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Design and Construction of a rectangular section channel-prototype, to determine the specific energy in the three types of regimens: Critical, subcritical and supercritical

Diseño y Construcción de un canal-prototipo de sección rectangular, para determinar la energía especifica en los tres tipos de regímenes: Crítico, subcrítico y supercrítico

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Abstract

The problem of water scarcity is not a transient issue, but to solve it has been a long lasting endeavor for humanity. Many human societies have tried diverse solutions to solve this problem and one of them was to efficiently move water for the subsistence of all people. For this purpose, civil and agricultural engineers seek to find novel ways to conduct water as close as possible to where it is needed, e.g., cultivated fields and water supply reservoirs, or to build up infrastructure to greatly reduce the immense problem of floods generated by high intensity rains. The main goal of this paper is to determine the water specific energies occurring in critical, subcritical and supercritical flow regimes, by means of a prototype rectangular section channel operation. Application of Bernoulli´s equation for uniform flow conditions is the adopted methodology. As final conclusions we can state that development of new channel prototypes facilitates the experimentation of fluids, allowing to a great extent the stabilization of flow, thus, optimizing the measurement of different types of key water variables.

Conduction, Flooding, Specific energy

Resumen

El problema de la escasez del agua no es tema de actualidad. Muchas sociedades han tratado de solucionar este problema y uno de ellos fue trasladar eficientemente el agua para la subsistencia de todas las personas, se han construido canales lo más cerca posible de donde sea necesitada el agua, en sitios tales como sembradíos y embalses, o la infraestructura para aliviar en gran medida el inmenso problema de las inundaciones generados por lluvias de alta intensidad. El objetivo es determinar las energías específicas del agua en los siguientes regímenes: crítico, subcrítico y supercrítico, mediante la operación de un prototipo-canal de sección rectangular. La metodología empleada consiste en la aplicación de la ecuación de Bernoulli para condiciones de flujo uniforme. Como conclusiones podemos afirmar que el desarrollo de nuevos prototipos de canales facilita la experimentación de fluidos permitiendo en gran medida la estabilización de flujos, por lo que optimiza la medición de los diferentes tipos de importantes variables del agua.

Conducción, Inundaciones, Energía específica

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1. Introduction

Fluids are liquid or gaseous substances that having low cohesion, adopt the shape of the bowl that contains them. Some of these containers can be classified either channels or pipelines. In channels, the fluid presents a surface open atmosphere and flows under the action of gravity, on the contrary, inside the latter the fluid is totally confined causing it to exert gravity, pressure and viscosity forces on the surrounding walls. Furthermore, in channels surface tension is present as well as other forces that can cause sediment dragging and accumulation, thus affecting the initial flow conditions (Sotelo, 2002).

Channels also have specific characteristics that must be considered in order to fully understand fluid dynamics. One of such characteristic is freeboard, which is defined as the distance or height from the free surface of the water to the top of the channel (the allowable limit before overflow occurs). Another characteristic is the longitudinal slope of the channel bottom, which is necessary for water to flow downstream (Chow, 2004). These and other characteristics should be taken into account for the design and construction of channels as conduction works. Despite the similarity between the two kinds of conduits, it is much more difficult to describe water flow along open channels than in pressurized pipelines. The flow conditions in open channels are complex due to the fact the position of the free surface can change with respect to time and space, as well as water depth, flow rate and longitudinal slope of the channel (Chow, 1994).

Examples of complex and detailed water works are the following: navigation channels, spillways, diversion tunnels hydroelectric inlet conduits, irrigation and drainage waterways and weirs, as well as channels constructed and operated at research laboratories as prototypes for experimental procedures.

The main objective of this paper is to characterize the three types of regimens occurring during the design and construction phases of a rectangular section prototype channel: critical, subcritical and supercritical flows by means of Froude number calculations, a number which represent the relation between the mean velocity of the uniform flow regime and the relative wave speed.

2. Background

Channels can be either natural or artificial depending on their origin. The former is usually created by aquatic ecosystems to conduct and drain water, forming rivers or streams. On the other hand, artificial channels are manmade, built by civil engineers, either for navigation purposes of defense works to prevent flooding. One of the main characteristics of natural channels is the irregularity of their shape, something which causes dimension and depth variations along the channel. In contrast, Artificial channels have a well-defined geometric shape, and in several sections the dimensions may remain constant.

Hydraulic engineering is as old as civilization itself, this fact is evident if we think of man´s long struggle for survival and to achieve better living conditions, something which has driven societies to learn how to better use and control water.

The history of hydraulic engineering in Mexico dates back to pre-Hispanic times and can be described through its hydraulic works. These works have solved to the needs of catchment, conduction, storage, distribution and irrigation during the different periods through which the country has passed (Peña Santana, 1989).

The Mexica people, one of the most representative pre-Hispanic societies, had a close relationship with their water resources. As a proof of this, there exist data about the fact that their cities were designed to have efficient irrigation systems through a network of aquatic communication schemes, formed by “chinampas”, a local nahuatl word for a type man-made floating farming rafts, water channels and irrigation ditches; a novel solution with which they were able to solve a recurring problem of Mesoamerica cultures: water use and transportation (Villagómez, 2013).

Besides the water use and transportation purposes of channels, flood prevention and protection are some additional and important objectives for efficient design and construction of these kind of water works. Every year and all over the world occur frequent and severe flood episodes that inflict material and personal damages to human settlements and existing environmental conditions.

There are numerous cases of many Mexican cities that suffer severe flooding caused episodes by high intensity rains, such as several cities located in the state of Tabasco that experienced extreme flooding events during the 2016 and 2021, rainy season when the city streets became water became channels (Cama-Pinto *et al,* 2016)

Furthermore, floods are frequently accompanied by water channel clogging caused by solid material coming down from the upper parts of watersheds, the quantity of which depends on the intensity of runoff, vegetation cover, soil type as well as terrain slope, all of which define the areas of deposition of the material (Eslava *et al,* 2006)

3. Channel design and construction

The process of calculating the main channel parameters and dimensions is based on well-known existing equations seeking to carry out a proper design. Among the parameters to be determined are the following: general geometry of the channel, the occurring water specific energy and the channel depths for each regime conditions.

3.1 Geometry of the channel

Based on the present conditions of the Laboratory of Hydraulics of the Polytechnic University of the Metropolitan Zone of Guadalajara and the specific characteristics of the existing hydraulic bank, the construction of a rectangular channel was chosen.

The equations to be used in order to obtain the eigenvalues of the channel are taken from literature provided by several authors (Chow, 2004, Rodríguez, 2008. Morales Nava *et al,* 2013), initial dimensions proposed for design of the channel are: channel width b = 0.11 m and channel height HT= 0.09 m.

4. Methodology

Freeboard height (FB) is obtained by a simple Rule of Three calculation, taking into account that it would approximately be 30% of the height of the channel.

$$FB = \frac{30\% * 0.09\,m}{100\%} = 0.027\,m \tag{1}$$

The hydraulic or flow depth (y) is:

$$HT = BL + y \;\therefore$$
$$y = HT - BL = 0.090 - 0.0275 = 0.0625\,m \tag{2}$$

Geometric Calculations

The area (A) of the channel is:

$$A = b * y = 0.11\,m * 0.037\,m = 0.0041\,m^2 \tag{3}$$

Wetted perimeter (P)

$$P = b + 2y = 0.11 + (2 * 0.037) = 0.184\,m \tag{4}$$

Hydraulic radius (R)

$$R = \frac{A}{P} = \frac{0.0041}{0.184} = 0.022\,m \tag{5}$$

Section factor (Z)

$$Z = b * y^{1.5} = 0.11 * 0.037^{1.5} = 0.00078\,m \tag{6}$$

From Manning´s equation we have that:

$$V = \frac{R^{3/4}\,s^{1/2}}{n} \tag{7}$$

Where
R = hydraulic radius (m),
S = slope of the channel (dimensionless factor)
n= roughness coefficient (s/m^3).

The flow rate (m^3/s) is defined as:

$$Q = V * A \tag{8}$$

Where
V = is the velocity of water inside the channel (m/s)
A = cross-sectional area of the channel (m^2)

By replacing equation (7) in (8), we obtain another expression for the flow rate, which will be used later on

$$Q = A * \frac{R^{3/4}\,s^{1/2}}{n} \tag{9}$$

Now, the section factor (Z) can also be calculated by the following expression:

$$Z = \frac{Q}{\sqrt{g}} \tag{10}$$

Finally, by equating the equations and replacing the value of the channel width (b) and the gravity force at sea level g = 9.81 m/s², we arrive at equation (11), which will be used together with equation (9), in order to determine the critical slope of the channel Sc, a dimensionless factor.

$$Q = 0.344 * y^{1.5} = 0.344 * 0.037^{1.5} = 0.00245\, m^3/seg \qquad (11)$$

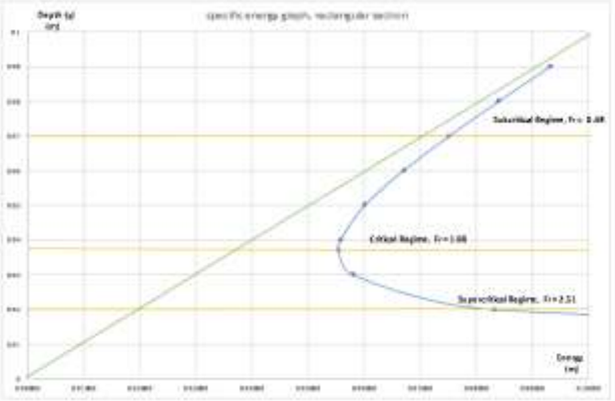
4.1 Graph of the curve of depth vs specific energy

In order to determine the depth vs specific energy curve graph, the critical depth range yc (m) and subsequently the operation flow, it is necessary to perform iterations using equations (9) and (11), in order to obtain the value of the critical point directly from the specific energy curve, as show in Graph 1.

The performed iterations are shown in table 1, where flow depth values are given from a range of 0.01 to 0.09 m, with a roughness coefficient n = 0.010, which is the roughness value corresponding to plastic. These data will be used to obtain the graph of the specific energy in addition to obtaining the operating point of the equipment (Chow, 1994).

Depth (m)	Area (m²)	Wetter perimeter (m)	Hydraulic radius (m)	Energy (m)	Froude
0.010	0.0011	0.13	0.0846	0.2684	7.11
0.020	0.0022	0.15	0.0146	0.0831	2.51
0.030	0.0033	0.17	0.0194	0.058	1.36
0.037	0.0040	0.184	0.0217	0.0554	0.99
0.040	0.0044	0.19	0.0231	0.0558	0.88
0.050	0.0055	0.21	0.0261	0.0601	0.63
0.060	0.0066	0.23	0.0286	0.067	0.48
0.070	0.0077	0.25	0.0308	0.0751	0.38
0.080	0.0088	0.27	0.0325	0.0839	0.31
0.090	0.0099	0.29	0.0341	0.0931	0.26

Table 1 Maximum and minimum depths, to obtain the critical conditions or each regime
Source: Caro Becerra et al., 2022



Graph 1 Graph of the specific energy, to obtain the Froude number, speed and energy available in each regime
Source: Caro Becerra, et al, 2022

When constructing the graph of the specific energy, it is evident that the graph is an asymptotic curve, and precisely in the point where the change of slopes occurs we can locate the operating flow rate, as can be seen in graph 1, yc = 0.037 m, Qc = 0.00245 m³/s.

Therefore, the operating flow rate will be given by the following equation:

$$Qop = \frac{Qc*ymax}{yc} = \frac{0.00245 * 0.09}{0.0375} = 0.00588\, m^3/s \qquad (12)$$

Finally, we determine the operating speed of the channel.

$$Vop = \frac{Qop}{A} = \frac{0.0058}{0.0099} = 0.593\, m/s \qquad (13)$$

Depth correction – operating flow rate – critical velocity

$$ycc = \sqrt[3]{\frac{Qop^2}{g* b^2}} = \sqrt[3]{\frac{0.0058^2}{9.81*0.11^2}} = 0.065\, m \qquad (14)$$

$$Vcc = \sqrt[3]{\frac{Qop *g}{b}} = \sqrt[3]{\frac{0.0058*9.81}{0.11}} = 0.802\, m/s \qquad (15)$$

$$Qcc = Acc * Vcc = 0.065 * 0.11 * 0.802 = 0.00573\, m^3/s \qquad (16)$$

4.2 Normal depth calculation

For the calculation of the normal depth, the iteration method is used again, making use of the equations proposed by (Streeter et al, 2000), which are shown below:

$$A = C * P^{\frac{2}{5}} = b * yn \quad (17)$$

$$P = b + 2y \quad (18)$$

$$C = \left(\frac{Qop*n}{S^{0.5}}\right)^{\frac{3}{5}} \quad (19)$$

$$C = \left(\frac{0.00585 * 0.010}{0.0057^{0.5}}\right)^{3/5} = 0.0136$$

S represent the slope of the channel template and the value used in our case is 0.0057 (dimensionless).

Having done enough iterations, a normal depth was obtained yn = 0.06 m.

The results obtained show that yn < ycc, which indicates that the slope of the channel is moderate and it is in zone 1. It sholuld also be noted that the profile can change with the value of the flow rate used, which indicates that three types of regimes can be obtained in the same channel: critical, subcritical and supercritical.

Figure 1 Design and construction of a rectangular channel-prototype for the elaboration of uniform flow practice and obtaining these results, by students of the University Polytechnic of the Metropolitan Zone of Guadalajara and University of Guadalajara
Source: Caro, J. L. 2022

Figure 2 Appreciation of the critical, subcritical and supercritical flow in the rectangular section channel with the dimensions and results obtained in the practice
Source: Caro, J. L. 2022

4.3 Final prototype of the channel and its dimensions

Figure 1 shows the final prototype of the channel once it is in operation for different flow rates; Figure 2 and table 2 shows the general dimensions of the channel and data base.

Length	L = 5 m
Width	b = 0.11 m
Maximum height of the channel	H = 0.09 m
Operating range of the channel	Q = 0 – 0.00585 m³/s
Channel speed variation	V = 0 – 0.802 m/s
Water level variation	h = 0 – 0.0725 m
Channel slope variation	S = 0 – 0.0057

Table 2 Range of data base obtained with the prototype-channel
Source: Caro, J. L. 2022

From graph 2, the experiment values of yc and Emin were obtained for each of the runs carried out with a constant flow rate (Chow, 2004; Mejía, 2008) are given at the inflection point of the curve of the specific energy graph and are detailed in the following table 3.

Experiment 1	Q1 = 0,0050 m³/sec	yc1exp = 0.06 m	E1exp = 0.10 m
Experiment 2	Q2= 0,0025 m³/sec	yc2exp = 0,038 m	E2exp = 0.057 m
Experiment 3	Q3 = 0.0011 m³/sec	yc3exp = 0,022 m	E3exp = 0.030 m

Table 3 Experimental data obtained from the specific energy graph for different design flow rates
Source: Caro, et al., 2022

5. Results and discussion

To validate the operation of the prototype channel already built, an experiment was carried out to determine the relationship between the specific energy and the hydraulic load above and below a triangle-shaped block submerged in the channel to determine the specific energy before and after the block. Sudden changes in the flow are not taken into account because there are no changes in the geometry of the section, in order to obtain multiple critical stresses.

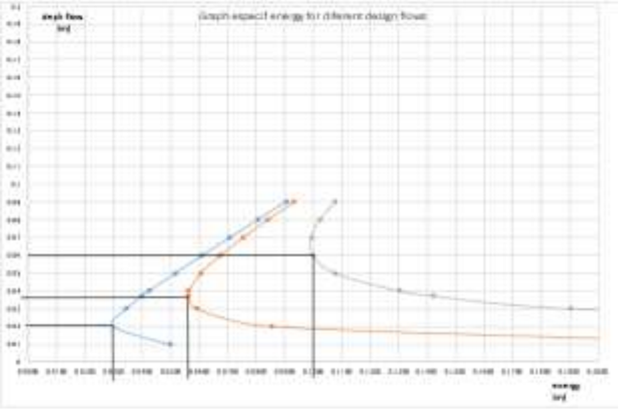
According to (Mejía, 2008; Marbello, 2005), it is important to remember that the specific energy is defined as the sum of the potential energy (depth of flow) plus kinetic energy.

$$E = y + \frac{V^2}{2g} \quad (21)$$

$$E = y + \frac{Q^2}{2g\,y^2} \quad (22)$$

Where
E = specific energy (m)
y = depth of flow (m)
Q = flow rate (m^3/s)
g = gravitational force (m^2/s)

Three flow rates were used with the rectangular channel prototype, which are as follows: Q1 = 0.0050 m^3/s, Q2 = 0.0025 m^3/s, Q3 = 0.0011 m^3/s, for each of the experiments performed, were obtained directly from the flow sensor, for each value of Q depths were taken before and after the values were reported with the use of the Vernier which offers an accuracy of $\mp 0.05\ mm$.



Graph 2 Graph of specific energy for different types of regimen and flow
Source: González, G. K. 2022

6. Conclusions

From the results obtained, the following can be concluded: the design and construction of the rectangular channel with variable a slope represents a low-cost investment compared to those existing in the market. The construction of the channel has also increased the free development of laboratory practices in the areas of hydraulic and fluid mechanics at the Polytechnic University of the Metropolitan Zone of Guadalajara. The results obtained as validation of the prototype, show that the channel effectively meets the necessary conditions to study and validate the different physical phenomena that can be represented at low scale and thus can be used as a modeling for real studies.

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