Numerical investigation of transition between free surface flow and pressurized flow for a circular pipe flowing full upstream

Tanjina Afrin[1], Abdul A. Khan[2], Nigel B. Kaye[3]

AUTHORS: [1] Assistant Professor, Virginia Military Institute, Nichols Engineering Hall, Lexington, VA 24450, USA. [2]Professor, Clemson University, Lowry Hall, Clemson, SC 29634, USA. [3] Associate Professor, Clemson University, Lowry Hall, Clemson, SC 29634, USA.
REFERENCE: *Proceedings of the 2016 South Carolina Water Resources Conference*, held October 17-18, 2018 at the Columbia Metropolitan Convention Center.

ABSTRACT. The simulated brink depth-discharge relationship using Computational Fluid Dynamics (CFD) is used to investigate different flow regimes for pipe outflow running partially full, i.e., cavity outflow and bubble washout flow, and the transition between these two regimes. The simulated data for several controlling parameters gave good agreement with available data in the literature and significantly increased the amount of data in the bubble washout flow regime. The end depth ratio (EDR), that is the ratio of the brink depth to the critical depth, was found to be 0.75 for the cavity outflow regime. For the bubble washout regime, End Depth Ratio (EDR) varies linearly with the dimensionless critical depth. These findings provide insight into the mechanics of a pipe free overfall when the pipe runs partially full at the outlet and, in particular, explains the transition between the cavity flow and bubble washout regimes.

INTRODUCTION

A free overfall is an abrupt end to a conduit in which the flow separates from the entire perimeter of the conduit and then falls as a free jet at atmospheric pressure. In drainage system, pipes and channels ending with a free overfall are common. For a partially full conduit at an overfall, there is a direct relationship between the brink depth (y_b), conduit geometry, and discharge (Q). Therefore, a free overfall can also be used as a flow measurement device. For a pipe flowing partially full at the brink with pressurized flow upstream, two flow regimes are observed depending on the discharge i.e., bubble washout regime ((Wallis et al., 1977; Hager, 1999; see Fig. 1a) and cavity flow regime (Hager, 1999; see Fig. 1b). However, the transition from partially full conduit flow to full conduit flow or transition between cavity and the bubble washout flow regimes is still not completely understood. Since most of the irrigation facilities, urban drainage facilities, and sewer lines are circular in shape, and a free overfall offers a simple and inexpensive way to measure discharge, it is useful for engineers to understand fully the characteristics of a free overfall. The objective of this study is to improve our understanding of the hydraulics of a circular pipe free overfall with particular emphasis on larger brink depths for $0.5 < \frac{y_b}{D} < 1.0$, where D is the pipe diameter. Computational Fluid Dynamics (CFD) simulations of a free overfall were used to develop a non-dimensional brink depth-discharge curve, determine the EDR, and investigate the transition between the cavity and the bubble washout flow regimes.

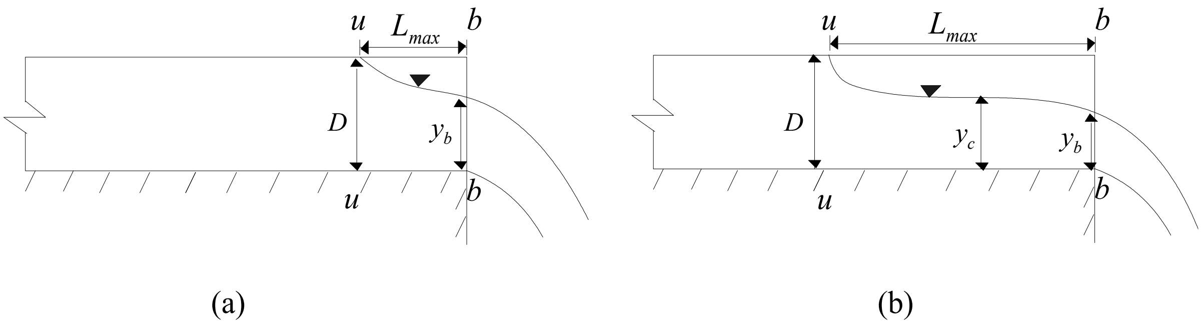

Figure 1: Schematic Diagram of circular free overfall, where D is the pipe diameter, $u-u$ and $b-b$ represent upstream and brink sections, respectively. (a) Bubble washout flow (b) Cavity flow with a section of horizontal free surface

LITERATURE REVIEW

Vanleer (1922) proposed a power law equation relating brink depth to discharge conducted an early analysis of the relationship between the brink depth and discharge. Rouse (1936) proposed the term End Depth Ratio (EDR) as the ratio between the critical depth for parallel flow (y_c) and the brink depth at the free overfall. Their experiments found a constant EDR value of 0.715 for rectangular channels. Several studies (Smith, 1962; Rajaratnam and Muralidhar, 1964; Sterling and Knight, 2001) have found that this unique relationship is also valid for circular pipes.

In available literatures, using the integral (control volume) form of the momentum equation, a limiting discharge was established, below which a pipe would flow partially full at a free overfall (Smith, 1962) and a constant EDR which ranged from 0.725 to 0.75 for $\frac{y_c}{D}$ <0.82 to 0.90 (Rajaratnam and Muralidhar, 1964; Clausnitzer and Hager, 1997; Dey, 1998; Hager, 1999). A constant EDR ranged from 0.72 to 0.74 was found by treating free overfalls as flow over a sharp-crested weir with zero crest height (Dey, 2001; Ahmad and Azamathulla, 2012). Using free vortex theorem, Nabavi et al. (2011) found EDR=0.756 in the range of 0.10< $\frac{y_c}{D}$ <0.7. Ali and Ridgway (1977)'s finding contradicts the finding of other researchers as it shows a decreasing trend in EDR for $\frac{y_c}{D} \geq$ 0.6. The relation between brink depth and discharge for a circular free overfall has also been established empirically by several researchers based on numerous experiments (Rohwer, 1943; Hager, 1999; Sterling and Knight, 2001; Dey, 2001; Sharifi et al., 2011). In general all these models and experiments agree well though there is little data available for the bubble washout regime and little discussion of the transition between the bubble washout and cavity flow regimes. Among other approaches, Subramanya and Kumar (1993)'s general analytical approach, Montes (1997)'s potential flow approach, Pal and Goel (2006)'s support vector machine approach were worth to mention. Recently, Bashiri-Atrabi et al., (2016) developed 1-D model and derived Boussinesq equation for circular pipe.

The various analytical models developed (e.g. Dey, 1998; Dey, 2001; Ahmad and Azamathulla, 2012) diverge from the available experimental results of Smith (1962), Rajaratnam and Muralidhar (1964), and Sterling and Knight (2001), when $\frac{y_b}{D}$ is greater than around 0.55. Moreover, there is little data in these publications when the brink depth is larger than half of the pipe diameter. Rohwer (1943) and Smith (1962) both mentioned this discontinuity in the discharge-depth curve once $\frac{y_b}{D}$ is greater than approximately 0.55-0.60.

METHODS

Three dimensional (3D) numerical simulations were carried out to simulate flows through a pipe of 10 cm diameter and 3 m (30 diameter) length. The simulations were run using ANSYS FLUENT (FLUENT, 2011). For this study the Volume of Fluid (VOF) method was used as the two-phase flow model to track the water surface in the domain. Air and water were the primary and secondary phases, respectively. In this study, realizable k - ε transport model was used, where k and ε represent turbulent kinetic energy and the turbulent energy dissipation rate, respectively.

A mesh sensitivity study was conducted. The optimum number of cell was 875,052. For the whole domain, hexahedral cells were used. Mass flow inlet and pressure outlet were as boundary conditions. A combination of the Pressure Implicit with Splitting of Operators (PISO) scheme as pressure-velocity coupling was selected for this study. More details about the methodology can be found at Afrin et al., 2017.

RESULTS

The results are presented in non-dimensional form with flow depths scaled with the pipe diameter ($\frac{y_b}{D}$) and the non-dimensional discharge, Q^* (Rajaratnam and Muralidhar, 1964) given by $Q^* = \frac{Q}{\sqrt{gD^5}}$. CFD simulations were run for a broad range of Q^* values. Surface profiles exhibited both the bubble washout flow regime for larger Q^* and the cavity flow regime for lower Q^*. The simulation results indicate that $Q^* = 0.505$ is the transition point between the cavity outflow regime and the bubble washout regime. A detailed investigation into the variation of brink depth, critical depth, and cavity length for a large range of Q* was conducted as part of this study. Simulation results for the brink depth as a function of the non-dimensional discharge, and EDR as a function of the critical depth are presented in Figures 2 and 3, respectively. The transition in both brink depth-discharge and cavity length-discharge curve were observed at around Q*=0.5. The simulated results agree well with previously published experimental data. In addition to transition between cavity outflow regime and the bubble washout regime, two more transitions, namely, full outflow to bubble washout and cavity flow to wavy cavity flow were observed. The simulation results of this study are similar to those reported in the literature.

A constant EDR=0.75 is found up to $\frac{y_c}{D} \approx 0.7$.

For $\frac{y_c}{D} > 0.7$, the EDR is observed to vary linearly with $\frac{y_c}{D}$ and can be well approximated by

$$EDR = y_b / y_c = 1.69(y_c / D) - 0.51 \quad (1)$$

Figure 4 indicates that the cavity length (L_{max}) grows very rapidly with decreasing Q^*.

The main focus of this study was the bubble washout regime and the transition from cavity to bubble washout flow. The key to understand the transition from bubble. A possible interpretation of this is that the cavity flow weir model represents the minimum energy line for the flow and, as such, represents the minimum possible brink depth for a given discharge. In the bubble washout regime the upstream and brink forces are both small and so there is little increase in momentum as the flow approaches the brink and the brink depth is above the minimum energy line. As the flow rate decreases the momentum model approaches the minimum energy line (see Fig. 2) and the flow adjusts by flattening the cavity and extending its length. This adds additional retarding wall friction which leads to a higher brink depth compared to that which would be expected if the cavity shape continued to follow the bubble washout shape at lower flow rates.

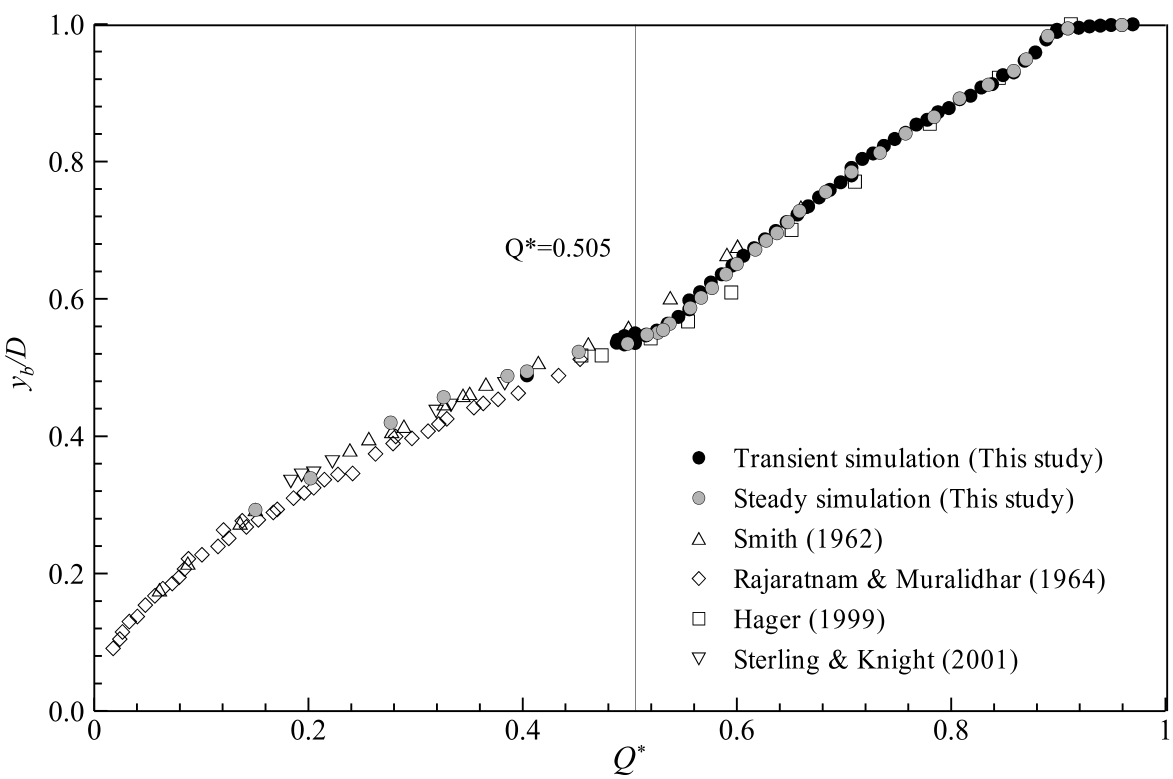

Figure 2: Non-dimensional discharge-brink depth curve.

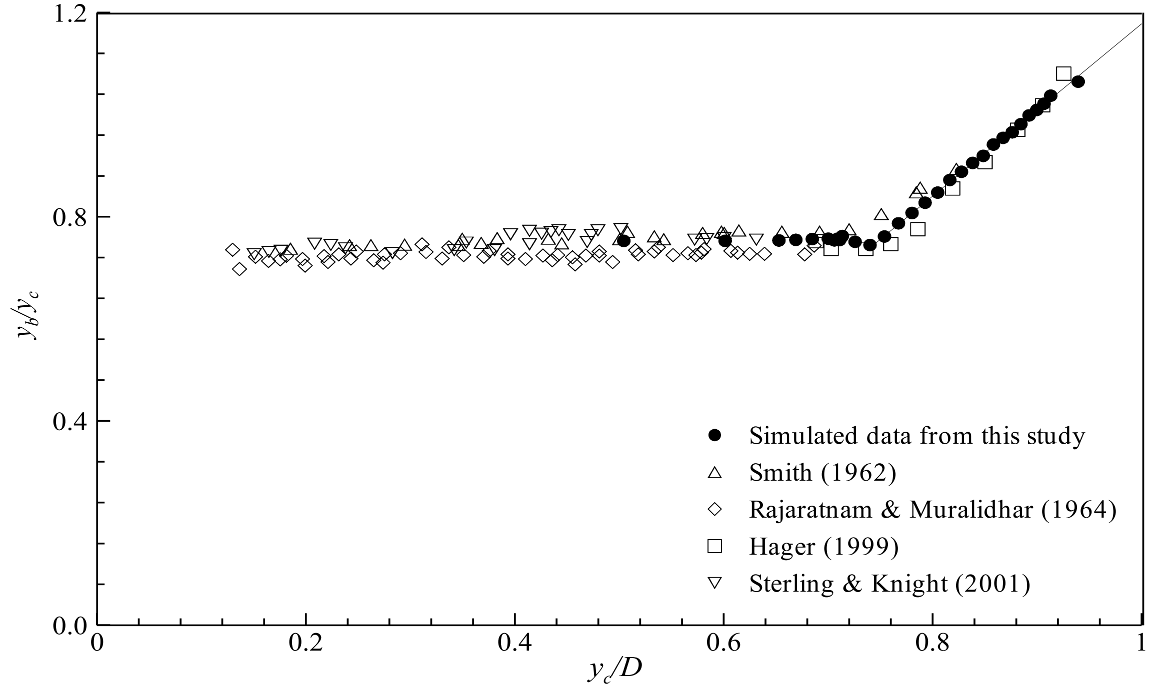

Figure 3: EDR as a function of $\frac{y_c}{D}$. The solid line represents Equation 1.

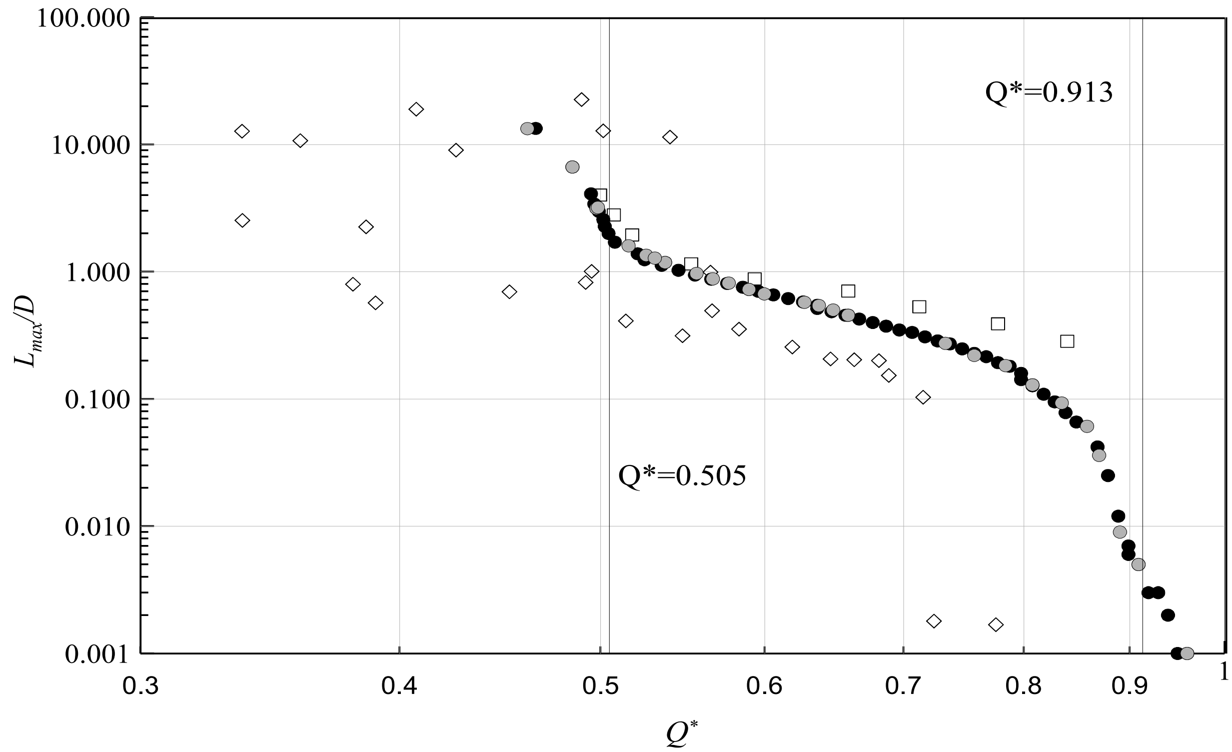

Figure 4: Variation of $\frac{L_{\max}}{D}$ as a function of Q^*, where $L_{\max}$ is the horizontal distance from the upstream separation point to the brink. The black and grey circles represent the data for the transient and steady simulations in this study, respectively. The diamonds are the experimental data from Blaisdell (1963) and Montes (1997), the squares is the experimental data of Hager (1999).

APPLICATION

Results from this study can be used for culvert and storm sewer design. For example, let's consider a 30 ft. long and 5 ft. diameter circular culvert. For flooded upstream, maximum cavity length, $L_{\max}$ can be 29.99 ft. From Figure 4, for $\frac{L_{\max}}{D} = 5.998$, Q^* is around 0.47. That gives us Q=149 ft^3/s. That simply means any flow less than 149 ft^3/s will cause the culvert to have partially flow at its full length. Similarly, for Q= 290 ft^3/s (Q^*=0.913), cavity length is zero, i.e., culvert will have a fully pressurized flow such that the flow is no longer controlled at the brink.

DISCUSSION

A detailed 3D CFD study was conducted to examine the flow over a free overfall from a smooth, horizontal circular pipe that is running full at the inlet. This study mainly focused on bubble washout flow regime for which available experimental data is very limited and characteristics of transition between two flow regime namely cavity outflow and bubble washout. Where available analytical models diverge from the experimental data for bubble washout regime, the simulation results show good agreement with prior experimental results and significantly increase the amount of data in this regime. Precise values of Q^* for various flow transitions were established. A more complete quantification of the EDR was also presented, showing that EDR increases linearly with $\frac{y_c}{D}$ in the bubble washout regime. Results from this study have application in designing drainage facilities.

LITERATURE CITED

Afrin, T., Kaye, N. B., Khan, A. A., & Testik, F. Y. (2017). Numerical Investigation of Free Overfall from a Circular Pipe Flowing Full Upstream. *Journal of Hydraulic Engineering*, *143*(6), 04017004.

Ahmad, Z., & Azamathulla, H. M. (2012). Direct solution for discharge in circular free overfall. *Journal of hydrology*, *446*, 116-120.

Ali, K. H. M., & Ridgway, A. (1977). The circular free overfall. *Water Power and Dam Construction*, *29*(5), 42-45.

Bashiri-Atrabi, H., Hosoda, T., & Shirai, H. (2016). Propagation of an Air-Water Interface from Pressurized to Free-Surface Flow in a Circular Pipe. *Journal of Hydraulic Engineering*, 04016055.

Blaisdell, F.W. (1963). Discussion to Brink depth for a circular channel, by CD. Smith. J*ournal of the Hydraulics Division, ASCE*, pp. 249-252.

Clausnitzer, B., & Hager, W. H. (1997). Outflow characteristics from circular pipe. *Journal of Hydraulic Engineering*, *123*(10), 914-917.

Dey, S. (1998). End depth in circular channels. *Journal of Hydraulic Engineering*, *124*(8), 856-863.

Dey, S. (2001). EDR in circular channels. *Journal of irrigation and drainage engineering*, *127*(2), 110-112.

Dey, S. (2002). Free overall in open channels: state-of-the-art review. *Flow Measurement and Instrumentation*, *13*(5), 247-264.

FLUENT, ANSYS (2011). *Ansys, Inc.* Version 14.0, Canonsburg, PA 15317

Hager, W. H. (1999). Cavity outflow from a nearly horizontal pipe. *International journal of multiphase flow*, *25*(2), 349-364.

Montes, J. S. (1997). Transition to a free-surface flow at end of a horizontal conduit. *Journal of Hydraulic Research*, *35*(2), 225-241.

Nabavi, S. V., Beirami, M. K., Chamani, M. R., & Sterling, M. (2011). Free overfalls in flat-based circular and U-shaped channels. *Flow Measurement and Instrumentation*, *22*(1), 17-24.

Pal, M., & Goel, A. (2006). Prediction of the end-depth ratio and discharge in semi-circular and circular shaped channels using support vector machines. *Flow measurement and instrumentation*, *17*(1), 49-57.

Rajaratnam, N., & Muralidhar, D. (1964). End depth for circular channels. *Journal of the Hydraulics Division, ASCE, 90*(2), 99-119.

Rohwer, C. (1943). Discharge of pipes flowing partly full. *Civil Engineering*, *13*(10), 488-490.

Rouse, H. (1936). Discharge Characteristics of the Free Overfall: Use of Crest Section as a Control Provides Easy Means of Measuring Discharge. *Civil Engineering*, *6*(4), 257-260.

Sharifi, S., Sterling, M., & Knight, D. W. (2011). Prediction of end-depth ratio in open channels using genetic programming. *Journal of Hydroinformatics*. *13*(1), 36-48.

Smith, C. D. (1962). Brink depth for a circular channel. *Journal of Hydraulic Division, ASCE*, *88*(6), 125-134.

Sterling, M., & Knight, D. W. (2001). The free overfall as a flow measuring device in a circular channel. In *Proceedings of the Institution of Civil Engineers-Water and Maritime Engineering.148* (4), pp. 235-243. Thomas Telford Ltd.

Subramanya, K., & Kumar, N. (1993). End depth in a horizontal circular free overfall. *Journal of Institution of Engineers (India)*, *73*, 185-187.

Vanleer, B. R. (1922). The California Pipe Method of Water Measurement. *Engineering News Record*, *3*.

Wallis, G. B., Crowley, C. J., & Hagi, Y. (1977). Conditions for a pipe to run full when discharging liquid into a space filled with gas. *Journal of Fluids Engineering*, 99(2), 405-413.