specific energy at critical depth

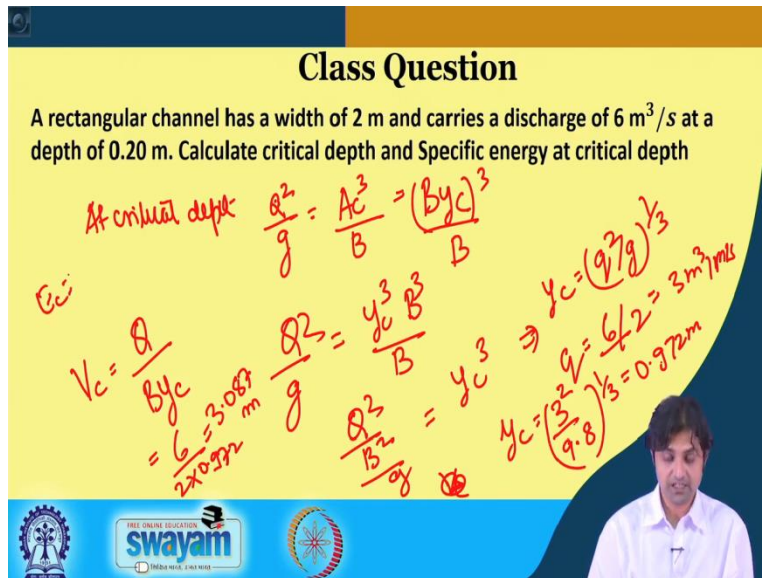
At critical depth $\frac{Q^2}{g} = \frac{A^3}{B} = \frac{(By_c)^3}{B}$

$V_c = \frac{Q}{By_c}$
 $= \frac{6}{2 \times 0.20} = 3.087 \text{ m/s}$

$\frac{Q^2}{g} = \frac{y_c^3 B^3}{B}$
 $\frac{Q^2}{B^2} = y_c^3$
 $y_c = \left(\frac{Q^2}{B^2 g}\right)^{1/3} = \left(\frac{6^2}{2^2 \times 9.8}\right)^{1/3} = 0.972 \text{ m}$

$y_c = (9.79)^{1/3} = 3 \text{ m}^3/\text{s}$

$y_c = \left(\frac{Q^2}{B^2 g}\right)^{1/3} = \left(\frac{6^2}{2^2 \times 9.8}\right)^{1/3} = 0.972 \text{ m}$



So, we will solve a small question. The question is, a rectangular channel has a width of 2 meter and carries a discharge of 6 meters cube per second at a depth of 0.20 meter. Calculate the critical depth and specific energy at critical depth. So, we have already seen that at, so if we write in terms of Q, we can write actually A c, you know, in terms of area, this if this is the B, you know, this is the channel width. And A c is, you know, Ac simply is the area, so we write By c. So, not b y c, a whole cube / B.

Hence, Q^2 / g is equal to $y_c^3 B^3 / B$. Therefore, we can write Q^2 / B^2 is equal to y_c^3 . I mean we already know y_c is Q^2 / g to the power $1/3$. So, Q we already know from this question, Q we know, so 6 divided by 2 per unit width is 3 meter cube per meter per second. Simply, y_c we can get, y_c is Q^2 / g is 3 square divided by 9.8 to the power $1/3$ is 0.972 meter.

And velocity is, so 6 divided by 2 into 0.972 and that comes out to be 3.087 meters or specific energy is $3/2$, you know, you can either do $3/2 y_c$ or just you can, you know V_c , you know y_c , I will just erase everything.

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Class Question

A rectangular channel has a width of 2 m and carries a discharge of $6 \text{ m}^3/\text{s}$ at a depth of 0.20 m. Calculate critical depth and Specific energy at critical depth

Handwritten solution:

$$q = \frac{Q}{B} = \frac{6}{2} = 3 \text{ m}^2/\text{s} \rightarrow q$$

$$y_c = \left(\frac{q^2}{g} \right)^{1/3} = \left(\frac{3^2}{9.8} \right)^{1/3} = 0.972 \text{ m} \rightarrow y_c$$

$$V_c = \frac{q}{y_c} = \frac{3}{0.972} = 3.087 \text{ m/s} \rightarrow V_c$$

$$E_c = \frac{3}{2} y_c = 1.458 \text{ m}$$


And now, simply try to, you know, do it with the knowledge that you have. So, in the derivation we know that Q / B , so $6 / 2$ is 3 meter cube per meter per second. And y_c by our formula is q^2 / g to the power $1 / 3$, that is what it came. So, substituting the value, so $3^2 / 9.8$ to the power $1 / 3$ and this gives 0.972 meter. V_c is the q / y_c because that was the equation that we are using.

V_c is q / y_c . So, 3 divided by 0.972 is equal to 3.087 meters per second. E_c is equal to, so everything you know, V_c is known, y_c is known and this is q . So, this is how you will solve this question. So, just going at critical depth.

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Class Question

A rectangular channel has a width of 2 m and carries a discharge of $6 \text{ m}^3/\text{s}$ at a depth of 0.20 m. Calculate critical depth and Specific energy at critical depth

Solution:

At critical depth, $\frac{Q^2}{g} = \frac{A_c^3}{T_c}$

For a rectangular channel $A_c = B y_c$

Top Width $T_c = B$

Hence $\frac{Q^2}{g} = \frac{y_c^3 B^3}{B}$

Or, $\frac{Q^2}{B^2} = \frac{q^2}{g} = y_c^3$



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Where q = discharge intensity = discharge per unit width

$$y_c = (q^2/g)^{1/3} \quad \text{Here } q = 6/2 = 3 \text{ m}^3/\text{s/m}$$

$$y_c = \left(\frac{3^2}{9.8}\right)^{1/3} = 0.972 \text{ m}$$

$$V_c = \frac{Q}{By_c} = \frac{6.0}{2 \times 0.972} = 3.087 \text{ m/s}$$

$$E_c = \text{Specific energy at critical depth} = y_c + \frac{V_c^2}{2g} = 0.972 + \frac{(3.087)^2}{2 \times 9.81} = 1.458 \text{ m}$$


It is a general approach. So, I have included these solutions so that it is easy for you to, you know, when you get the slides you can actually see, so this is a different method of solution.

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Class Question

Water flows up a 0.5 ft tall ramp in a constant width rectangular channel at a rate $q = 5.75 \text{ ft}^2/\text{s}$. If the upstream depth is 2.3 ft, determine the elevation of the water surface downstream of the ramp $y_2 + z_2$. Neglect viscous effects.



So we have another question, but we will like to stop at this point right now and start our next class by solving this question. Thank you so much.