MSD Publications
Research is creating new knowledge

MSD Annals of Energy & Environmental Sciences and Toxicology

Review Article

Received: 20 March, 2025
Accepted: 10 April, 2025
Published: 15 April, 2025

***Corresponding author:** Farhad Sakhaee, School of Engineering, Parks College of Engineering, Aviation and Technology, Saint Louis University, USA;
Email: farhad.sakhaee@slu.edu

Citation: Farhad S (2025) Hydraulic jump, Super-critical & Sub-critical Flow Conditions. MSD Ann Ener Environ Sci Toxicol. 4(1): 001-005.
DOI: 10.37179/msdaeest.000009

Hydraulic jump, Super-critical & Sub-critical Flow Conditions

Farhad Sakhaee*

School of Engineering, Parks College of Engineering, Aviation and Technology, Saint Louis University, USA.

Abstract

In this study, the formation of water surface profiles in subcritical and supercritical branches of alternate depths has been investigated in the presence of both an upward and downward obstacle, delta Z (Δz). The observations yielded an interesting result in the presence of both upward and downward obstacles in subcritical flow conditions. In subcritical flow conditions, the behavior is unusual, with an upward ΔZ. The water surface profile drops down instead of moving upward. Conversely, in the presence of a downward ΔZ, the water surface profile does not drop; instead, it rises according to the height of ΔZ. The reason for this strange behavior in the water surface profile is presented mathematically as well as graphically, based on the energy depth diagram in detail.

Keywords: Hydraulic jump, Energy Dissipation, Supercritical & Sub-critical Flow.

Introduction

Recently, a variety of energy dissipation structures have been used to reduce the destructive kinetic energy of water flow and prevent damage to downstream hydraulic facilities. In open channels, one of the most common structures used to dissipate energy is the vertical drop. A vertical drop alone cannot completely dissipate the kinetic energy of the flow, and this excess energy can cause downstream damage [1]. A hydraulic jump model was developed for a type III stilling basin to investigate the influence of a stepped chute on hydraulic jumps. The result showed that type III basins are adequate with a stepped chute [2], Figure 1. Below shows a Type III hydraulic jump stilling basin with a stepped chute. A hydraulic jump is defined as the sudden transition from a supercritical flow to a subcritical condition in a short distance. Furthermore, the hydraulic jump is a phenomenon where the water surface moves upwards at critical depth as kinetic energy is converted to potential energy. Hydraulic jumps are usually used to dissipate excessive energy downstream of the hydraulic structures [3]. A flow over labyrinth weirs with semicircular and sinusoidal configurations in a rectangular channel under a wide range of flow discharges has been conducted. Labyrinth weirs have nearly the same discharge coefficient as broad-crested weirs, and the flow discharge exceeded the linear weir's efficiency by ~30%. Additionally, reliable equations for estimating the discharge coefficient [4].

Characteristic of free and submerged jump has been investigated by the flow 3d model [5] (Figure 3). Below shows a hydraulic jump occurring under a thin opening under a rectangular sluice gate, including an estimate of the hydraulic jump length [6-8] (Figure 4). shows a hydraulic jump with its geometrical parameters for subcritical and supercritical

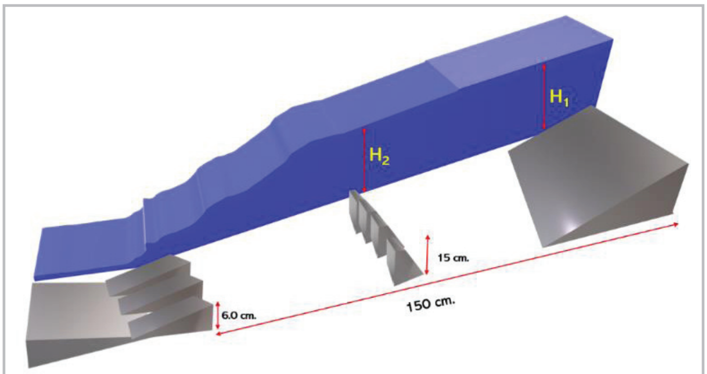

Figure 1: Type III hydraulic jump stilling basin.

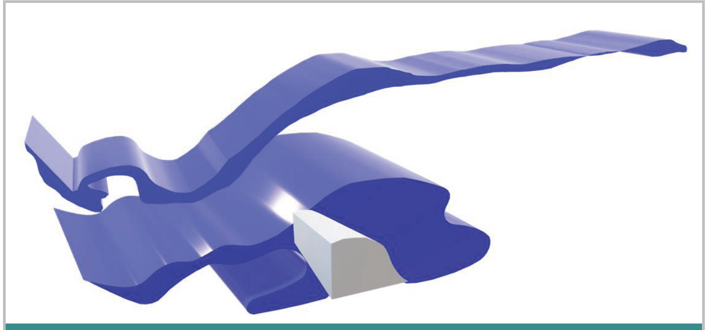

Figure 2: Schematic of hydraulic jump. Hydraulic Jump and its Characteristics A schematic of a hydraulic jump is shown in Figure 2. Below.

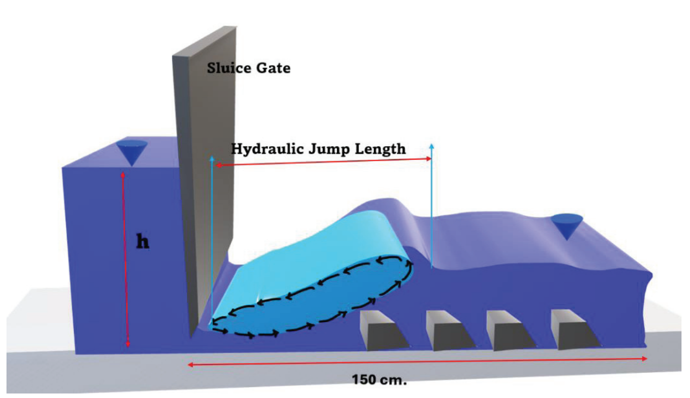

Figure 3: The schematic view of the formed hydraulic jump over the rough bed.

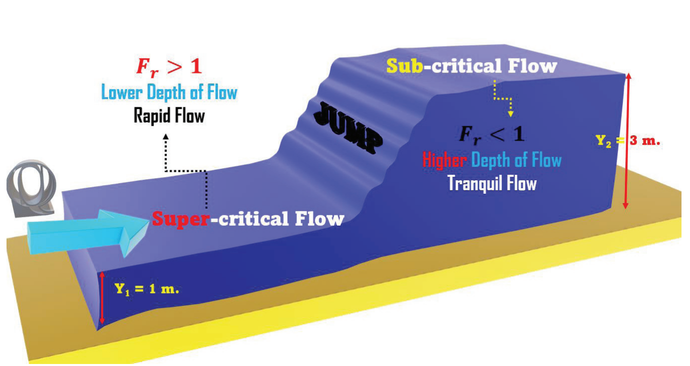

Figure 4: Laboratory flume for hydraulic jump + geometrical parameters.

branches of flow. A thin fast fast-flowing flow enters the control volume at the very beginning of the section, which represents the supercritical flow condition. It is a rapid flow with a Froude number higher than one, accompanied by lower depth in comparison to the other side [9-12]. Somewhere in the middle the hydraulic jump occurs, where the depths of flow increases while its energy dissipates to a great extent and eventually it reaches to a tranquil flow state, which has a lower velocity in comparison to the flow before the jump and represents a subcritical flow condition with higher for depth, lower velocity and a Froude number less than one [13-16]. A hydraulic jump is an abrupt change in the water depth accompanying the transition of the flow into a shallow canal from super-critical to subcritical. This transition causes energy dissipation, which defines the application of hydraulic jumps in engineering [17].

Hydraulic jumps are classified based on their Froude number, starting from a numeric value of one, which represents undular jumps, up to a Froude number of 9 and higher, which stands for a strong jump. Undular, weak, and oscillating jumps are shown in Figure 5. Below. Undular jump categorized by smooth downstream and Froude number between 1 and 1.7. The smoothness of the downstream water surface is due to a low energy dissipation rate. (Figure 5). (a) [18-20] Weak jump is pretty like an undular jump with a slight difference in Froude number. In this case Froude number is between 1.7 and 2.5. Figure 5. (b) [21, 22] In an oscillating jump, there is turbulence at the downstream section of the flow, and the Froude number is between 2.5 and 4.5. Figure 5. (c) [23-25] In a steady jump, turbulence is already confined, and the Froude number is high, between 4.5 and 9. Figure 6. (a) [26-27] Froude number higher than 9, considered be strong jump, while the energy dissipation rate is very high, and the water surface profile has a lot of variations in terms of depth change. Figure 6. (b) [27, 28].

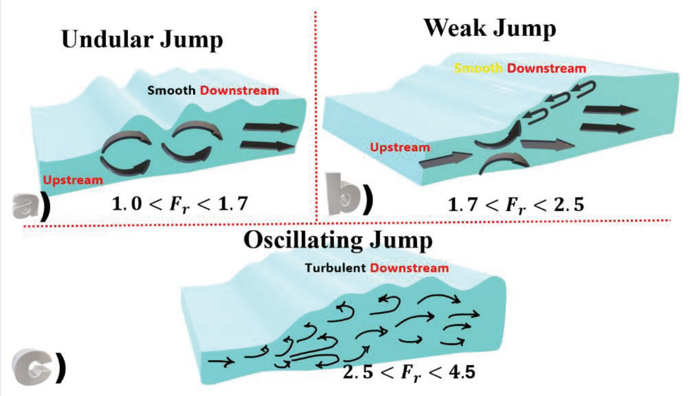

Figure 5: Undular, Weak and Oscillating Jump.

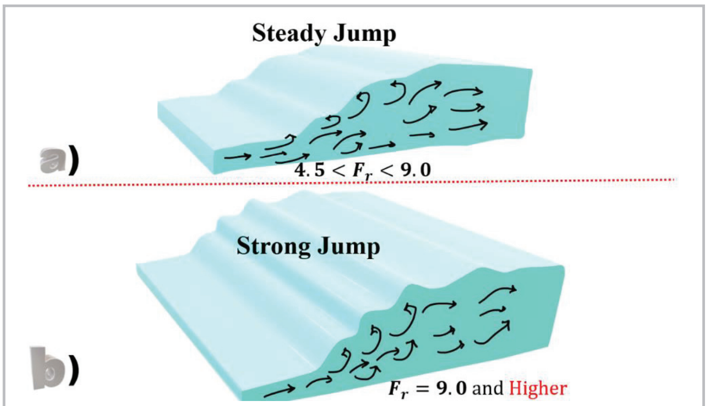

Figure 6: Undular, Weak and Oscillating Jump.

Supercritical Flow

In a supercritical flow condition, the water surface profile moves upward due to an upward ΔZ accordingly. Figure 7(a) below shows a supercritical flow with upward ΔZ, which results in an upward jump in the water surface profile at the location of the obstacle. Likewise, in Figure 7(b) a drops of water surface according to a downward ΔZ are observed.

Subcritical Flow

In subcritical flow conditions, however, the water surface profile behaves differently in the presence of an upward and downward ΔZ. Figure 8(a) shows the unusual behavior of a subcritical flow with an upward ΔZ, in which the water surface profile drops down instead of moving upward. Accordingly, in Figure 8(b), in the presence of a downward ΔZ instead of having a downward drop in water surface profile, it just rises according to the height of ΔZ. The reason for this strange behavior in the water surface profile is presented mathematically as well as graphically based on the energy depth diagram in Figures 9 and 10, respectively. In the presence of an upward ΔZ, E_2 is always smaller than E_1. As it is shown in Figure 9 height of water before the upward ΔZ (y_1) is larger than the height of water at the location of Δz (y_2+ΔZ). $y_1 = y_2 + ΔZ$ + plus Epsilon (Ɛ). In the sub-critical branch of flow, you can see the horizontal distance of points 1 and 2 to the line of 45° from the vertical axis, respectively. By moving from point 1 to point 2, this distance is increasing by the amount of epsilon(Ɛ), which means there is a drop in water surface elevation at the location of ΔZ.

In the presence of a downward ΔZ, E_2 is always larger than E_1. As it is shown in Figure 10 height of water before the upward ΔZ (y_1) is smaller than the height of water at the location of Δz (y_2+ΔZ). $y_2 = y_1 + ΔZ$ + plus Epsilon (Ɛ). In the sub-critical branch of the flow, you can see the horizontal distance of points 1 and 2 to the line of 45° from the vertical axis, respectively. By moving from point 1 to point 2, this distance is decreasing by the amount of epsilon(Ɛ), which means there is a rise in water surface elevation at the location of ΔZ.

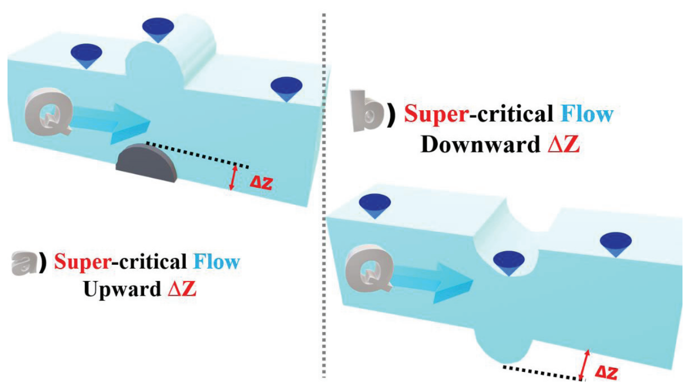

Figure 7: Super-critical flow in a hydraulic channel, with upward ΔZ(a) and downward ΔZ (b).

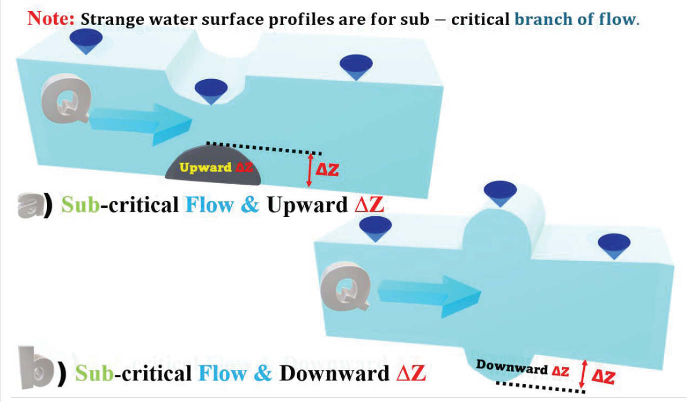

Figure 8: Sub-critical flow in the hydraulic channel, with upward ΔZ(a) and downward ΔZ(b).

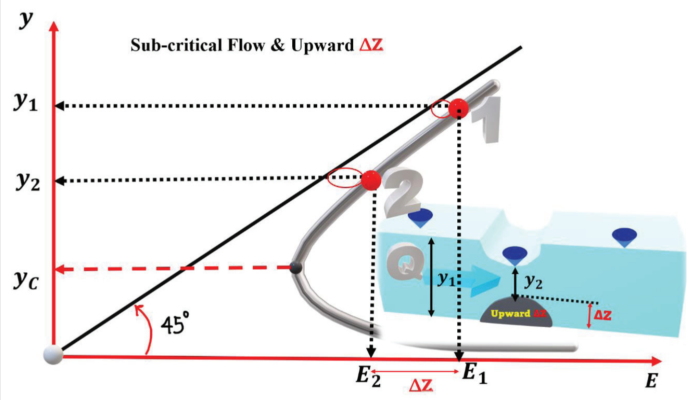

Figure 9: Energy-Depth Diagram in a sub-critical flow in a hydraulic channel, with upward ΔZ.

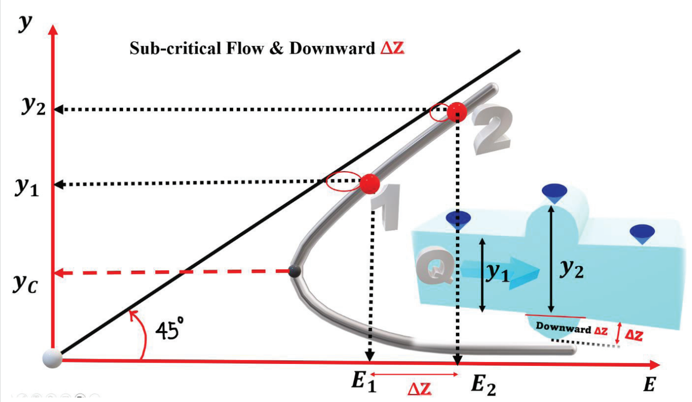

Figure 10: Energy-Depth Diagram in a sub-critical flow in a hydraulic channel, with downward ΔZ.

Conclusion

In this study, supercritical and subcritical flow conditions were investigated with the presence of upward and downward obstacles, respectively. The behavior of the water surface profile was compatible with our intuitive perception of vertically blocking and widening the flume; however, in subcritical flow conditions for both upward and downward scenarios, the behavior of the water surface profile was surprising. The logic behind a subcritical flow with an upward ΔZ in which the water surface profile drops down instead of moving upward has been explained. Likewise, in the presence of a downward ΔZ instead of having a downward drop in water surface profile, it just rises according to the height of ΔZ. The two points of subcritical and supercritical branches of flow have the same momentum cause they both consider alternate depths for upstream and downstream of a hydraulic jump. Figure 11 below shows water momentum vs. Water depth.

Declaration of Conflict of Interests

The author declares that there is no conflict of interest. They have no known competing financial interests or personal relationships that could be perceived as influencing the work reported in this paper.

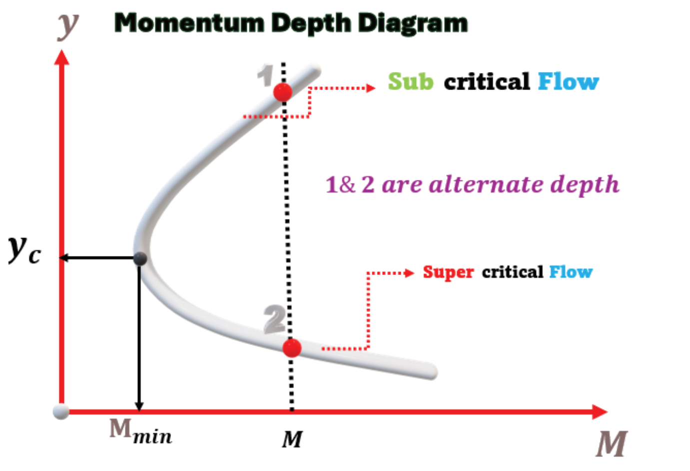

Figure 11: Momentum vs. water depth.

References

1. Daneshfaraz R, Mohammad B, Reza E, Reza N, John A (2020) Study of the performance of support vector machine for predicting vertical drop hydraulic parameters in the presence of dual horizontal screens. Water Supply 21: 217-231. Link: https://bit.ly/4j5Bfim
2. Valero D, Bung DB, Crookston BM (2018) Energy dissipation of a Type III basin under design and adverse conditions for stepped and smooth spillways. Journal of Hydraulic Engineering 144: 7. Link: https://bit.ly/4co2B0q
3. Nikmehr S, Y Aminpour (2020) Numerical Simulation of Hydraulic Jump over Rough Beds. Periodica Polytechnica Civil Engineering 64: 396-407. Link: https://bit.ly/44kaFNH
4. Safarrazavi Zadeh, MM Esmaeili Varaki, R Biabani (2019) Experimental study on flow over sinusoidal and semicircular labyrinth weirs. ISH Journal of Hydraulic Engineering 27: 304-313. Link: https://bit.ly/4jjNwiM
5. Ghaderi A, Mehdi D, Francesco A, Ali Ghahramanzadeh (2020) Characteristics of free and submerged hydraulic jumps over different macroroughnesses. Journal of Hydroinformatics 22: 1554-1572. Link: https://bit.ly/4ctXMTq
6. De Padovam, DM Mossa (2021) Hydraulic jump: a brief history and research challenges. Water 13 : 1733. Link: https://bit.ly/4i7tCXm
7. Gharangik AM, MH Chaudhry (1991) Numerical simulation of hydraulic jump. Journal of hydraulic engineering 117: 1195-1211. Link: https://bit.ly/44fT3CD
8. Hager WH (2013) Energy dissipators and hydraulic jump. Springer Science & Business Media. Link: https://bit.ly/3R7H1Ul
9. Ohtsu I, Y Yasuda (1994) Characteristics of supercritical flow below sluice gate. Journal of Hydraulic Engineering 120: 332-346. Link: https://bit.ly/42D6onh
10. Ippen AT (1951) High-velocity flow in open channels: a symposium: mechanics of supercritical flow. Transactions of the American society of Civil Engineers 116: 268-295. Link: https://bit.ly/4jvLGM1
11. Cartigny MJ (2014) Morphodynamics and sedimentary structures of bedforms under supercritical□flow conditions: new insights from flume experiments. Sedimentology 61: 712-748. Link: https://bit.ly/3RbMXLZ
12. Bae JH, JY Yoo, H Choi (2005) Direct numerical simulation of turbulent supercritical flows with heat transfer. Physics of fluids 17: 105104. Link: https://bit.ly/42DAOG3
13. Pradhan B, S Pradhan, KK Khatua (2024) Experimental investigation of three-dimensional flow dynamics in a laboratory-scale meandering channel under subcritical flow condition. Ocean Engineering 302: 117557. Link: https://bit.ly/4icW1uV
14. Ohtsu I, Y Yasuda (1991) Transition from supercritical to subcritical flow at an abrupt drop. Journal of hydraulic research 29: 309-328. Link: https://bit.ly/42hcDgJ
15. Aydin MC, HS Aytemur, AE Ulu (2022) Experimental and numerical investigation on hydraulic performance of slit-check dams in subcritical flow condition. Water Resources Management 36: 1693-1710. Link: https://bit.ly/425UNNp
16. Perkins TK (1993) Critical and subcritical flow of multiphase mixtures through chokes. SPE Drilling & Completion 8: 271-276. Link: https://bit.ly/42pYHzw
17. Mukha T, SK Almeland, RE Bensow (2020) LES of a classical hydraulic jump: Influence of modelling parameters on the predictive accuracy 7: 101. Link: https://bit.ly/4cnRhRX
18. Montes J, H Chanson (1998) Characteristics of undular hydraulic jumps: experiments and analysis. Journal of hydraulic engineering 124: 192-205. Link: https://bit.ly/3YnCdxY
19. Chanson H, JS Montes (1995) Characteristics of undular hydraulic jumps: Experimental apparatus and flow patterns. Journal of hydraulic engineering 121: 129-144. Link: https://bit.ly/4cq73fb
20. Svendsen IA, J VEERAMONY, J BAKUNIN, T KIRBY (2000) The flow in weak turbulent hydraulic jumps. Journal of Fluid Mechanics 418: 25-57. Link: https://bit.ly/3Yo1Pe4
21. Meyer RE (1967) Note on the undular jump. Journal of Fluid Mechanics 28: 209-221. Link: https://shorturl.at/ngQvV
22. Disimile PJ, JM Pyles, N Toy (2009) Hydraulic jump formation in water sloshing within an oscillating tank. Journal of aircraft 46: 549-556. Link: https://shorturl.at/79ZHX
23. Alexander NA, JH Macdonald, AR Champneys (2017) Numerical investigation of a simple model of human jumping on an oscillating structure. Procedia engineering 199: 2844-2849. Link: https://shorturl.at/bhFbp

24. Hellmers S, Sebastian F, Lena E, Andrea H, Juergen MB, et al. (2017) Understanding jump landing as an oscillating system: a model-based approach of balance and strength analyses. in International Conference on Health Informatics. SCITEPRESS. Link: https://shorturl.at/PbMHH

25. Stevenson R, J Hope, A Carvalho (2011) Engineering steady states using jump-based feedback for multipartite entanglement generation. Physical Review A—Atomic, Molecular, and Optical Physics, 84: 022332. Link: https://shorturl.at/4XtEH

26. Ipatova A, K Smirnov, E Mogilevskiy (2021) Steady circular hydraulic jump on a rotating disk. Journal of Fluid Mechanics 927: A24. Link: https://rb.gy/jd04r2

27. Bush JW, JM Aristoff, A Hosoi (2006) An experimental investigation of the stability of the circular hydraulic jump. Journal of Fluid Mechanics 558: 33-52. Link: https://rb.gy/jufevd

28. Lin C, Shih-Chun Hsieh, I-Ju Lin, Kuang-An Chang, Rajkumar V. Raikar (2012) Flow property and self-similarity in steady hydraulic jumps. Experiments in Fluids. 53: 1591-1616. Link: https://rb.gy/yn8lce