

Ideal Velocity: A New Concept for Open Channel Flows

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Abstract-It is common knowledge that both fresh water and precipitation have no homogeneous mixture temporally or spatially on the earth planet. Transportation of water from one region to another has always been a part of human existence. The transfer is achieved by water conveyance structures (i.e. channels, pipes, tunnels, galleries, and drains). However, the flow in such structures occurs hydraulically and can be divided into two main classes: (1) pipe flow and (2) open channel flow. There are many published studies in the current literature on modeling pipe or open canal flows. In this study, following a relevant discussion on existing literature, a new concept of “ideal velocity” is introduced. Furthermore, ideal discharge and Reynolds and Froude numbers, which are currently used in computational hydraulics, are re-modified following the new concept. The simplification of such equations by the new concept will conveniently solve many hydraulic problems, particularly in pipe and open canal manufacturing sectors.

Keywords- *Ideal Velocity; Open Canal Hydraulics; Open Canal Flows; Open Canal Manufacturing*

I. INTRODUCTION

It is well-known that precipitation and fresh water resources are not homogeneously distributed, either spatially or temporally. For example, one-fourth of annual precipitation occurs in regions where one-third of the total world population lives. Two-thirds of the world's population use only one-fourth of total fresh water resources [1]. Therefore, transfer of water from one region to another (water transport) has always been a key part of human existence. In the last few decades, world fresh water consumption has increased in unprecedented ways as a result of world population growth, industrialization, technological developments, and diversity in water use based on the rise of living standards. The world population has dramatically increased, and it continues to do so. According to the 2006 Revision (UN), the world population is likely to increase by 2.5 billion over the next 43 years, growing from the current 6.7 billion to 9.2 billion in 2050 [2]. More people are bound to need more water for a variety of uses. The more water used, the more water must be distributed, which also increases distribution networks. It is expected that distribution of precipitation and fresh water resources will completely change both spatially and temporally as a result of global climate change [2-3]. This situation means that fresh water requirements will increase gradually every year. It is clear that for supplying domestic, industrial, and irrigation water, transfer of water from one region to another (water transport) will be a vital requirement in every instance.

The use of fossil energy sources produces greenhouse gases and, consequently, IPCC reports claim that emission of such gases is a consequence of human activities at high percentages, 98% or 99% [4-5] (IPCC, 2007; IPCC, 2013-AR5). Among all the publications we reviewed, about 90% of scientific articles present evidence on the existence of global warming or global climate change [6-7]. Alashan et al., (2015) indicates that producing energy is very important, but that it is even more important to produce clean, sustainable, and inexhaustible energy sources with marginal pollution effects that are almost negligible in practice (i.e., hydropower, solar, wind, wave, geothermal, and hydrogen energy, among others) [8]. According to Toprak (2014) and Toprak et al. (2014), hydropower is a key strategy to protect fresh water resources (i.e. rivers) against chemical, biological, nuclear, and physical pollutants [9-10]. However, water transport is also needed for hydropower. Global and local water trade and inter-basin water transfer are another two important factors that affect water transport.

Given the above considerations, it is possible to say that due to inhomogeneous distribution of precipitation and water resources, population growth, industrialization, technological developments, diversity in water use, global climate change, supplying the domestic, industrial, irrigation, and hydropower water, water trade, and inter-basin water transfer, currently water transport is globally becoming a key issue. We expect it will become a vital, long-term requirement in the future.

Water transfer is technically done by hydraulic structures, such as canals, pipes, tunnels, galleries, drains, and balloons. However, the type of flow that occurs in those structures is categorized hydraulically as open canal and pipe flows. Due to this issue's vital importance, there are many published studies on pipe and open canal flow modeling. We discuss some of the key studies in the section below.

II. A BRIEF DISCUSSION ON THE CURRENT LITERATURE

Toprak (2009) states that to minimize environmental impacts and maximize the benefits of water resources, optimization of effective sections for any water flow is particularly important; not only for irrigation and drainage systems, but also for flood flow in natural channels. The author indicates that up to the end of the 20th century, modelers used well-known empirical

conventional equations such as Chezy, Gauckler-Strickler, and Manning approaches for this purpose [11]. However, the recent availability of computers' large capacity and transaction speed allows for the use of artificial intelligence methods (i.e. fuzzy logic-FL, genetic algorithms-GAs, and artificial neural networks-ANNs).

There are many published works on this subject in the current literature. The essential articles are given here in reverse chronological order: Toprak (2016), Swamee & Chahar (2015), Meniconi et al. (2014), Wertel et al. (2010), Greiner (2009), Froehlich (2008), Bhattacharjya & Satish (2007), Das (2007a), Das (2007b), Kentel & Aral (2007), Abdeen (2006), Bhattacharjya (2006), Chahar (2005), Depeweg & Urquieta (2004), Jain et al. (2004), Guenter & Schmidt (2002), Swamee et al. (2002a), Swamee et al. (2002b), Swamee et al. (2001), Babaeyan et al. (2000), Das (2000), Swamee et al. (2000a), Swamee et al. (2000b), Swamee et al. (2000c), Hankin & Beven (1998), Federico (1998), Reddy (1996), Reddy (1995), Swamee (1995), Froehlich (1994), Garcianavarro et al. (1994), Monadjemi (1994), Loganathan (1991), Dubos (1988), Flynn ve Marino (1987), Guo & Hughes (1984), Mironenko et al. (1984) [12-48].

These valuable studies offer modifications for existing equations and/or propose several modeling techniques for optimization of artificial and natural channels' cross-sections. The studies' value lies in the fact that the researchers tried to investigate the possibility of obtaining maximum flow with minimum energy or minimum construction cost in a canal. However, most of the studies' analyses and results are not simple; rather, they solve this problem with several complex differential equations that require commercial software. There is a general lack of discussion of novel approaches or new perspectives on flow in an open canal. In Toprak (2016), the new concept of "ideal velocity" is introduced [12]. Furthermore, the well-known equations used in computational hydraulic are re-modified according to this new concept. The "ideal velocity" depends on the assumption of circular distribution of the velocity through the cross-section of a pipe or an open canal flow. In engineering studies, it is too difficult to model any natural events with deterministic and analytical models due to the complexity of mathematical expressions. It is considered that the simplification of such equations by using the new concept will conveniently solve hydraulic problems, particularly in pipe and open canal manufacturing sectors [12]. In this study, "ideal velocity" (as introduced by Toprak (2016)) is suggested for rectangular open canal flows. Moreover, by substituting continuity and Froude Number equations with ideal velocity, the ideal discharge and ideal Froude Numbers are derived for a rectangular open canal flow.

III. IDEAL VELOCITY CONCEPT FOR OPEN CANAL FLOWS

A. Derivation of Ideal Velocity

In his 2016 study, Toprak defines "ideal velocity" in depth [12]. Therefore, there is no need to extensively discuss the concept's definition here. However, we can define the concept briefly as circular cross-sectional velocity. In other words, the parabolic cross-sectional velocity is assumed to be circular [12].

By assumption of ideal velocity distribution, the ideal mean cross-sectional flow velocity (V , m/s) for a rectangular open canal flow, which has a depth of y (as given in Fig. 1), can be derived by the following steps. In this case, the maximum cross-sectional velocity (u_{\max}) will be equal to the semi-diameter of the circular velocity distribution, which is equal to flow depth (y , m). According to the ideal velocity definition, the velocity can be expressed by flow depth (y , m) for the rectangular open canal flows, as given by Equations (1), (2), and (3).

The mean cross-sectional velocity (V , m/s) can be formulated as given in Eq. (1).

$$V = \frac{\left[\frac{\pi D^2}{4} \right]}{y} \quad (1)$$

Due to the assumptions in the ideal velocity definition, from Figure 1, it is possible to say that the depth is equal to the semi-diameter of the velocity distribution as given in Eq. (2)

$$y = \frac{D}{2} \Rightarrow D = 2y \quad (2)$$

Accordingly, the ideal mean cross-sectional velocity can be obtained as presented in the following expression:

$$V_i = \frac{\frac{\pi * 4y^2}{4}}{y} = \frac{\pi * y}{4} = 0.785 y \quad (3)$$

This equation (Eq. 3) is dimensionally not homogeneous, as is well-known in the Manning-Strickler equation.

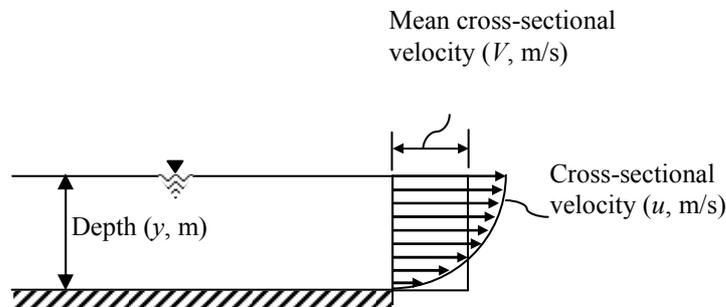


Fig. 1 The distribution of the cross-sectional velocity in a rectangular open canal flow

B. Derivation of Ideal Discharge

By substituting continuity equation with ideal velocity, the ideal discharge for a rectangular open canal flow can be obtained in a form as presented in Eq. (8). The derivation steps are given in Eqs. (4-7).

$$Q = \int_A u dA = V * A \quad (4)$$

$$V = \frac{\int u dA}{A} = \frac{Q}{A} \quad (5)$$

$$Q = VA \quad (6)$$

$$Q_i = V_i A \quad (7)$$

$$Q_i = \frac{\pi * y}{4} B y = 0.7854 B y^2 \quad (8)$$

Herein, Q , Q_i , A , B are the discharge, ideal discharge, cross-sectional area, and open canal width respectively. Eq. (8) is dimensionally not homogenous.

C. Derivation of Ideal Froude Number

By substituting the ideal velocity into the equation of Froude Number (Eq. 9), the ideal Froude Number can be obtained for a rectangular open canal flow in a form as presented in Eq. (10).

$$Fr = \frac{V}{\sqrt{gy}} \quad (9)$$

and therefore,

$$Fr_i = \frac{\frac{\pi y}{4}}{g^{1/2} y^{1/2}} = \frac{\pi y}{4 g^{1/2} y^{1/2}} = \frac{\pi y^{1/2}}{4 g^{1/2}} = 0.251 y^{1/2} \quad (10)$$

Herein Fr , Fr_i , and g are Froude Number, ideal Froude Number, and acceleration of gravity. Since the ideal Froude Number is dimensionless, the coefficient of 0.251 has a dimension of $m^{-1/2}$ in both SI and MKS unit systems.

IV. CONCLUSION

In this study, Toprak's concept of "ideal velocity" (2016) is applied to rectangular open canal flows. By assuming the cross-sectional flow velocity as circular, ideal velocity can be expressed by depth (y , m) for a rectangular open canal flow, as $0.7854 y$. Ideal discharge for a rectangular open canal flow can be expressed as $0.7854 By^2$. The expression of the ideal discharge varies for the open canal flows according to the geometry of the canal (i.e. trapezoidal, triangular, rectangular, square, and so on). Ideal Froude Numbers can be expressed in terms of the depth for rectangular open canal flows as $0.251 y^{1/2}$. The equations of ideal velocity and ideal discharge are not dimensionally homogeneous. However, the ideal Froude Number is dimensionless – therefore, the coefficient of 0.251 should have a dimension of $m^{-1/2}$ in both SI and MKS unit systems. We conclude that the simplification of such equations by using the new concept is capable of conveniently solving hydraulic problems, particularly in open canal manufacturing sectors.

ABBREVIATIONS

UN United Nations
 IPCC Intergovernmental Panel on Climate Change
 FL Fuzzy Logic
 GAs Genetic Algorithms
 ANNs Artificial Neural Networks
 s Second
 m Meter
 SI International system of units
 MKS System of units (stands for meters, kilograms, seconds)

SYMBOLS

R_e Reynolds Number (dimensionless)
 R_{ei} Ideal Reynolds Number (dimensionless)
 D Diameter of pipe (m)
 V Cross-sectional mean velocity for pipe and open canal flows (m/s)
 V_i , ideal cross-sectional mean velocity (m/s)
 u Cross-sectional velocity (m/s)
 y water depth in open channel (m)
 Q Discharge for both pipe and open canal flows (m^3/s)
 Q_i Ideal discharge for both pipe and open canal flows (m^3/s)
 A Cross-sectional area (m^2)
 ν Cinematic viscosity (m^2/s)
 F_r Froude Number (dimensionless)
 F_{ri} Ideal Froude Number (dimensionless)
 g Acceleration of gravity (m/s^2)

REFERENCES

- [1] Aytek, and Z. F. Toprak, "Fresh Water-Saltwater Distribution and Freshwater Potential of Turkey," in *Proc. International Symposium on Water Resources and Environmental Impact Assessment*, 2001, pp. 233-238.
- [2] Z. F. Toprak, M. Songur, N. Hamidi, and H. Gulsever, "Determination of Losses in Water-Networks Using a New Mathematical Approach," in *Proc. 3rd International Water Congress and Exhibition*, 2013, pp. 537-554.
- [3] Z. F. Toprak, N. Hamidi, Ş. Toprak, and Z. Şen, "Climatic identity assessment of the climate change." *Int. J. Global Warming*, vol. 5 (1), pp. 30-45, 2013.
- [4] The Intergovernmental Panel on Climate Change (IPCC), established by WMO and UNEP Fourth Assessment Report, "Climate Change

- 2007", February 2007.
- [5] The Intergovernmental Panel on Climate Change (IPCC), "Climate Change 2013", The Physical Science Basis IPCC Working Group I Contribution to AR5, 2013.
- [6] Z. Şen, "İklim Değişikliğinin Su Ve Enerji Kaynaklarımıza Etkisi," in *Proc. March 22 World Water Day*, 2005.
- [7] Z. Şen, *İklim değişikliği yerel yönetimler ve sektörler*, 1th ed., Su Vakfı Ed., 2009.
- [8] S. Alashan, Z. Sen, and Z.F.Toprak, "Hydroelectric Energy Potential of Turkey: A Refined Calculation Method," *The Arabian Journal for Science and Engineering (Arab J Sci Eng)*, 2015.
- [9] Z. F. Toprak, "Türkiye'de ve Dünyada Hidrolik Enerji Potansiyeli," *Mimar ve Mühendis Grubu Dergisi*, vol. 75, pp. 60-64, 2014.
- [10] Z. F. Toprak, N. Hamidi, O. Kisi, and R. Gerger, "Modeling dimensionless longitudinal dispersion coefficient in natural streams using artificial intelligence methods," *KSCE Journal of Civil Engineering*, vol. 18, pp. 718-730, March 2014.
- [11] Z. F. Toprak, "Flow Discharge Modeling in Open Canals Using a New Fuzzy Modeling Technique (SMRGT)," *CLEAN-Soil, Air, Water*, vol. 37 (9), pp. 742-752, 2009.
- [12] Z. F. Toprak, "Ideal Velocity as a New Concept for Flows," in *Proc. 19th International Water Technology Conference (IWTC 2016)*, 2016.
- [13] P. K. Swamee, and B. R. Chahar, "Minimum Water Loss Canal Section, Springer Transactions," *Civil and Environmental Engineering-Design of Canals*, pp. 97-106, 2015.
- [14] S. Meniconi, H. Duan, B. Brunone, M. Ghidaoui, P. Lee, and M. Ferrante, (2014) "Further Developments in Rapidly Decelerating Turbulent Pipe Flow Modeling," *J. Hydraul. Eng. (ASCE)*, vol. 140 (7), pp. 04014028-1-04014028-9, 2014.
- [15] J. Wertel, J. Vazquez and R. Mose, "3D staggered grid turbulent flow modeling in sewer net pipe," *Houille Blanche-Revue Internationale De L Eau*, vol. 1, pp. 83-89, 2010.
- [16] W. Greiner, *Classical Mechanics: Systems of Particles and Hamiltonian Dynamics*, 2nd Ed, Springer Science & Business Media, pp. 580, 2009.
- [17] D. C. Froehlich, "Most hydraulically efficient standard lined canal sections," *Irrigation and Drainage Engineering-ASCE*, vol. 134 (4), pp. 462-470, 2008.
- [18] R. K. Bhattacharjya, and M. G. Satish, "Optimal design of a stable trapezoidal channel section using hybrid optimization techniques," *Irrigation and Drainage Engineering-ASCE*, vol. 133 (4), pp. 323-329, 2007.
- [19] Das, "Optimal design of channel having horizontal bottom and parabolic sides," *Irrigation and Drainage Engineering-ASCE*, vol. 133 (2), pp. 192-197, 2007.
- [20] Das, "Flooding probability constrained optimal design of trapezoidal channels," *Irrigation and Drainage Engineering-ASCE*, vol. 133 (1), pp. 53-60, 2007.
- [21] Kentel, and M. Aral, "Fuzzy multiobjective decision-making approach for groundwater resources management," *Hydrologic Engineering(ASCE)*, vol. 12 (2), pp. 206-217, 2007.
- [22] M. A. M. Abdeen, "Development of artificial neural network model for simulating the flow behavior in open channel infested by submerged aquatic weeds," *Mechanical Science and Technology*, vol. 20 (10), pp. 1576-1589, 2006.
- [23] R. K. Bhattacharjya, "Optimal design of open channel section incorporating critical flow condition," *Irrigation and Drainage Engineering-ASCE*, vol. 132 (5), pp. 513-518, 2006.
- [24] B. R. Chahar, "Optimal design of parabolic canal section," *Irrigation and Drainage Engineering-ASCE*, vol. 131 (6), pp. 546-554, 2005.
- [25] H. Depeweg, and E. R. Urquieta, "GIS tools and the design of irrigation canals," *Irrigation and Drainage*, vol. 53 (3), pp. 301-314, 2004.
- [26] Jain, R. K. Bhattacharjya, and S. Sanaga, "Optimal design of composite channels using genetic algorithm," *Irrigation and Drainage Engineering-ASCE*, vol. 130 (4), pp. 286-295, 2004.
- [27] G. Leugering, and J. P. G. Schmidt, "On the Modelling and Stabilization of Flows in Networks of Open Canals," *SIAM J. Control Optim.*, vol. 41 (1), pp. 164-180, 2002.
- [28] P. K. Swamee, G. C. Mishra, and B. R. Chahar, "Design of minimum water-loss canal sections," *Hydraulic Research*, vol. 40 (2), pp. 215-220, 2002.
- [29] P. K. Swamee, G. C. Mishra, and B. R. Chahar, "Optimal design of transmission canal," *Irrigation and Drainage Engineering-ASCE*, vol. 128 (4), pp. 234-243, 2002.
- [30] P.K. Swamee, G. C. Mishra, and B. R. Chahar, "Design of Minimum Earthwork Cost Canal Sections," *Water Resources Management*, vol. 15, pp. 17-30, 2001.
- [31] K. Babaeyan-Koopaei, E.M. Valentine, and D.C. Swailes, "Optimal design of parabolic-bottomed triangle canals," *Irrigation and Drainage Engineering-ASCE*, vol. 126 (6), pp. 408-411, 2000.
- [32] Das, "Optimal channel cross section with composite roughness," *Irrigation and Drainage Engineering-ASCE*, vol. 126 (1), pp. 68-72, 2000.
- [33] P. K. Swamee, G. C. Mishra, and B. R. Chahar, "Comprehensive design of minimum cost irrigation canal sections," *Irrigation and Drainage Engineering-ASCE*, vol. 126 (5), pp. 322-327, 2000.
- [34] P. K. Swamee, G. C. Mishra, and B. R. Chahar, "Design of minimum seepage loss canal sections," *Irrigation and Drainage Engineering-ASCE*, vol. 126 (1), pp. 28-32, 2000.
- [35] P. K. Swamee, G. C. Mishra, and B. R. Chahar, "Minimum cost design of lined canal sections," *Water Resources Management*, vol. 14 (1), pp. 1-12, 2000.

- [36] Federico, "Determining optimal canal sections under conditions of constraint," *Genio Rurale*, vol. 61 (9), pp. 30-35, 1998.
- [37] B. G. Hankin, and K. J. Beven, "Modeling dispersion in complex open channel flows: Fuzzy calibration (2)," *Stochastic Environmental Research and Risk Assessment (SERRA) (Stochastic hydrology and hydraulics)*, vol. 12 (6), pp. 397-412, 1998.
- [38] J. M. Reddy, "Design of global control algorithm for irrigation canals," *Journal of Hydraulic Engineering-ASCE*, vol. 122 (9), pp. 503-511, 1996.
- [39] J. M. Reddy, "Kalman Filtering in the Control of Irrigation Canals," *Applied Mathematical Modelling*, vol. 19 (4), pp. 201-209, 1995.
- [40] P. K. Swamee, "Optimal Irrigation Canal Sections," *Irrigation and Drainage Engineering-ASCE*, vol. 121 (6), pp. 467-469, 1995.
- [41] D. C. Froehlich, "Width and depth-constrained best trapezoidal section," *Irrigation and Drainage Engineering-ASCE*, vol. 120 (4), pp. 828-835, 1994.
- [42] P. Garcianavarro, F. Alcrudo, and A. Priestley, "An Implicit Method For Water-Flow Modeling in Channels and Pipes," *Hydraulic Research*, vol. 32(5), pp. 721-742, 1994.
- [43] P. Monadjemi, "General formulation of best hydraulic channel section," *Irrigation and Drainage Engineering-ASCE*, vol. 120 (1), pp. 27-35, 1994.
- [44] G. V. Loganathan, "Optimal-design of parabolic canals," *Irrigation and Drainage Engineering-ASCE*, vol. 117 (5), pp. 716-735, 1991.
- [45] Dubos, "Application of the Manning and Strickler Formula to Land Improvement Projects in Cote-Divoire," *Oleagineux*, vol. 43 (2), pp. 49-54, 1988.
- [46] L. E. Flynn, and M. A. Marino, "Canal design: optimal cross-sections," *Irrigation and Drainage Engineering-ASCE*, vol. 113 (3), pp. 335-355, 1987.
- [47] C. Y. Guo, and W. C. Hughes, "Optimal channel cross-section with freeboard," *Irrigation and Drainage Engineering-ASCE*, vol. 110 (3), pp. 304-314, 1984.
- [48] A. P. Mironenko, L. S. Willardson, and S. A. Jenab, "Parabolic canal design and analysis," *Irrigation and Drainage Engineering-ASCE*, vol. 110 (2), pp. 241-246, 1984.