

Hydraulic Engineering
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Lecture – 37
Non-Uniform Flow and Hydraulic Jump (Contd.)

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Class Question

- Water on the horizontal apron of the 30 m wide spillway shown in Fig. has a depth of 0.20 m and a velocity of 5.5 m/s. Determine the depth, after the jump, the Froude numbers before and after the jump.

Fr *Fr* *y₂*

$b = \text{width} = 100 \text{ ft}$
Spillway apron
 $y_1 = 0.60 \text{ ft}$
 $V_1 = 18 \text{ ft/s}$
Hydraulic jump
 y_2
 V_2
Downstream obstacles

Welcome back students. So, we start with solving some questions that are related to hydraulic jumps, so rapidly varied flow. So, this entire lecture will be dedicated to solving some of the basics and a little more complex problems, those type of problems which you encountered in exams like GATE or IES.

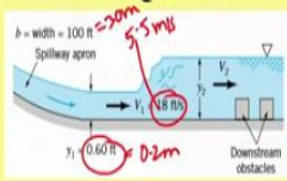
So, we start with one problem as below, it says that water on the horizontal apron of 30 metre wide spillway. So, it is 100 feet or, sorry, that is 30 meter has a depth of 0 point, so 0.06 feet is equivalent to 0.20 metre and a velocity of 18 feet per second that means, 5.5 metres per second. The question is determining the depth after the jump, the Froude numbers before and after the jump. So, this is simple application of the formula that we have.

So, if you see, in this figure, so the water is coming and it is undergoing hydraulic jump, and we have to calculate y_2 , the depth after the jump, so that is y_2 , Fr_1 and after the jump Fr_2 , simple.

So, we know the conditions here, at number 1, so it is pretty simple to calculate Froude number 1. We will go step by step, the way you should be solving to.

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Class Question



Conditions across the jump are determined by the upstream Froude number F_{r1}

$$F_{r1} = \frac{V_1}{\sqrt{gy_1}} = \frac{5.5}{\sqrt{9.8 \times 0.2}} = 3.92 > 1 \Rightarrow \text{hydraulic jump will occur}$$

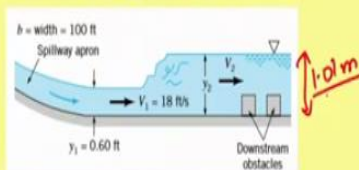
Upstream flow is super critical, and therefore it is possible to generate hydraulic jump

So, in this question, the conditions across the jump are determined by the upstream Froude number Fr_1 , that also we have to find out actually. So, Fr_1 is given by V_1 divided by under root gy_1 , V_1 was given 5.5, y_1 was given 0.2, you see, 18 feet per second means, 5.5 metres per second and this is 30 meter. So, the Froude number 1 comes out to be 3.92 and this is greater than 1, which means hydraulic jump will occur.

As I said that the upstream flow is supercritical and therefore, it is possible to generate hydraulic jump, first step.

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Class Question



We obtain depth ratio across the jump as

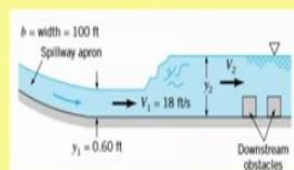
$$\frac{y_2}{y_1} = \frac{1}{2}(-1 + \sqrt{1 + 8Fr_1^2}) = \frac{1}{2}(-1 + \sqrt{1 + 8 * 3.92^2}) = 5.07$$

$$y_2 = \underline{5.07} * 0.2 = 1.01 \text{ m}$$

So, in the second step, we obtain depth ratio, we had the formula which said y_2 by y_1 is equal to $1/2$ into multiplied by $-1 + 1 + 8 Fr_1$ square. Fr_1 whole square which already we found out in the previous slide was 3.92, plug these values here, so what comes out is y_2 by y_1 is 5.07. Therefore, y_2 is going to be 5.07 into 0.2 and that is 1.01 metre, so this is going to be 1.01 metre.

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Class Question



We obtain V_2 by equating the flow rate

$$V_2 = \frac{(y_1 V_1)}{y_2} = \frac{0.2 * 5.5}{1.01} = 1.08 \text{ m/s} \Rightarrow V_2 = 1.08 \text{ m/s}$$

$$Fr_2 = \frac{V_2}{\sqrt{g y_2}} = \frac{1.08}{\sqrt{9.8 * 1.01}} = 0.343$$

Subcritical flow

last slide

Subcritical flow

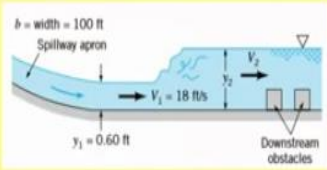
Now, the way we obtain V_2 is by equating the flow rate. So, $A_1 V_1$ is equal to $A_2 V_2$, V gets cancel out, so V_2 will be $V_1 y_1$ divided by y_2 , y_1 was known from before, V_1 was known from before, y_2 we just calculated using that y_2 by y_1 equation of hydraulic jump, so V_2 comes out to be 1.08 meters per second. So, therefore, Froude number at location 2 will be V_2 by under root

gy2. V_2 we have calculated here, this was the reason we were calculating V_2 , for calculating the Froude number and this we calculated in the last slide.

So, Froude number 2 comes out to be 0.343, so this means subcritical flow. So, when the system goes hydraulic, when it undergoes hydraulic jump, the supercritical flow turns from supercritical turns into, the supercritical flow turns into a subcritical flow. So, Froude number is more than 1 and after undergoing the hydraulic jump, the Froude number becomes, I mean, Froude number becomes less than 1. So, the flow becomes subcritical so, as it is written here it is a subcritical flow.

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Class Question



Head loss is obtained as

$$h_L = \left(y_1 + \frac{V_1^2}{2g}\right) - \left(y_2 + \frac{V_2^2}{2g}\right)$$

$$h_L = 0.671 \text{ m}$$

Now, we have to also obtain the head loss, that the energy loss. We simply use this equation, total energy at section 1 minus total energy minus section 2, y_1 we have, we know from before, V_1 we know from before, y_2 we have calculated, V_2 we have calculated. And after substituting in the values, you see, the head loss, that the energy loss, in terms of head is 0.671 metre.

This is the most simplest and the most common type of problems in hydraulic jump, which are the type of questions, you also will be expecting in your assignments and exams and competitive exams especially.

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Class Question

1) Prove that energy loss in a hydraulic jump occurring in a rectangular channel is

$$h_L = \frac{(y_2 - y_1)^3}{4y_1 y_2} \quad \text{Eq. 24}$$

The loss of mechanical energy that takes place in a hydraulic jump is calculated by the application of energy equation (Bernoulli's equation). If loss of total head in the pump is h_L , then we can write by Bernoulli's equation neglecting the slope of the channel.



Now, we go to another question, say that prove that the energy loss in a hydraulic jump occurring in a rectangular channel is, so we would try to obtain head loss directly, in terms of y_2 and y_1 . If we know the 2 depths, because sometimes in exams, in the objective type, you know, exams like IES and GATE, they simply give you y_2 and y_1 and asked you to calculate head loss. So, basically what you must do is, please learn, remember this equation.

In this particular question, we are trying to derive this, but you must remember this. We will derive this but in objective type of exam, it is very difficult to derive, I mean, all the time. So, basically, remember this equation. So, the loss of the mechanical energy that takes place in a hydraulic jump is calculated by the application of energy equation, Bernoulli's equation. If loss of total head in the pump is h_L , then we can write by Bernoulli's equation neglecting the slope of the channel

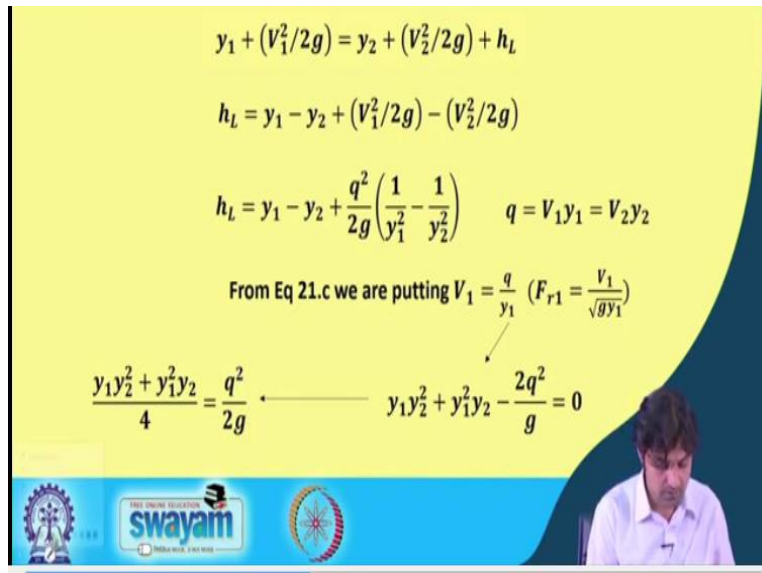
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$$y_1 + (V_1^2/2g) = y_2 + (V_2^2/2g) + h_L$$

$$h_L = y_1 - y_2 + (V_1^2/2g) - (V_2^2/2g)$$

$$h_L = y_1 - y_2 + \frac{q^2}{2g} \left(\frac{1}{y_1^2} - \frac{1}{y_2^2} \right) \quad q = V_1 y_1 = V_2 y_2$$

From Eq 21.c we are putting $V_1 = \frac{q}{y_1}$ ($F_{r1} = \frac{V_1}{\sqrt{gy_1}}$)

$$\frac{y_1 y_2^2 + y_1^2 y_2}{4} = \frac{q^2}{2g} \quad y_1 y_2^2 + y_1^2 y_2 - \frac{2q^2}{g} = 0$$


As $y_1 + V_1^2/2g$ is equal to $y_2 + V_2^2/2g + \text{head loss}$, this is what we generally write. So, head loss can be written as, $y_1 - y_2 + V_1^2/2g - V_2^2/2g$. So, this remains same, so instead of V_1 and V_2 , we write in terms of common quantity.

So, q can be written as $V_1 y_1$ is equal to $V_2 y_2$. So, we write, so V_1 , so we take out, sorry, very sorry, this equation, erase all, so this is the same, so V_1 is q by y_1 . Okay, I just wrote the opposite, q by y_2 . So, this we substitute here and this we substitute here and therefore, this q square we take out common and this is $1/y_1^2 - 1/y_2^2$.

Because q is equal to $V_1 y_1$ is equal to $V_2 y_2$. So, from equation number 21c, or we do not need to remember, V_1 is actually q by y_1 , so you remember equation, we are putting V_1 is equal to q by y_1 , Froude number 1 is $V_1 / \sqrt{gy_1}$.

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Hydraulic Jump Derivation

$$\left(\frac{y_2}{y_1}\right)^2 + \left(\frac{y_2}{y_1}\right) - 2Fr_1^2 = 0 \quad \text{Eq. 21c}$$

Where Fr_1 is upstream Froude number

Question : Obtain Eq. 21c from Eq. 21b

•Using quadratic formula we get

$$\frac{y_2}{y_1} = \frac{1}{2}(-1 \pm \sqrt{1 + 8Fr_1^2})$$


So, this one you see, you go back to the equation 21c, it is important to show you, so this one, this is the equation 21c. So, y_2 by y_1 + whole square + y_2 by y_1 - 2 Froude number 1 whole square is equal to 0. So, we can use this y_2 by y_1 here, so we can simply write, $y_1 y_2$ whole square + y_1 square y_2 by 4 is equal to q square by $2g$.

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$$h_L = y_1 - y_2 + \left(\frac{y_1 y_2^2 + y_1^2 y_2}{4}\right) \left(\frac{1}{y_1^2} - \frac{1}{y_2^2}\right)$$

Which Finally gives

$$h_L = \frac{(y_2 - y_1)^3}{4y_1 y_2}$$

Important Equation to remember



So, this equation becomes, so this q square by $2g$ is equal to this and we put it here. So, we get h_L is equal to $y_1 - y_2 + y_1$ into y_2 square + y_1 square y_2 by 4 and multiplied by, which will finally give, if you solve this, this is going to give you h_L is equal to $y_2 - y_1$ whole cube divided by $4y_1 y_2$, an important equation. I think you can, there are other ways of doing that as well but I think you should try this one at home, solving this one.

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Class Question

If, in a hydraulic jump occurring in a rectangular channel, the Froude number before the jump is 10.0 and the energy loss is 3.20 m. Estimate (i) the sequent depths (ii) the discharge intensity and (iii) the Froude number after the jump.

$Fr_1 = 10$ $h_L = 3.20 \text{ m}$ y_2, y_1

So, we go to another basic question, which says if in a hydraulic jump occurring in a rectangular channel, the Froude number before the jump is 10, so Fr_1 is 10, and energy loss is 3.20 metre. What is the sequent depths? So, we are talking about y_2 and y_1 and then it asked about the discharge intensity and the Froude number, h_L or E_L , whatever you want to call it. So, to solve this, we will take the help of white screen.

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Soln:

Given: $Fr = 10.0$, $E_L = 3.20 \text{ m}$

$$\frac{y_2}{y_1} = \frac{1}{2} \left[-1 + \sqrt{1 + 8Fr_1^2} \right] = \frac{1}{2} \left[-1 + \sqrt{1 + 8 \cdot 10^2} \right] = 13.657$$

Energy loss using previous question

$$E_L = \frac{(y_2 - y_1)^3}{4y_1 y_2}$$

$$\frac{y_2}{y_1} = 13.657 \Rightarrow y_2 = 13.657 y_1$$

$$\frac{E_L}{y_1} = \frac{(y_2 - y_1)^3}{4(y_2 y_1)} \Rightarrow \frac{3.20}{y_1} = \frac{(13.657 y_1 - y_1)^3}{4(13.657 y_1^2)}$$

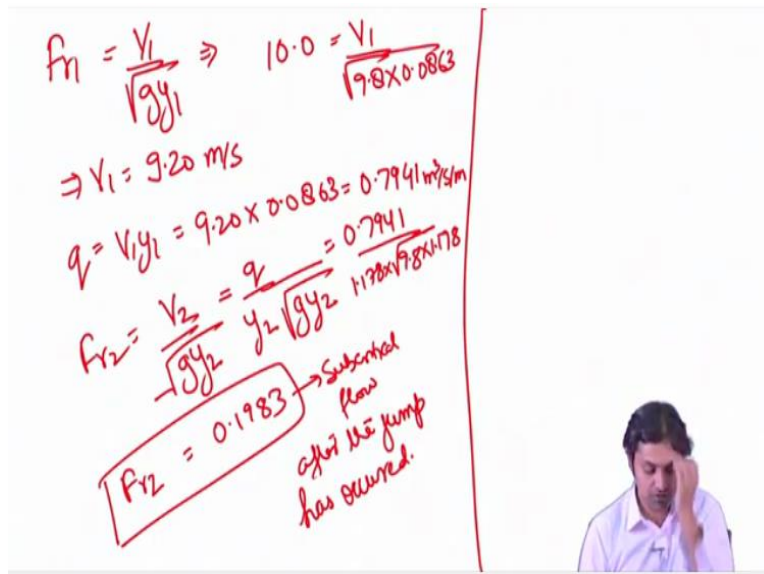
$$\Rightarrow y_1 = 0.0863 \text{ m}$$

So, the things that are given to us is, Froude number or Fr_1 , let us say is 10.0 and energy loss or head loss is 3.20 meter. So, from the formula, you remember, we had found y_2 by y_1 is equal to $1/2$ of $-1 + \sqrt{1 + 8Fr_1^2}$ whole square, so if we substitute $-1 + \sqrt{1 + 8}$ is into

10 square and it will give us 13.651 and energy loss using previous question that I asked you to remember, EL is written as $y_2 - y_1$ whole cube divided by $4y_1 y_2$.

So, if we say EL by y_1 is y_2 by $y_1 - 1$ whole cube divided by $4y_2$ by y_1 . So, EL we know is 3.20 divided by y_1 will be 13.651-1 whole cube divided by 4 into 13.651 and on solving this, y_1 is going to be 3.20 divided by 37.08, implies y_1 is going to be 0.0863 meter, so 0.0863 meter. Now, y_2 by y_1 we already know, we have found out y_1 , so y_2 by y_1 came out to be 13.651, implies y_2 is going to be 1.178 meter. So, the water level is increasing.

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Handwritten calculations on a whiteboard:

$$Fr_1 = \frac{V_1}{\sqrt{gy_1}} \Rightarrow 10.0 = \frac{V_1}{\sqrt{9.8 \times 0.0863}}$$

$$\Rightarrow V_1 = 9.20 \text{ m/s}$$

$$q = V_1 y_1 = 9.20 \times 0.0863 = 0.7941 \text{ m}^3/\text{s/m}$$

$$Fr_2 = \frac{V_2}{\sqrt{gy_2}} = \frac{q}{y_2 \sqrt{gy_2}} = \frac{0.7941}{1.178 \times \sqrt{9.8 \times 1.178}}$$

$$Fr_2 = 0.1983$$

Subcritical flow after the jump has occurred.

So, we have found out y_2 and y_1 , so we also need to find out Froude number 1, that is, V_1 by under root gy_1 . So, Froude number 1 we already know, 10 is equal to V_1 under root 9.8 into 0.0863 , implies V_1 is going to be 9.20 meters per second, small q is going to be $V_1 y_1$, so 9.20 into 0.0863 is 0.7941 meter cube per second per meter and Fr_2 is pretty simple, V_2 by under root gy_2 . And V_2 can be written, in terms of q by y_2 under root gy_2 .

So, q we have already found out, 0.7941 and y_2 is, y_2 we found out was 1.178 under root 9.8 into 1.178 . So, Froude number 2 is 0.1983 , subcritical flow after the jump has occurred. So, this is a very simple problem, we using the formulas, so you see, how this formula of energy loss is equal to $y_2 - y_1$ whole cube divided by $4y_1 y_2$ is important.

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$$\frac{E_L}{y_1} = \frac{(y_2/y_1 - 1)^3}{4(y_2/y_1)} \quad \frac{3.20}{y_1} = \frac{(13.651 - 1)^3}{4(13.651)} = 37.08$$

(i) $y_1 = \text{depth before the jump} = \frac{3.20}{37.08} = 0.0863 \text{ m}$
 $y_2 = \text{depth after the jump} = 13.651 \times 0.0863 = 1.178 \text{ m}$

(ii) $F_1 = \frac{V_1}{\sqrt{gy_1}} \quad 10.0 = \frac{V_1}{\sqrt{9.81 \times 0.0863}} \quad V_1 = 9.201 \text{ m/s}$

Discharge intensity $q = V_1 y_1 = 9.201 \times 0.0863 = 0.7941 \text{ m}^3/\text{s}/\text{m}$

(iii) Froude number after the jump $F_2 = \frac{V_2}{\sqrt{gy_2}} = \frac{q}{y_2 \sqrt{gy_2}} = \frac{0.7941}{1.178 \sqrt{9.81 \times 1.178}} = 0.19$

So, there is a solution as always here, you know, I have gotten it typed down. So, sequent depth ratio, so energy loss using this one, so after the jump Froude number is 9.2, discharge intensity, Froude number after the jump, same as we did it in the white board.

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Class Question

A rectangular channel has a width of 1.8 m and carries a discharge of 1.8 at a depth of 0.2 m. Calculate (a) the specific energy, (b) depth alternate to the existing depth and (c) Froude numbers at the alternate depths.

So, another question, it says a rectangular channel has a width of 1.8 meter and carries a discharge of 1.8 at the depth of 0.2 meters. Calculate specific energy, depth alternate to the existing depth and Froude number at alternate depths. So, in the beginning, we do not know what type of question this is. This is a hydraulic jump or not hydraulic jump but this is a very, this is a standard problem of open channel flow. So, we should start by, you know, writing down what are the things that we know from before, you know.

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Soln:

$y_1 = 0.20 \text{ m} = \text{Existing depth}$
 Area: $A_1 = B y_1 = 1.8 \times 0.2 = 0.36 \text{ m}^2$
 Velocity: $V_1 = \frac{Q}{A_1} = \frac{1.80}{0.36} = 5 \text{ m/s}$

a) Specific energy
 $E_1 = y_1 + \frac{V_1^2}{2g}$
 $E_1 = 0.20 + \frac{5^2}{2 \times 9.81} = 1.47 \text{ m}$

b) Let's say $y_2 = \text{depth alternate to } y_1 \text{ and specific energy diagram}$

$E_1 = E_2$
 $y_2 + \frac{V_2^2}{2g} = 1.47$
 $y_2 + \frac{1.8^2}{2 \times 9.81 \times (1.8 \times y_2)^2} = 1.47$
 $y_2 = 1.45 \text{ m}$ $\rightarrow$ by trial and error

$F_1 = \frac{5}{\sqrt{9.81 \times 0.2}} = 3.57$
 $V_2 = \frac{Q}{B y_2} = \frac{1.8}{1.8 \times 1.45} = 0.69 \text{ m/s}$
 $F_2 = \frac{V_2}{\sqrt{g y_2}} = \frac{0.69}{\sqrt{9.81 \times 1.45}} = 0.1829$

So to solve this, so what we know, we write it down, V_1 is equal to 0.20 meter and that is the existing depth, area is A_1 is $B y_1$, B is already given, width of 81.8 meter. So, it is 1.8 into 0.2, that is, 0.36 meter square. So, velocity V_1 is simply, Q by A_1 , Q is given 1.80 and area we know is calculated 0.36 and this gives us to be 5 meters per second.

So, the first part is specific energy; E_1 is equal to $y_1 + V_1^2$ by $2g$, so y_1 we already know, plus V , V we have already calculated, 2 into 9.81, so this comes out to be 1.47 meter, so specific energy at 1. So, we have to calculate y_2 , so let say y_2 is depth alternate to y_1 and specific energy diagram. I would like to remind you, when we are dealing with specific energy, we found out a cubic equation, for a particular Q , there were existing 3 values of y . One was negative, which is generally neglected and the remaining one, y_1 and y_2 are called alternate depths.

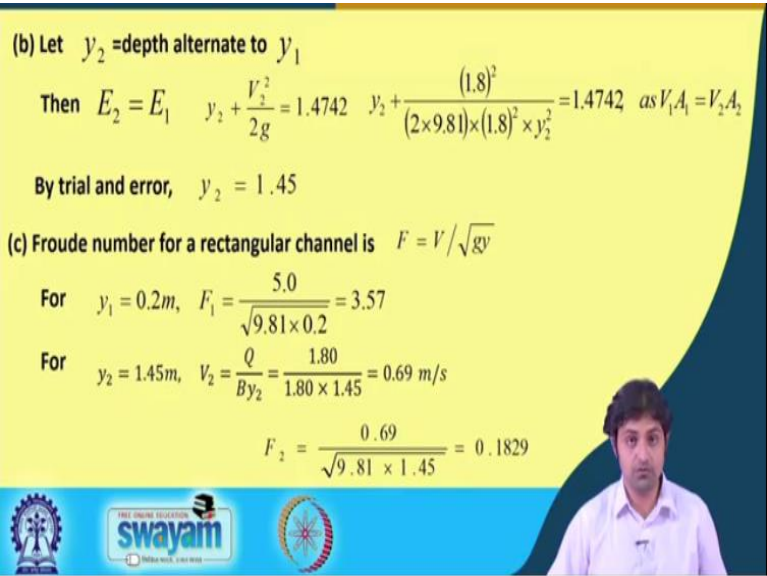
In this question, one is already given to us and we are asked about the other one. So, the best way of solving this is through specific energy. So, we have calculated specific energy at one point and now, we are going to equate the specific energy at the other point. So, we write E_1 is equal to E_2 , and E_1 is, so E_2 is y_2 , that we do not know, plus V_2^2 by $2g$ is equal to 1.4742 because that is E_1 which we have already calculated, 1.47 actually, you will just write it down, it is better not going into too much.

So, y_2 and V_2 is what? V_2 is similar to, you know, Q by A_2 . So, Q is 1 point, V_2 square is Q A_2 square divided by A_2 square. So, we still write, 2.981 into, that is, $2g$ and then it is 1.8 because all the depth is, I mean, B_1 into y_1 .

So, this is A square, A_2 square, is equal to 1.47. So, if you solve for this, y_2 will come out to be 1.45 meter, you can use by trial and error or you can, you know, it is not that big a problem. So, y_2 comes out to be 1.45 meter. So, now, we know y_1 , we knew y_1 , now we have y_2 . So, Froude number at first location is going to be V under root 9.81 into 0.2 , that is, 3.57 and for this y_2 , we need to find out first velocity.

So, V_2 is going out to be, Q by $B y_2$. So, Q is 1.8, B is 1.8 and y_2 is 1.45, so this comes out to be 0.69 meters per second. Therefore, F_2 is V_2 by under root $g y_2$ and this comes out to be 0.69 into 9.81 into 1.45, this equals 0.1829. So, F_2 comes out to be 0.1829. So, we have found using the concept of specific energy, everything that was required. So, F_1 , F_2 , you know, so we will close this.

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(b) Let y_2 = depth alternate to y_1

Then $E_2 = E_1$ $y_2 + \frac{V_2^2}{2g} = 1.4742$ $y_2 + \frac{(1.8)^2}{(2 \times 9.81) \times (1.8)^2 \times y_2^2} = 1.4742$ as $V_1 A_1 = V_2 A_2$

By trial and error, $y_2 = 1.45$

(c) Froude number for a rectangular channel is $F = V / \sqrt{g y}$

For $y_1 = 0.2m$, $F_1 = \frac{5.0}{\sqrt{9.81 \times 0.2}} = 3.57$

For $y_2 = 1.45m$, $V_2 = \frac{Q}{B y_2} = \frac{1.80}{1.80 \times 1.45} = 0.69 \text{ m/s}$

$F_2 = \frac{0.69}{\sqrt{9.81 \times 1.45}} = 0.1829$

Here now, and go to the solutions that which we have solved actually. So, the velocity using the specific energy concepts, the same solution, Froude number. So, this will be of help to you when you revise the course.

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Class Question

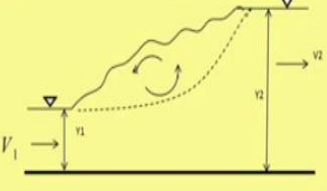
In hydraulic jump occurring in a rectangular horizontal channel, the discharge per unit width is $2.5 \text{ m}^3/\text{s}/\text{m}$ and the depth before the jump is 0.25 m . Estimate (i) the sequent depth and (ii) the energy loss

Solution:

$$q = 2.5 \text{ m}^3/\text{s}/\text{m} \text{ and } y_1 = 0.25 \text{ m}$$

$$V_1 = \frac{q}{y_1} = \frac{2.5}{0.25} = 10.0 \text{ m/s}$$

Initial Froude number $F_1 = \frac{V_1}{\sqrt{gy_1}} = \frac{10.0}{\sqrt{9.81 \times 0.25}} = 6.386$







So, now, we are going to solve one last problem of this module and after that we will end this, you know, lecture. So, instead of going to the white board, I will take you through the slides itself and so. So, the question is, in hydraulic jump occurring in a rectangular horizontal channel, the discharge per unit width is 2.5 meter cube per second per metre. So, we have been given, I will explain here only.

The discharge per unit width, small q we have been given and we say that y_1 , we already know. Now, it is asking, estimate the sequent depth and the energy loss. So, the way it is to be done is, you see. We know small q , depth we already know, so this is the phenomenon, y_1 , V_1 , V_2 , y_2 . So, q is 2.5 meters cube per meters per second, y_1 is 0.25 meters, already given. So, small v_1 , I mean, V_1 is q by y_1 , which comes to be 10 metres per second.

And if we know V_1 , we can calculate the initial Froude number that comes to be 6.386. This means, we definitely will have a hydraulic jump because, I mean, we will have a hydraulic jump, we might, because Froude number is greater than 1. So, we know Froude number at location 1 now, we know y_1 , so we will be easily able to find out y_2 by y_1 . Since, we know Froude number at location 1

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(i) The sequent depth ratio y_2/y_1 is given by $\frac{y_2}{y_1} = \frac{1}{2} \left[-1 + \sqrt{1 + 8F_1^2} \right]$

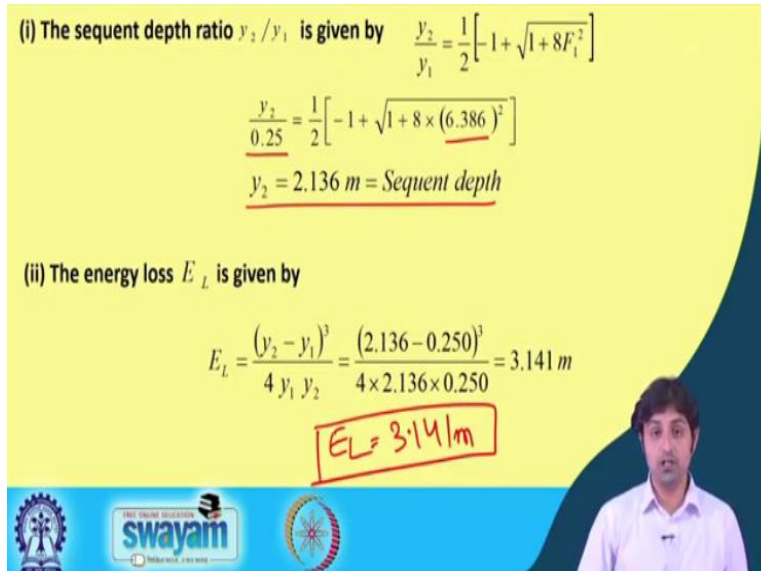
$$\frac{y_2}{0.25} = \frac{1}{2} \left[-1 + \sqrt{1 + 8 \times (6.386)^2} \right]$$

$$y_2 = 2.136 \text{ m} = \text{Sequent depth}$$

(ii) The energy loss E_L is given by

$$E_L = \frac{(y_2 - y_1)^3}{4 y_1 y_2} = \frac{(2.136 - 0.250)^3}{4 \times 2.136 \times 0.250} = 3.141 \text{ m}$$

$E_L = 3.141 \text{ m}$



By the formula, y_2 by y_1 is equal to $1/2 - 1 + \text{under root } 1 + 8 F_1 \text{ square}$. This we have derived, you remember, and putting in the values, you see, Froude number came out to be 6.836, other things, y_1 we already, because we were given that it is 0.25 meter, so y_2 will come out to be 2.136 meter, which is called the sequent depth. And now, the last part of this is we have to find out the energy loss E_L .

And the energy loss E_L is given by the formula; $y_2 - y_1$. So, we know y_2 , we know y_1 , so we can, we are easily able to find out energy loss, just in terms of y_2 and y_1 . So, $2.136 - 0.250$ whole cube divided by $4 y_1$ into y_2 and the energy loss comes out to be 3.141 metre. So, this is the final question of this topic and with this we finished the module called as open channel flow that went on for 2 weeks.

So, in the next week we are going to deal with the pipe flow. We are going to go and see the viscous fluid flow, we will see concepts about computational fluid dynamics and we will close down with the wave mechanics, which is a typical example of in viscid fluids. So, thank you so much and I will see you next week. Bye.