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Flow in a triangular open channel with hydraulic jump

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Abstract

Mathematical model for dredging a triangular open channel with hydraulic jump is developed using the method of successive approximation. Applying the model to a numerical example new parameters of the new (excavated) channel are determined and compared with those of the original channel. Another feature of the work is the application of our model in Bernoulli's equation which leads to the energy dissipated in the jump for both the original and new channel. Based on this, other parameters like jump efficiency, relative energy loss, power loss and height of the jump are also determined in the two channels and compared.

Keywords
Mathematical modeling, hydraulic jump, triangular channel, dredging (excavation)

AMS – Mathematical Subject Classification 2000:76B07.

1.0 Introduction

Recently Eyo [1] models a flow with hydraulic jump in a parabolic channel with abrupt change in slope using the conditions of geometrical and dynamical similarities coupled with continuity condition. He showed that the downstream parameters are generally greater in the original and new channels than the upstream ones, but that the trend is reversed in the case of the Froude number which is lower in the downstream section of both channels than the upstream one. Nasser et al. [2] discussed flow in a channel with a slot in the bed and showed that the coefficient of discharge for the slot can be expressed by means of a simple equation. They also showed that resolving the momentum equation along the flow direction yields an expression for the ratio of the brink depths at the beginning and at the end of the slot in terms of the force coefficients, performance factor and the approach Froude number. In studying a jet-assisted hydraulic jump in a rectangular channel, France [3] investigated the stability of the hydraulic jump and the effectiveness of the jets over a wide range of operating conditions. He observed that the stabilization of the jump is dependent on a number of parameters but concluded that the angle of inclination of the jets has the most pronounced effect. Notable contributors in this area include among others [4,5,6,7,8,9,10,11].

In the present work, a mathematical model governing the excavation of a triangular open channel section is developed. The study of the triangular open channel section is of interest because of its peculiar nature which makes it distinct from other channel sections. Here

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the flow is non-uniform and steady. From a numerical result, for a channel flow problem, certain parameters of the new channel exhibit interesting characteristics.

2.0 Mathematical model for dredging a triangular channel section

In what follows we shall denote the original channel (i.e. the channel before dredging) by the symbol O, while the new channel (i.e. the channel after dredging) shall be denoted by the symbol N. We shall also use the subscripts 1 and 2 to denote the upstream and downstream conditions of the channel respectively.

2.1 Mathematical model for the original triangular channel

2.1.1 Upstream Parameters

Consider a triangular section depicted in Figure 2.1 with side slopes of 1 vertical to k horizontal. Let h be the depth of flow in the channel.

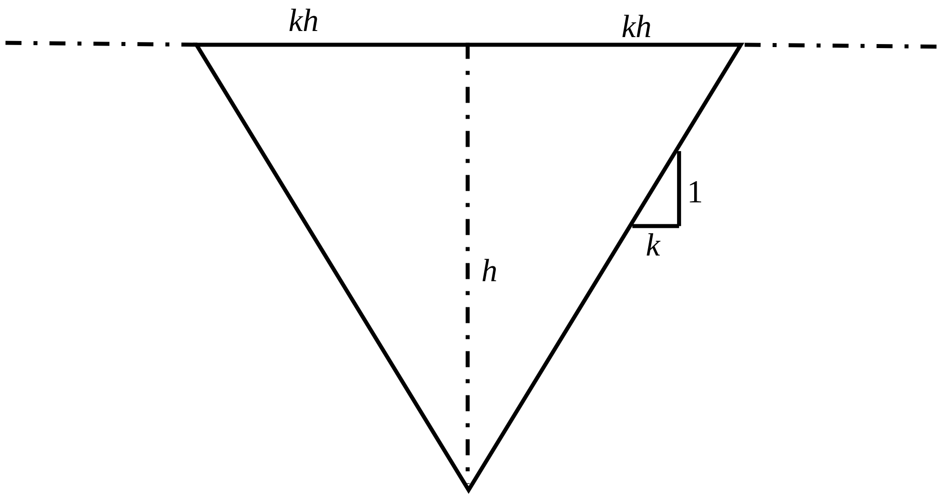

Figure 2.1: Triangular section.

(*i*) Cross-sectional area $(A_1)_0$

$$(A_1)_0 = k(h_1)_0^2 \tag{2.1}$$

where $(h_1)_0$ is the upstream depth of the original channel.

(*ii*) Wetted perimeter $(P_1)_o$

$$(P_1)_0 = 2(h_1)_0\left[1+k^2\right]^{1/2} \tag{2.2}$$

(*iii*) Hydraulic mean depth $(R_1)_0$

$$(R_1)_0 = \frac{(A_1)_0}{(P_1)_0} = \frac{k(h_1)_0^2}{2(h_1)_0\left[1+k^2\right]^{1/2}} = \frac{k(h_1)_0}{2\left[1+k^2\right]^{1/2}} \tag{2.3}$$

(*iv*) Discharge $(Q_1)_0$

Using Manning formula [5]

$$(Q_1)_0 = \frac{1}{n}(A_1)_0\left[(R_1)_0\right]^{2/3} S_0^{1/2} \tag{2.4}$$

where n is the roughness factor and S_0 is the bed slope of the channel.

(*v*) Mean Velocity $(u_1)_0$

$$(u_1)_0 = \frac{(Q_1)_0}{(A_1)_0} \tag{2.5}$$

(*vi*) Froude number $(F_1)_0$

Again, from [5] and using our modeling notation

$$(F_1)_0 = \frac{(u_1)_0}{\sqrt{g(h_1)_0}} \tag{2.6}$$

(vii) Critical depth $(h_c)_0$

$$(h_c)_0 = \left[\frac{2(Q_1)_0^2}{k^2 g}\right]^{1/5} \tag{2.7}$$

2.1.2 Downstream Parameters

(viii) Downstream depth *$(h_2)_0$*

The equation for conjugate depth of the jump is given by (see [5])

$$\left(\frac{h_2}{h_1}\right)^2 = 1 + 3F_1^2\left[1 - \left(\frac{h_1}{h_2}\right)^2\right] \tag{2.8a}$$

From (2.8a) we obtain using our modeling notation

$$\left[\frac{(h_2)_0}{(h_1)_0}\right]^2 = 1 + 3(F_1)_0^2\left[1 - \left[\frac{(h_1)_0}{(h_2)_0}\right]^2\right] \tag{2.8b}$$

for the determination of $(h_2)_0$; or, we obtain

$$\left[\frac{(h_2)_N}{(h_1)_N}\right]^2 = 1 + 3(F_1)_N^2\left[1 - \left[\frac{(h_1)_N}{(h_2)_N}\right]^2\right] \tag{2.8c}$$

for the determination of $(h_2)_N$, all by means of successive approximation.

2.2 Method of successive approximation.

We illustrate the method here by obtaining first approximation.

Expanding (2.8a) and simplifying we find

$$h_2^4 = \left(h_1^2 + 3F_1^2h_1^2\right)h_2^2 - 3F_1^2h_1^4 \tag{2.9}$$

Now, (2.9) can be written in the form $h_2^4 = \left(h_1^2 + 3F_1^2h_1^2\right)h_2^2 - \left(h_1^2 + 3F_1^2h_1^2\right)\times\dfrac{3F_1^2h_1^4}{\left(h_1^2 + 3F_1^2h_1^2\right)}$

i.e. $$h_2^4 = \left(h_2^2 - \frac{3F_1^2h_1^4}{h_1^2 + 3F_1^2h_1^2}\right)\left(h_1^2 + 3F_1^2h_1^2\right)$$

or $$\frac{h_2^4}{\left(h_2^2 - \dfrac{3F_1^2h_1^4}{h_1^2 + 3F_1^2h_1^2}\right)} = \left(h_1^2 + 3F_1^2h_1^2\right) \tag{2.10}$$

We assume $\left(h_2^2 - \dfrac{3F_1^2h_1^4}{h_1^2 + 3F_1^2h_1^2}\right) \sim \left(\dfrac{3F_1^2h_1^4}{h_1^2 + 3F_1^2h_1^2}\right)$ so that (2.10) becomes

$$\frac{h_2^4}{\left(\frac{3F_1^2h_1^4}{h_1^2+3F_1^2h_1^2}\right)} = h_1^2 + 3F_1^2h_1^2$$

i.e.
$$h_2^4 = 3F_1^2h_1^4$$
$$h_2 = \left(3F_1^2h_1^4\right)^{1/4} \tag{2.11}$$

In terms of our modeling notation (2.11) gives

$$(h_2)_0 = \left[3(F_1)_0^2(h_1)_0^4\right]^{1/4} \tag{2.12a}$$

which is our first approximation for $(h_2)_0$. Successive approximations yield the desired $(h_2)_0$. Similarly, (2.11) yields using our modeling notation

$$(h_2)_N = \left[3(F_1)_N^2(h_1)_N^4\right]^{1/4} \tag{2.12b}$$

This is also our first approximation for $(h_2)_N$. Further iterations yield the desired $(h_2)_N$

(*ix*) Cross-sectional area $(A_2)_0$

$$(A_2)_0 = k(h_2)_0^2 \tag{2.13}$$

(*x*) Wetted perimeter $(P_2)_0$

$$(P_2)_0 = 2(h_2)_0\left[1+k^2\right]^{1/2} \tag{2.14}$$

(*xi*) Hydraulic mean depth $(R_2)_0$

$$(R_2)_0 = \frac{k(h_2)_0^2}{2(h_2)_0\left[1+k^2\right]^{1/2}} = \frac{k(h_2)_0}{2\left[1+k^2\right]^{1/2}} \tag{2.15}$$

(*xii*) Discharge $(Q_2)_0$

$$(Q_2)_0 = \frac{1}{n}(A_2)_0\left[(R_2)_0\right]^{2/3}S_0^{1/2} \tag{2.16}$$

(*xiii*) Mean velocity $(u_2)_0$

$$(u_2)_0 = \frac{(Q_2)_0}{(A_2)_0} \tag{2.17}$$

(*xiv*) Froude number $(F_2)_0$

$$(F_2)_0 = \frac{(u_2)_0}{\sqrt{g(h_2)_0}} \tag{2.18}$$

2.3 Mathematical model for the new triangular section

2.3.1 Upstream parameters

(*xv*) Cross-section area $(A_1)_N$

$$(A_1)_N = k(h_1)_N^2 \tag{2.19}$$

where $(h_1)_N$ is the upstream depth of the new channel

(*xvi*) Wetted perimeter $(P_1)_N$

$$(P_1)_N = 2(h_1)_N\left[1+k^2\right]^{1/2} \tag{2.20}$$

(*xvii*) Hydraulic mean depth $(R_1)_N$

$$(R_1)_N = \frac{k(h_1)_N^2}{2(h_1)_N\left[1+k^2\right]^{1/2}} = \frac{k(h_1)_N}{2\left[1+k^2\right]^{1/2}} \tag{2.21}$$

(*xviii*) Discharge $(Q_1)_N$

$$(Q_1)_N = \frac{1}{n}(A_1)_N\left[(R_1)_N\right]^{2/3} S_0^{1/2} \tag{2.22}$$

(xix) Mean velocity $(u_1)_N$

$$(u_1)_N = \frac{(Q_1)_N}{(A_1)_N} \tag{2.23}$$

(xx) Froude number $(F_1)_N$

$$(F_1)_N = \frac{(u_1)_N}{\sqrt{g(h_1)_N}} \tag{2.24}$$

(xxi) Critical depth $(h_c)_N$

$$(h_c)_N = \left[\frac{2(Q_1)_N^2}{k^2 g}\right]^{\frac{1}{5}} \tag{2.25}$$

2.3.2 Downstream parameters

($xxii$) Downstream depth $(h_2)_N$

Applying the method of successive approximation described above to the equation for conjugate depth (2.8a) and using our modeling notation the downstream depth $(h_2)_N$ can be obtained.

($xxiii$) Cross-sectional area $(A_2)_N$

$$(A_2)_N = k(h_2)_N^2 \tag{2.26}$$

($xxiv$) Wetted perimeter $(P_2)_N$

$$(P_2)_N = 2(h_2)_N\left[1+k^2\right]^{1/2} \tag{2.27}$$

(xxv) Hydraulic mean depth $(R_2)_N$

$$(R_2)_N = \frac{k(k_2)_N^2}{2(h_2)_N\left[1+k^2\right]^{\frac{1}{2}}} = \frac{k(h_2)_N}{2\left[1+k^2\right]^{1/2}} \tag{2.28}$$

($xxvi$) Discharge $(Q_2)_N$

$$(Q_2)_N = \frac{1}{2}(A_2)_N\left[(R_2)_N\right]^{2/3} S_0^{1/2} \tag{2.29}$$

($xxvii$) Mean velocity $(u_2)_N$

$$(u_2)_N = \frac{(Q_2)_N}{(A_2)_N} \tag{2.30}$$

($xxviii$) Froude number $(F_2)_N$

$$(F_2)_N = \frac{(u_2)_N}{\sqrt{g(h_2)_N}} \tag{2.31}$$

3.0 Model for energy loss, jump efficiency, relative energy loss, power loss and height of the jump

The energy loss h_f occurring between the two sections of the channel as determined from Bernoulli's equation for any streamline between points 1 and 2 of the hydraulic jump is

$$h_f = \left[\frac{u_1^2}{2g} + h_1\right] - \left[\frac{u_2^2}{2g} + h_2\right] \tag{3.1}$$

or

$$h_f = E_1 - E_2 \tag{3.2}$$

where

$$E_1 = \frac{u_1^2}{2g} + h_1 \tag{3.3}$$

and

$$E_2 = \frac{u_2^2}{2g} + h_2 \tag{3.4}$$

Here E_1 and E_2 denote the specific energies before and after the jump respectively. It is elementary to see that (3.1) yields after simplification

$$h_f = \frac{(h_2 - h_1)^3}{4h_1h_2} \tag{3.5}$$

From (3.5) we obtain using our modeling notation

Energy loss in the original channel $(h_f)_0$:

$$(h_f)_0 = \frac{[(h_2)_0 - (h_1)_0]^3}{4(h_1)_0(h_2)_0} \tag{3.6}$$

Energy loss in the new channel $(h_f)_N$:

$$(h_f)_N = \frac{[(h_2)_N - (h_1)_N]^3}{4(h_1)_N(h_2)_N} \tag{3.7}$$

Next, from (3.6) and (3.7) we have

Jump efficiency for the original channel

$$\frac{(E_2)_0}{(E_1)_0} = \frac{\frac{(u_2)_0^2}{2g} + (h_2)_0}{\frac{(u_1)_0^2}{2g} + (h_1)_0} \tag{3.8}$$

Jump efficiency for the new channel

$$\frac{(E_2)_N}{(E_1)_N} = \frac{\frac{(u_2)_N^2}{2g} + (h_2)_N}{\frac{(u_1)_N^2}{2g} + (h_1)_N} \tag{3.9}$$

Relative energy loss for the original channel

$$\frac{(E_1)_0 - (E_2)_0}{(E_1)_0} = 1 - \frac{(E_2)_0}{(E_1)_0} \tag{3.10}$$

Relative energy loss for the new channel

$$\frac{(E_1)_N - (E_2)_N}{(E_1)_N} = 1 - \frac{(E_2)_N}{(E_1)_N} \tag{3.11}$$

Let P^* denote the power loss in the jump, while H^* denotes the height of the jump. Then using our modeling notation we have

Power loss upstream of the original channel $\left(P_1^*\right)_0$

$$\left(P_1^*\right)_0 = \rho g \left(Q_1\right)_0 \left(h_f\right)_0 \tag{3.12}$$

Power loss downstream of the original channel $\left(P_2^*\right)_0$

$$\left(P_2^*\right)_0 = \rho g \left(Q_2\right)_0 \left(h_f\right)_0 \tag{3.13}$$

Similarly,

Power loss upstream of the new channel $\left(P_1^*\right)_N$

$$\left(P_1^*\right)_N = \rho g \left(Q_1\right)_N \left(h_f\right)_N \tag{3.14}$$

Power loss downstream of the new channel $\left(P_2^*\right)_N$

$$\left(P_2^*\right)_N = \rho g \left(Q_2\right)_N \left(h_f\right)_N \tag{3.15}$$

Consequently

Height of jump in the original channel $\left(H^*\right)_0$:

$$\left(H^*\right)_0 = \left(h_2\right)_0 - \left(h_1\right)_0 \tag{3.16}$$

Height of jump in the new channel $\left(H^*\right)_N$:

$$\left(H^*\right)_N = \left(h_2\right)_N - \left(h_1\right)_N \tag{3.17}$$

4.0 Numerical illustration

Consider, for example, a triangular channel with hydraulic jump having sides 1 vertical to 2 horizontal and slope 1 in 500. The channel conveys water at a depth of 1.25*m*, Manning coefficient n being 0.012. Using the model we wish to determine, after dredging the channel (*i*) the new discharge, (*ii*) the new cross-sectional area, (*iii*) the new downstream depth, (*iv*) the new critical depth, (*v*) the new energy dissipated in the jump, (*vi*) the new relative energy loss, (*vii*) the new jump efficiency, (*viii*) the new power loss and (*ix*) the new height of the jump if the excavation must be to the depth of 2.0m upstream. [Take $g = 9.81 m/s^2$].

4.1 Solution

4.1.1 Original channel

4.1.1.1 Upstream data

From the problem $\left(h_1\right)_0 = 1.25\,m,\ k = 2,\ n = 0.012,\ S_0 = \frac{1}{500}$. Substituting these data appropriately in the expressions (2.1) – (2.7) we obtain respectively

$$\left(A_1\right)_0 = 3.125 m^2, \left(P_1\right)_0 = 5.590 m, \left(R_1\right)_0 = 0.55901 m$$
$$\left(Q_1\right)_0 = 7.906 m^3\!/\!s, \left(u_1\right)_0 = 2.529 m/s, \left(F_1\right)_0 = 0.72248$$
$$\left(h_c\right)_0 = 1.260 m$$

4.1.1.2 Downstream data

Substituting the value of $\left(F_1\right)_0$ and that of $\left(h_1\right)_0$ above in (2.12b) yields the first approximation for $\left(h_2\right)_0$. Continuing the iterative process using this first approximation we finally obtain the downstream depth for the original channel given by $\left(h_2\right)_0 = 1.501 m$.

Applying this value with $k = 2, n = 0.012, S_0 = \frac{1}{500}$ in the expressions (2.13)-(2.18) we find respectively

$$(A_2)_0 = 4.50m^2, (P_2)_0 = 6.708m, (R_2)_0 = 0.67082m$$
$$(Q_2)_0 = 12.854m^3/s, (u_2)_0 = 2.856m/s, (F_2)_0 = 0.74468$$

4.1.2 New channel

4.1.2.1 Upstream data

Here $(h_1)_N = 2.0m, k = 2, n = 0.012, S_0 = \frac{1}{500}$. Appropriate substitution of the above data in the model (2.19)-(2.25) gives respectively

$$(A_1)_N = 8.0m^2, (P_1)_N = 8.944m, (R_1)_N = 0.89442m$$
$$(Q_1)_N = 27.679m^3/s, (u_1)_N = 3.459m/s, (F_1)_N = 0.78111$$
$$(h_c)_N = 2.081m$$

4.1.2.2 Downstream data

Similar substitution of the value of $(F_1)_N$ and that of $(h_1)_N$ above in (2.12c) yields the first approximation for $(h_2)_N$. After successive approximations we finally obtain the downstream depth for the channel given by $(h_2)_N = 2.514m$.

The parameters $(A_2)_N, (P_2)_N, (R_2)_N (Q_2)_N, (u_2)_N$ and $(F_2)_N$ for the new channel are determined respectively by appropriately substituting the above data in (2.26)-(2.31). The result is

$$(A_2)_N = 12.50m^2, (P_2)_N = 11.180m, (R_2)_N = 1.11803m,$$
$$(Q_2)_N = 50.178m^3/s, (u_2)_N = 4.014m/s, (F_2)_N = 0.80827$$

Furthermore, the energy loss, jump efficiency, relative energy loss, power loss upstream and downstream as well as height of the jump for the original channel are determined respectively by appropriate substitution of the above data in the model (3.6), (3.8), (3.10), (3.12), (3.13) and (3.16). Thus,

$$(h_f)_0 = 0.0021m, \frac{(E_2)_0}{(E_1)_0} = 1.2162,$$
$$1 - \frac{(E_2)_0}{(E_1)_0} = -0.2162, (P_1^*)_0 = 162.871W,$$
$$(P_2^*)_0 = 264.805W, (H^*)_0 = 0.251m$$

Finally, the energy loss, jump efficiency, relative energy loss, power loss upstream and downstream as well as height of the jump for the new channel are determined respectively via appropriate substitution of the above data in the expressions (3.7), (3.9), (3.11), (3.14), (3.15) and (3.17). Thus, we obtain

$$(h_f)_N = 0.0067m, \frac{(E_2)_N}{(E_1)_N} = 1.2779$$
$$1 - \frac{(E_2)_N}{(E_1)_N} = -0.2779$$
$$(P_1^*)_N = 1833.377W, (P_2^*)_N = 3323.646W$$

$$\left(H^*\right)_N = 0.514m$$

4.2 Results

The new parameters (*i*) - (*ix*) that are determined for the new channel are shown in Table 4.2 and can be compared with their counterparts for the original channel in Table 4.1 (see Tables 4.1 and 4.2 below)

Table 4.1: Result for the original channel

.	Original Channel with Jump	
	Upstream Parameters	**Downstream Parameters**
Bed slope	$\frac{1}{500}$	$\frac{1}{500}$
Manning's n	0.012	0.012
Side slope	1 vertical to 2 horizontal	1 vertical to 2 horizontal
Depth	1.25m	1.501m
Area of cross section	$3.125m^2$	$4.50m^2$
Wetted perimeter	5.590m	6.708m
Hydraulic mean depth	0.55901m	0.67052m
Discharge	$7.906m^3/_S$	$12.854m^3/_S$
Mean velocity	2.529m/S	$2.856^3/_S$
Froude number	0.72248	0.74468
Power loss	162.871W	264.805W
Critical depth	1.260m	
Energy loss	0.0021m	
Jump efficiency	1.2162	
Relative energy loss	-0.2162	
Height of jump	0.251m	

Table 4.2: Result for the new channel

	New Channel with Jump	
	Upstream Parameters	**Downstream Parameters**
Bed slope	$\frac{1}{500}$	$\frac{1}{500}$
Manning's n	0.012	0.012
Side slope	1 vertical to 2 horizontal	1 vertical to 2 horizontal
Depth	2.0m	2.514m
Area of cross section	$8.0m^2$	$12.50m^2$
Wetted perimeter	8.944m	11.180m
Hydraulic mean depth	0.89442m	1.11803m
Discharge	$27.679m^3/_S$	$50.178m^3/_S$
Mean velocity	3.459m/s	4.014m/s
Froude number	0.78111	0.80827
Power loss	1833.377W	3323.646W
Critical depth	2.081m	
Energy loss	0.0067m	
Jump efficiency	1.2779	

Relative energy loss	-0.2779
Height of jump	0.514m

5.0 Discussion and conclusion

Tables 4.1 and 4.2 show respectively the results of the analysis of the flow problem for the original and new (excavated) triangular channels. Comparison of the two Tables indicates that the downstream parameters, namely, the downstream depth, area of cross section, wetted perimeter, hydraulic mean depth, discharge, mean velocity, Froude number and power loss are generally greater in the original and new channels than the upstream ones. This is in agreement with the model (2.8b) (2.12)-(2.18) and (2.8c),(2.26)-(2.31) of the original and new channels respectively. In particular, these same parameters upstream and downstream are greater in the new channel than their counterparts in the original one. This is also evident from the two Tables. It should be noted that the mean velocity and the Froude number are expected to be lower downstream than their counterparts upstream in both the original and new channels. However, this is not the case for the triangular channel since, unlike other channel sections, the triangular channel section does not satisfy the condition for best hydraulic performance; that is, the triangular channel is inefficient hydraulically. This peculiarity or feature of the triangular channel also results in the negative value of the relative energy loss for both original and new channels. Another feature is that the critical depth, energy loss, jump efficiency and height of the jump are greater in the new channel than in the original one (see Tables 4.1 and 4.2).

Nevertheless, the triangular channel section is of considerable value in the analysis of open channel flow because of its economic importance. For instance, it becomes very clear from the two Tables that the new channel maintains a higher water level than the original one. This high water level in the new channel, apart from enhancing navigation, can be harnessed for water distribution purposes and for mixing of chemicals used for water purification or waste water treatment.

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