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OPEN CHANNEL SURGES

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Abstract

The open channel Surges due to sudden changes of flow depth creates Celerity (Wave Velocity) in the flow in addition to the normal water velocity of the channels. These waves travel in the downstream and sometimes upstream of the channels depending on the various situations. The propagation of the Surges becomes positives or negatives depending on its crest and the trough of the waves. Therefore on this topic, these principals are presented in the analytical methods.

Keywords: *surge, dam, sluice gate*

1. Introduction

The sudden changes of flow in open channel results in the increase or decrease of flow depth is called the **"SURGE"** in open channel. This could take place when there is a breaching of dams due to earthquake or regulating the hydropower sluice gates. Hence results in positive and negative surges in downstream river channel or in downstream tail channel of hydropower projects. This phenomenon also governs when there would be flood (unsteady flow) during monsoon period in natural river channels and the hydrograph significantly varies with rising and falling as the rainfall takes it peak period. The flood wave which generates during the positive or negative surges is called the celerity (wave velocity) of the flood in unsteady flow situation.

This positive or negative surge sometimes travels downstream or upstream depending on the situation. The increase in flow depth would become the crest of the surges and the decrease in the flow depth would become the trough of the surges.

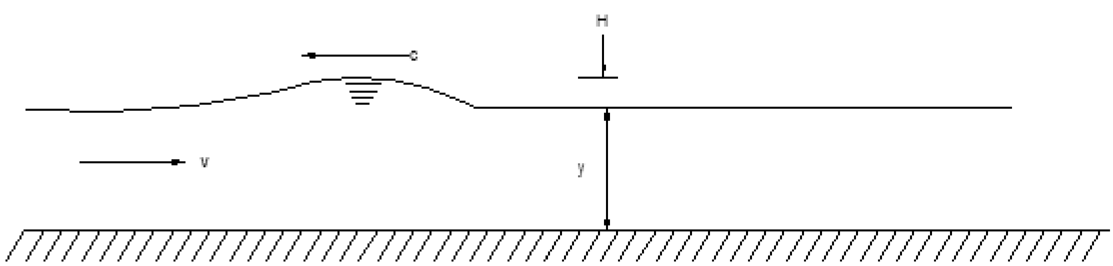

Fig 1 Propagation of low wave in channel

The celerity or speed of propagation relative to the water is given by $\sqrt{gy}$ where y is the water depth. Therefore the velocity of the wave relative to a stationary observer is:

$$c = \sqrt{gy} \pm v \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots .1$$

This can be noted that the Froude number F_r expressed by $\frac{v}{\sqrt{gy}}$ is the ratio of water velocity to wave celerity. If the Froude number is greater than unity, which corresponds with supercritical flow, a small gravity wave cannot be propagated upstream. Waves of finite height are dealt with in section of open channel surges.

The examples of Surges in downstream River Channel is when regulating the sluice gates of one of the 12MW Jhimruk Hydropower Project as shown below which is located in Puythan district of Western Region of the Nepal.

Fig 2 Downstream end showing photograph of 12MW Jhimruk Hydropower Project

(Source: Butwal Power Company (BPC))

A surge is produced in the channel by a rapid change in the rate of flow, for example, by the rapid opening or closure of sluice gates of the project. The former causes a positive surge wave to move downstream (shown in fig) and the latter produces a positive surge wave which moves upstream (shown in Fig)

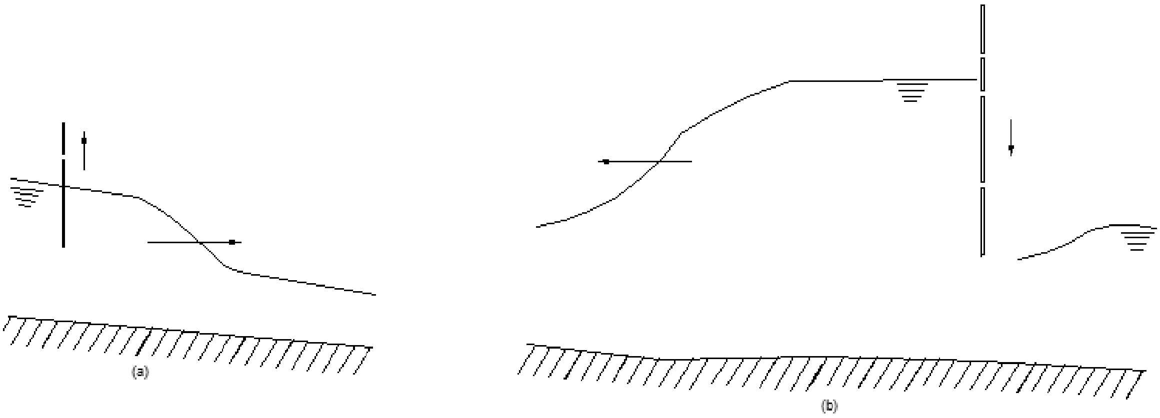

Fig 3 Positive Surge Waves

A stationary observer therefore sees an increase in depth as the wave front of a positive surge wave passes. A negative surge wave, on the other hand, leaves a shallower depth as the wave front passes. (Shown in fig)

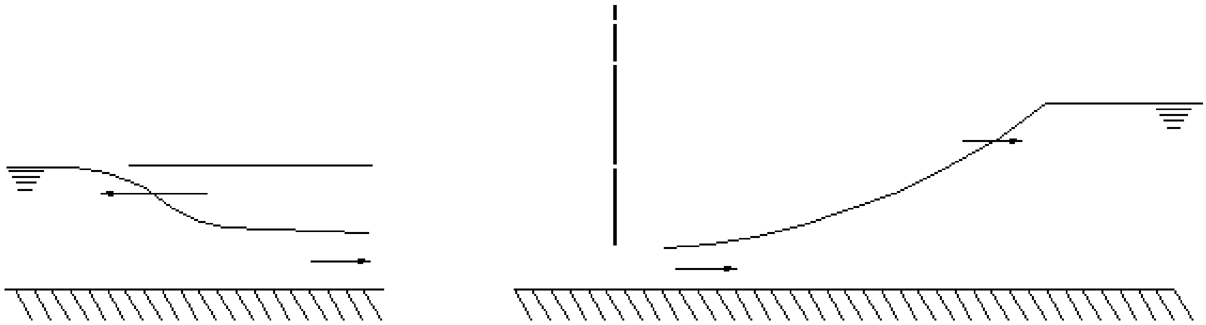

Fig 4 Negative Surge Waves

Negative Surge waves in the downstream River Channel are produced to a 12MW Jhimruk hydropower plant when the sluice gates are suddenly being closed (shown in above fig).It is illustrated from the figure that each type of surge can move upstream or downstream.

2. Analytical Methods

2.1 The upstream positive surge wave

Consider the propagation of a positive wave upstream in a frictionless channel resulting from gate closure (shown in fig)

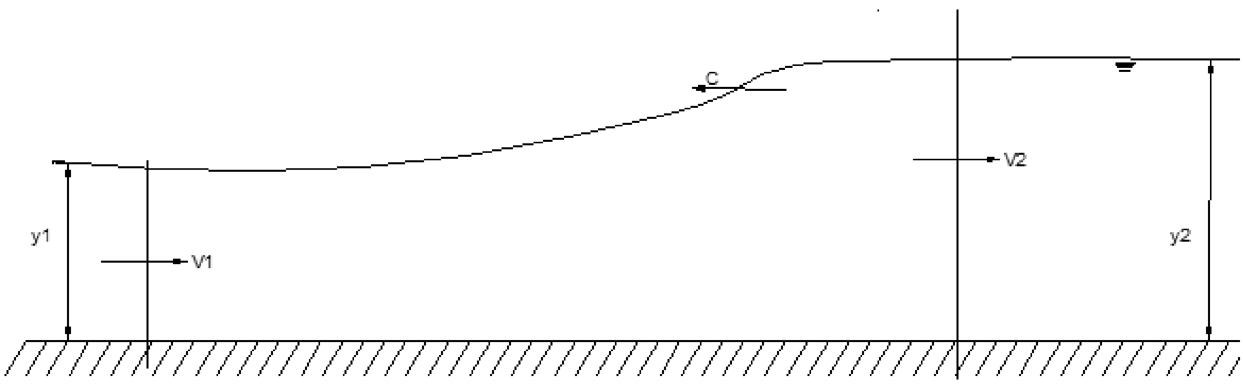

Fig 5 Upstream Positive Surges

The front of the surge wave is propagated upstream at celerity, c, relative to the stationary observer. To the observer, the flow situation is unsteady as a wave front passes; to an observer travelling at a speed, c, with the wave the flow appears steady although non-uniform. The following fig shows the surge reduced to steady state.

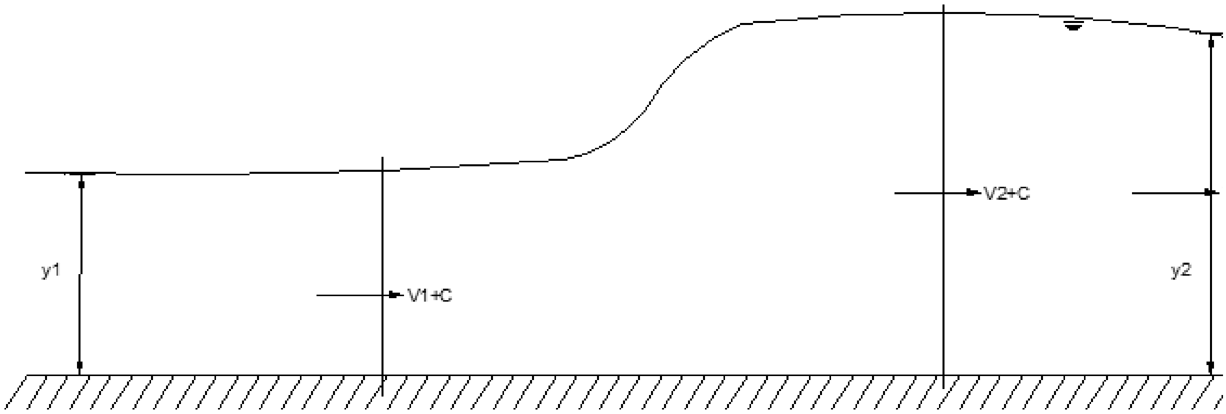

Fig 6 The continuity equation is:

$$A_1(V_1+c) = A_2(V_2+c) \dots\dots\dots\dots\dots\dots .2$$

The momentum equation is:

$$gA_1\overline{y_1} - gA_2\overline{y_2} + A_1(V_1+c)(V_1-V_2) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots .3$$

Where $\overline{y_1}$ and $\overline{y_2}$ are respective depths of the centres of area. From simplification, we get

$$c = \left[gA_2\frac{(A_2\overline{y_2}-A_1\overline{y_1})}{A_1(A_2-A_1)}\right]^{\frac{1}{2}} - v_1 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 4$$

In the special case of rectangular channel,

$$A = by{:}\, \bar{y} = \frac{y}{2}$$

From the above equation, it can be written as

$$c = \left[\frac{gy_2}{2}\frac{(y_2^2-y_1^2)}{y_1(y_2-y_1)}\right]^{\frac{1}{2}} - v_1$$

then; $\boxed{c = \left[\frac{gy_2}{2}\frac{(y_2+y_1)}{y_1}\right]^{\frac{1}{2}} - v_1 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots .5}$

The hydraulic jump in a stationary surge. Putting $c = 0$, in the above equation,

$$v_1^2 = \frac{gy_2}{2}\frac{(y_2+y_1)}{y_1}$$

$$\frac{2v_1^2y_1}{g} = y_2^2 + y_2y_1$$

Now $F_1^2\{(Froudenumber)^2\} = \frac{v_1^2}{gy_1}$

$$\therefore y_2^2 + y_2y_1 - 2F_1^2y_1^2 = 0$$

where, Jump equation is:

$y_2 = \frac{y_1}{2}(\sqrt{1+8F_1^2} - 1)$

In the case of a low wave where y_2 approaches y_1 then equation becomes

Then $c = \sqrt{gy} - v_1$ … 6

And in still water ($v_1 = 0$)

$c = \sqrt{gy}$……………………………..…………………………………7

2.2 The downstream positive surge

This type of wave may occur in channel downstream from a slice gate at which the opening is rapidly increased. See figure below

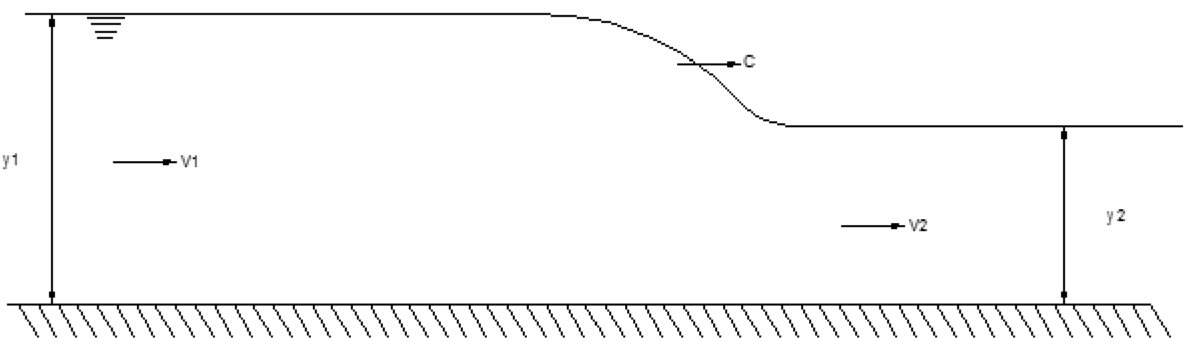

Fig 7 Downstream Positive Surges

Reducing the flow to steady state. From continuity equation:

$$(c - v_1)A_1 = (c - v_2)A_2 \text{ … … … … … … } 8$$

Momentum: $gA_1\overline{y}_1 - gA_1\overline{y}_2 + (c - v_2)A_2(v_2 - v_1) = 0$……………….9

Similarly, $\boxed{c = \left[\frac{gy_1}{2y_2}(y_1 + y_2)\right]^{\frac{1}{2}} + v_2 \text{ … … … … … … … … … … … … … … …10}}$

2.3 Negative Surge Waves

The negative surge wave appears to a stationary observer as a lowering of the liquid surface. Such wave occurs in the channel downstream from the control gate the opening of which is rapidly reduced or in the upstream channel as the gate is opened. The wave front can be considered to be composed of a series of small waves superimposed on each other. Since the uppermost wave has the greatest depth it travels faster than those beneath; the retreating wave front therefore becomes flatter. Shown in fig below

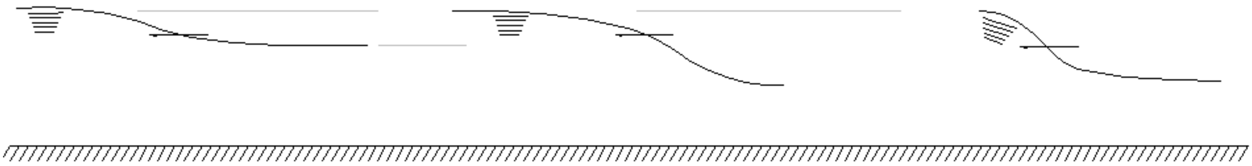

Fig 8 Propagation of Negative Surges

The above figure shows a small disturbance in a rectangular channel caused by a reduction in downstream discharge; the wave propagates upstream as described below:

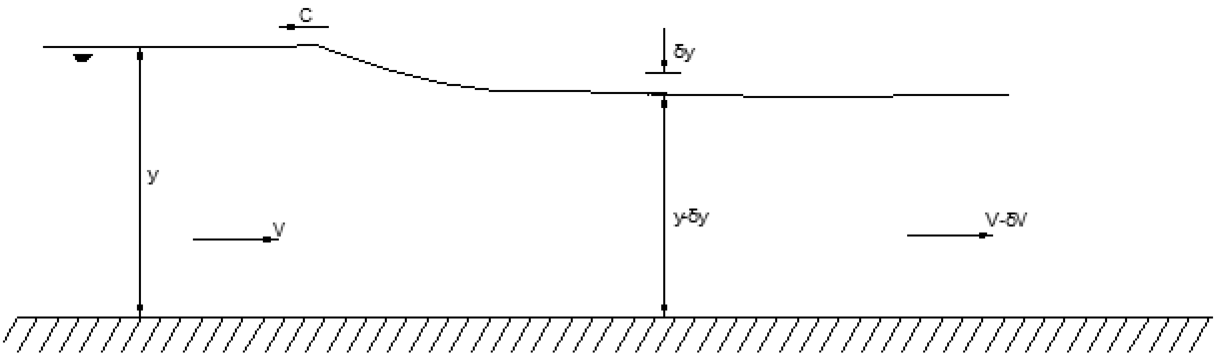

Fig 9 Neglecting the product of small quantities

$$\delta y = -\frac{y\delta v}{(V+c)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .11$$

The momentum equation is $\frac{\rho g}{2}\{y^2 - (y-\delta y)^2\} + \rho y(v+c)\{v+c-(v-\delta v+c)\} = 0$

Where $\frac{\delta y}{\delta v} = -\frac{(v+c)}{g}$

Or $\delta y = -\frac{\delta v(V+c)}{g}$……………………………………………………..12

Equating the above equations;

$$\frac{y\delta v}{(v+c)} = \frac{(v+c)\delta v}{g}$$

Where, $c = \sqrt{gy} - v \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots ..13$

Substituting for (v +c) from above equations;

$$\delta y = -\frac{\delta v}{g}\sqrt{gy}$$

And in the limit as $\delta y \to 0$

$$\frac{dy}{\sqrt{y}} = -\frac{dv}{\sqrt{g}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .14$$

For a wave of finite height, integration of above equation yields

$$v = -\sqrt{2gy} + constant$$

When $y = y_1, v = v_1$; Where $const = v_1 + \sqrt{2gy_1}$

$$v = v_1 + 2\sqrt{gy_1} - 2\sqrt{gy} \ldots\ldots\ldots\ldots 15$$

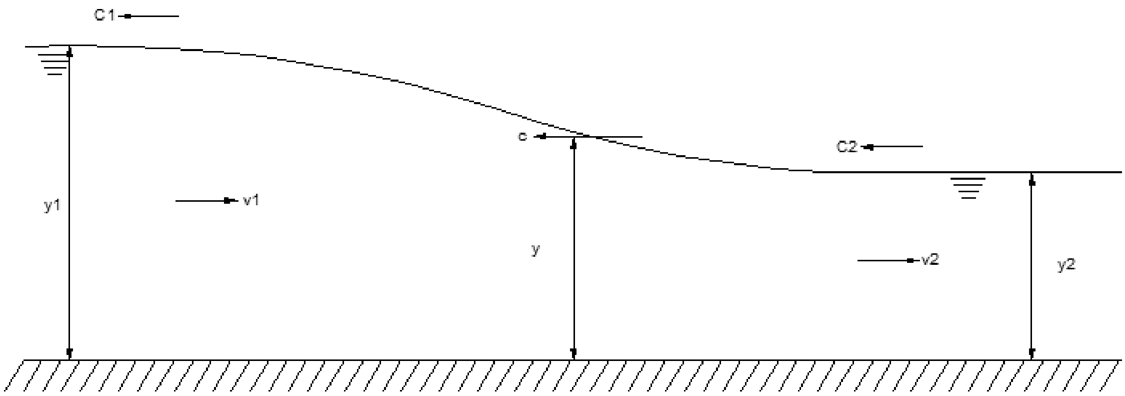

Fig 10 Negative surges of finite height

From equation $c = \sqrt{gy} - v$ and substituting in above equation then it becomes;

$\boxed{c = 3\sqrt{gy} - 2\sqrt{gy_1} - v_1;}$ The wave speed at;

the **crest** is therefore, $\boxed{c_1 = \sqrt{gy_1} - V_1;}$ the **trough** $\boxed{c_2 = 3\sqrt{gy_2} - 2\sqrt{gy_1} - V_1}$

In the case of a downstream negative surge in a frictionless channel as shown below a similar approach yields; $\boxed{c = \sqrt{gy} + v;}$ again $v = 2\sqrt{gy} - 2\sqrt{gy_2} + v_2$;$c = 3\sqrt{gy} - 2\sqrt{gy_2} + v_2$;

$\boxed{c_1 = 3\sqrt{gy_1} - 2\sqrt{gy_2} + v_2}$ $\boxed{c_2 = \sqrt{gy_2} + v_2}$

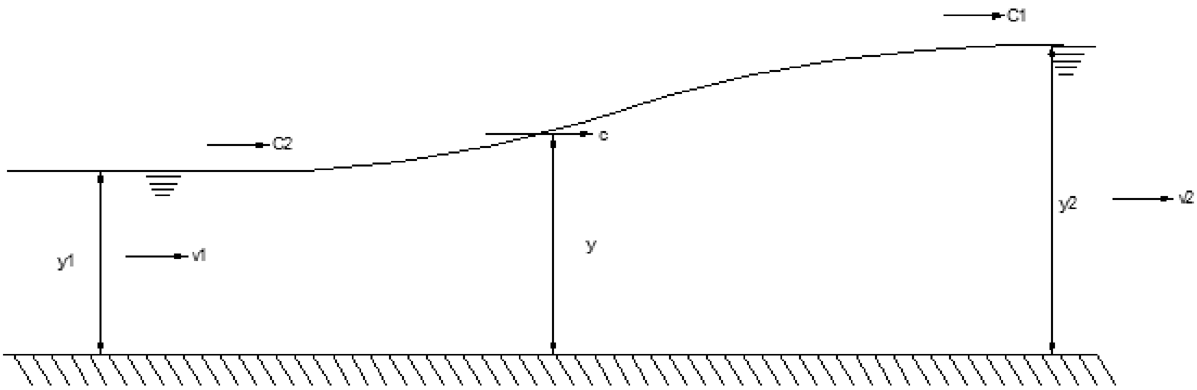

Fig 11 Downstream negative surges

2.4 The Dam Break

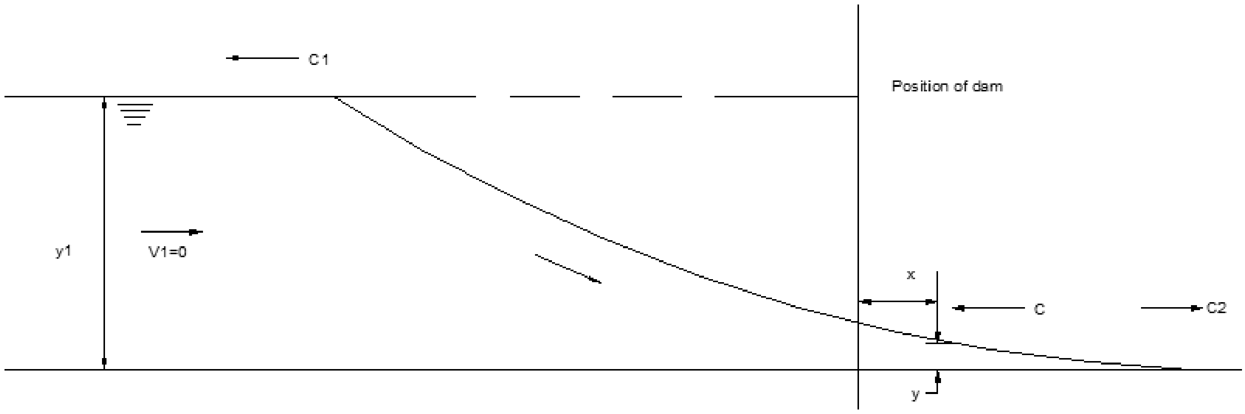

Fig 12 Dam Break illustration

The dam, or gate, holding water upstream at depth y_1 and Zero velocity, is suddenly removed.

From equation $\boxed{c = 3\sqrt{gy} - 2\sqrt{gy_1}}$

The equation to the surface profile is therefore

$$\boxed{x = (ct) = \left(3\sqrt{gy} - 2\sqrt{gy_1}\right)t}$$

If $x = 0, y = \frac{4y_1}{9}$ and remains the constant with time. The velocity at

$x = 0\ is \boxed{v = v_1 + 2\sqrt{gy_1} - 2\sqrt{gy}}$ from the above equation

i.e. $v = \frac{2}{3}\sqrt{gy_{1,}}$ since $v_1 = 0$

3. Illustration

A rectangular tailrace channel of hydropower project, 15m wide having bed slope 0.0002 and manning roughness coefficient as 0.017 conveys a steady discharge of 45m^3/s from the hydropower installation. A power increase results in a sudden increase in flow to the Turbines to 100m3/s. Determine the depth and celerity of the resulting surge wave in the tailrace channel.

Solution:

Using Manning equation to calculate the depth of the uniform flow under initial conditions at a discharge of 45m3/s; the initial flow depth is then; 2.42m.

Using above equation i.e. $(c + V_1)y_1 = (c - V_2)y_2$

$$c = \frac{V_1 y_1 - V_2 y_2}{(y_1 - y_2)}$$

$$c = \frac{\frac{Q_1 y_1}{b y_1} - V_2 y_2}{(y_1 - y_2)}$$

$$V_2 = \frac{Q_2}{by_2} = \frac{45}{15 \times 2.42} = 1.24 m/s$$

$Q_1 = 100 m^3/s$, then; $c = \frac{6.67-3}{(y_1-2.42)} = \frac{3.67}{(y_1-2.42)}$

Substituting this in above equation,

$$\boldsymbol{c = \left[\frac{gy_1}{2y_2}(y_1 + y_2)\right]^{\frac{1}{2}} + v_2}$$

$$\frac{3.67}{(y_1 - 2.42)} = \left[\frac{gy_1}{2 \times 2.42}(y_1 + 2.42)\right]^{\frac{1}{2}} + 1.24$$

By trial and error,

$$y_1 = 2.95 m$$

$$c = \frac{3.67}{(2.95 - 2.42)} = 6.92 m/s$$

4. Conclusion & Recommendation

The application of the surge waves in the design of canals, especially for the hydropower & irrigation projects these principals play a vital role for the optimum design of the canals. The design depth of the flow in the canals during the surges must be able to accommodate the required amount of discharges accumulated during the propagation of the surges in downstream or upstream of the canals. Therefore, it is recommended to keep the sufficient amount of free board in the canals to accommodate the additional height of the surges in addition to the normal depth of the canal flow.

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