CHOKING FEATURES OF DROP MANHOLES IN SEWER SYSTEMS

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CHOKING FEATURES OF DROP MANHOLES IN SEWER SYSTEMS

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ABSTRACT

Drop manholes are implemented in steep urban sewer systems to reduce flow velocities. The dominant hydraulic features of drop manholes depend on the operating conditions, affected by the manhole geometry and the approach flow features, characterized in terms of the dimensionless impact parameter.

A water pool develops onto the manhole bottom from which the outflow is discharged into the downstream sewer. A high pool level results in a large discharge but a minimum drop height is required to avoid negative backwater effects to the approach flow sewer. Moreover, the presence of a drop manhole may promote pipe choking in the downstream, corresponding to the sudden and abrupt transition from free surface to pressurized sewer flow.

An experimental research has been conducted on two circular manhole models of different size. It was observed that the pool water level inside a drop manhole in supercritical flow depends mainly on the *flow regime*. Besides, the pool height is affected by various dimensionless parameters as changes in the flow regime. A novel parameter to characterize choking inception in the downstream pipe of the manhole was introduced to account for the relative drop height and the approach flow conditions. Empirical equations to estimate the pool depth and to predict choking inception are proposed in this paper.

INTRODUCTION

Drop manholes are commonly implemented in urban drainage systems of hilly regions, where topography would induce excessive flow velocities. High velocities can damage sewer pipes and lead to poor hydraulic performances at junctions and bend manholes. The insertion of drops allows to release the design of sewers from the slope of urban areas. Drop structures in sewer systems should operate such that the up- and downstream energy heads are roughly equal (Granata et al., 2009). An excessive energy dissipation combined with scarce manhole aeration can lead to the choking of the downstream sewer. Choking of pipe flow corresponds to a sudden and abrupt transition from free surface to pressurized flow (Fig. 1). This phenomenon has received scarce attention until now, despite its relevance for overcharged sewers. It depends on many factors, among which a great importance must be given to the height of the water pool inside of the manhole. Therefore, an experimental study was performed at the *Laboratorio di Ingegneria delle Acque*, University of Cassino, Italy, to investigate these particular flow features in drop manholes crossed by supercritical flow. A special interest was to evaluate the pool depth as a function of hydraulic parameters of the approach flow and of manhole geometry. Moreover, the conditions for which choking occurs have been investigated.

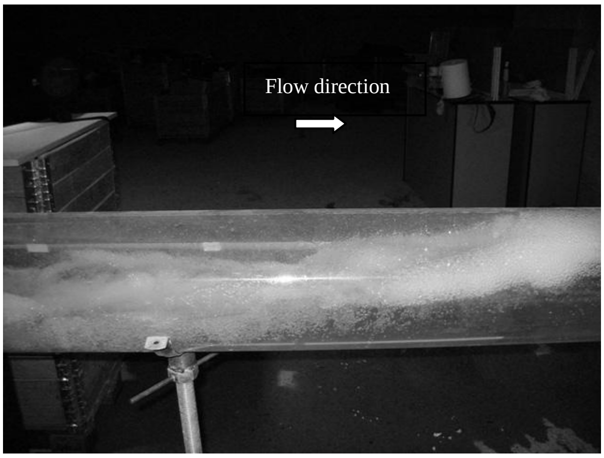


Fig. 1 – Incipient choking

EXPERIMENTAL FACILITY AND OPERATING CONDITIONS

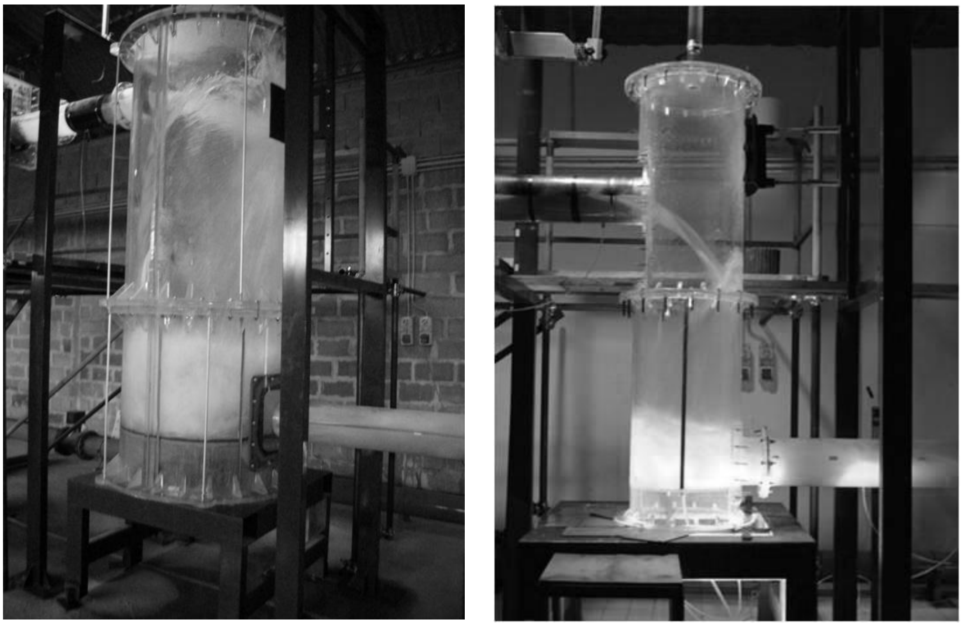
The experimental setup consisted of plexiglass circular manhole models connected to a recirculation system (Fig. 2). The tests were performed using two different manhole models: Model 1 of internal manhole diameter D_M = 1 m (Fig. 2 a) was tested with drop heights of s = 0.5, 1.0, 1.5, 2.0 m with the water discharge Q varied from 3 l/s to 80 l/s. Model 2 (Fig. 2 b) had the characteristics D_M = 0.48 m, s = 1.0, 1.2, 1.5 m, and 1.5 l/s $\leq Q \leq$ 60 l/s.

Both the inlet (subscript *in*) and outlet (subscript *out*) plexiglass pipes had a diameter of $D_{in} = D_{out}$ = 200 mm, while the manhole bottom was plane. A jet-box placed upstream of the manhole controlled the approach (subscript *o*) flow Froude number F_o and the approach flow depth h_o. This device consists of a plexiglass frame in which plates of various filling ratios are inserted. The depth h_o was measured both with a piezometer and a point gauge of ±0.5 mm reading accuracy. The pool (subscript p) depth h_p was measured by a set of piezometers connected to the manhole bottom, by considering time-averaged values.

The main features of the hydraulics of circular drop manholes depend on the operating conditions, i.e. on the manhole *flow regimes*. These conditions establish mainly on the basis of the jet impact location and depend on the hydraulic features of the approach flow and manhole size and shape. The flow regimes were introduced by Chanson (2004) for rectangular drop manholes, while de Marinis et al. (2007) describe the basic flow patterns in circular drop manholes, extending the previous characterization. Granata et al. (2009) introduced a dimensionless parameter I to classify the regimes for supercritical approach flows, namely the *Impact number*

$$\mathsf{I} = (2 \cdot s/g)^{0.5} \cdot (V_o/D_M) \tag{1}$$

where g = gravity acceleration, V_o = approach flow velocity and D_M = manhole diameter. It accounts for both the hydraulic approach flow features and the manhole geometry, relating the dimensionless drop height $S = s/D_M$ to the velocity head $V_o^2/(2g)$. This parameter describes the ratio between the horizontal jet location and the manhole diameter. The features of all flow regimes R1 to R3 are described in de Marinis et al (2007). Test data indicate that regime transitions can be approximated as $\mathsf{I} \cong 0.6$ between R1 and R2, $\mathsf{I} \cong 0.95 \div 1$ between R2 and R3a, and $\mathsf{I} \cong 1.5$ between R3a and R3b.



(a) (b)

Fig. 2 – Experimental setup: (a) detailed view of Model 1, (b) lateral view of Model 2

POOL DEPTH

It is important to predict the water pool height h_p for a given discharge to avoid undesired backwater effects (Fig. 3). Therefore, the manhole drop height s has to be larger than the pool height for stormwater flows, because the approach flow would be submerged otherwise, and the manhole does no more work under fully-aerated flow conditions.

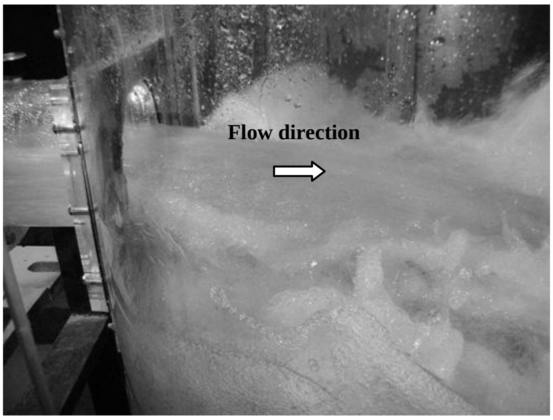


Fig. 3 – Water pool depth equals drop height. A further increase leads to backwater effects in the approach flow pipe

The pool depth increases with the impact number, as shown by Fig. 4, where experimental data relate to fully-aerated flow. In regime R1 the pool height is unaffected by the upstream filling ratio. In regime R2 the pool height increases, while in regime R3a small variations are observed. However, a remarkable increase is observed under regime R3b. The effects of the approach flow depth h_o and jet shape become important at the transition from regime R2 to R3. For a given value of l, the pool depth increases with h_o.

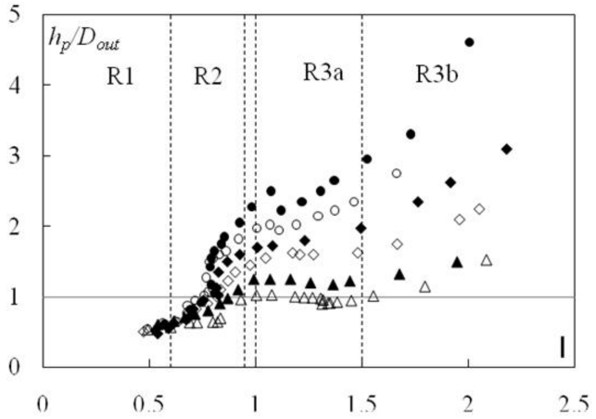
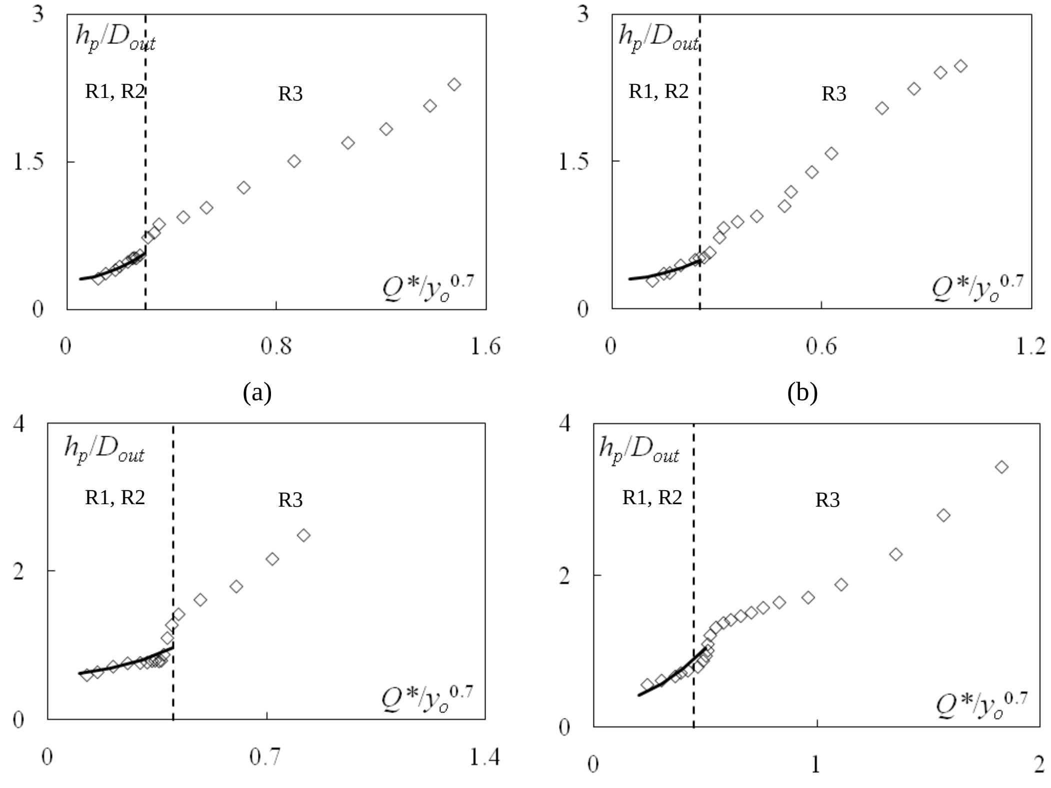


Fig. 4 - Pool height h_p/D_{out} versus l for D_M = 1.0 m, s = 2.0 m, jet-box opening (△) 30%, (▲) 40%, (◇) 50%, (◆) 60%, (○) 70%, (●) 80%

By momentum considerations for regimes R1 and R2, the ratio h_p/D_{out} may be demonstrated to depend on the ratio $Q^*/y_o^{0.7}$, where $Q^*=Q/(gD_{out}^5)^{0.5}$ is the manhole Froude number. An analysis of the test data for regimes R1 and R2 leads to the fit

$$\frac{h_p}{D_{out}} = 0.3 + \left(1+\frac{s}{D_M}\right)\cdot\frac{Q^{*2}}{y_o^{1.4}} \tag{2}$$



(a) (b)

(c) (d)

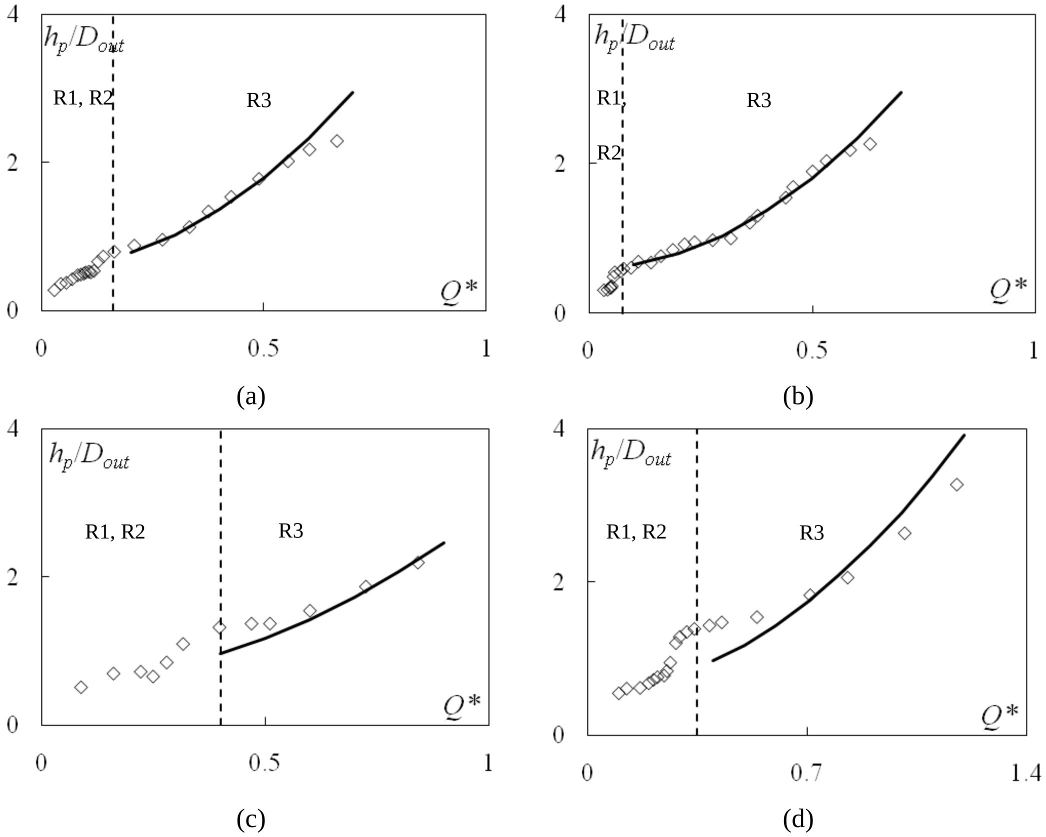
Fig. 5 - Manhole pool height h_p/D_{out} versus $Q^*/y_o^{0.7}$: (a) D_M = 0.48 m, s = 1.0 m, plate 40%; (b) D_M = 0.48 m, s = 1.0 m, plate 70%; (c) D_M = 1.0 m, s = 1.0 m, plate 45%; (d) D_M = 1.0 m, s = 2.0 m, plate 65%; (◇) test data, (—) Eq. (2)

Typical results for the relative pool depth in regimes R1 and R2 are shown in Fig. 5. Equation (2) indicates that in regimes R1 and R2 the relative pool height depends on both relative drop height s/D_M and the jet shape expressed by $Q^*/y_o^{0.7}$.

If the manhole operates under regime R3 (for which normally $h_p/D_{out} > 1.3$), the drop manhole outflow is similar to orifice flow. Energy considerations and a data analysis lead to

$$\frac{h_p}{D_{out}} = 0.6 + \left(7.3 - \frac{D_M}{D_{out}}\right) \cdot Q^{*2} \tag{3}$$

Equation (3) indicates that in regime R3 the relative pool height depends on the discharge and the ratio D_M/D_{out}, but is not affected by the upstream filling ratio (Fig. 6). A similar behavior was observed by Camino et al. (2009) for stacked drop manholes for a large water discharge.



(a) (b)

(c) (d)

Fig. 6 - Manhole pool height h_p/D_{out} versus Q^*: (a) D_M = 0.48 m, s = 1.0 m, plate 50%; (b) D_M = 0.48 m, s = 1.5 m, plate 65%; (c) D_M = 1.0 m, s = 1.0 m, plate 35%; (d) D_M = 1.0 m, s = 2.0 m, plate 55%; (◇) Test data, (—) Eq. (3)

Christodoulou (1991) examined water level in manhole for circular drop manholes in supercritical approach flow whereas Chanson (2007) considered similar questions for rectangular dropshafts with a subcritical approach flows.

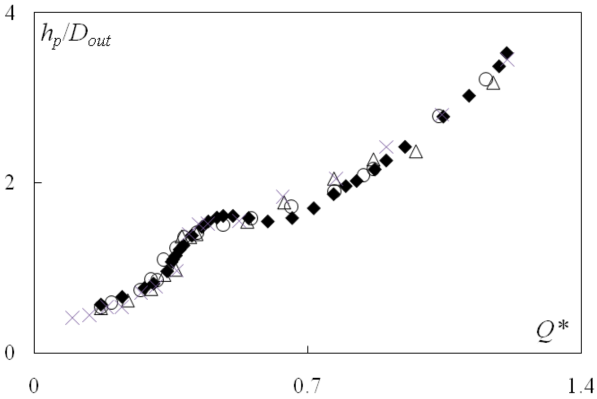


Fig. 7 - Manhole pool height h_p/D_{out} versus Q^* for various downstream pipe slopes: (♦) = 0, (Δ) = 0.015, (○)= 0.025, (×)= 0.04

Christodoulou stated that the manhole pool height is affected by downstream pipe slope. This influence has not been observed in this research. The pool height depends essentially on the outflow conditions. As indicated in Fig. 7, given the geometric setup, the relative pool heights have similar values for various downstream pipe slopes.

Chanson found a linear empirical relation between the pool height and the discharge, using the critical depth. The experimental data here discussed indicate that in most cases Chanson’s equation is unsuitable to estimate the pool depth of circular drop manholes for supercritical approach flow (Fig. 8).

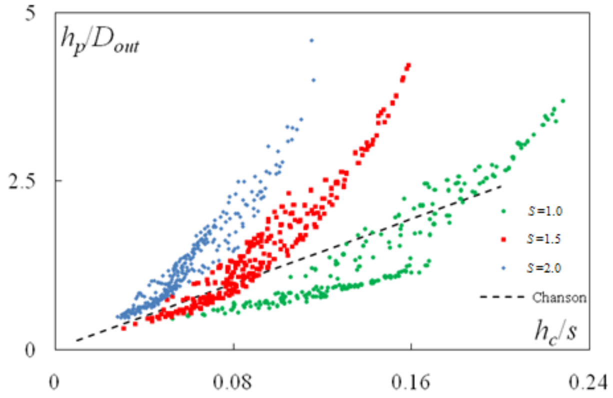


Fig. 8 - Manhole pool height h_p/D_{out} versus h_c/s, where h_c is critical flow depth at the brink, and $S = s/D_M$ is dimensionless drop height

DOWNSTREAM FLOW CHOKING

As pointed out by Hager (1999), the effect of the approach flow conditions is essential and manhole outflows subjected with a supercritical approach flow may undergo dangerous flow features mainly because of shock wave generation. The presence of manholes significantly affects the choking phenomena in a sewer system, leading eventually to choking inception both in the up- and downstream pipes. Choking downstream of manholes may developed by:

- Touching of sewer vertex by a wave maximum,
- Cut-down of air transport, which can be followed by,
- Breakdown of supercritical flow structure,
- Development of moving hydraulic jumps,
- Abrupt transition from free surface to pressurized sewer flow.

For supercritical approach flow the sewer filling ratio has to be limited sufficiently below the soffit. The manhole outflow may choke if the filling ratio is too large.

In a sewer manhole the transition from free surface to pressurized pipe flow is often characterized by the capacity (subscript C) pipe Froude number (Hager, 1999) $\mathsf{F}_c = Q_C/(gD^5)^{0.5}$. Sewer choking was previously studied relative to abrupt cross-sectional manhole changes (Gargano and Hager, 2002), bend manholes (Gisonni et al., 2000) and junction manholes (Gisonni and Hager, 2002).

As for drop manholes, De Martino et al. (2002) performed tests for small relative drops ($s/D \leq 1$) proposing a choking condition depending on the filling ratio y_o, the ratio s/D and F_C. Choking downstream of a drop manhole with $s/D > 2$ is a complex phenomenon affected by many factors. A functional dependence between F_C and y_o has not yet been found. The test data indicate the importance of the manhole pool height. The pool blocks the air flow from the manhole to the downstream pipe as its level increases.

Experimental evidence indicates that choking generally occurs in regime R3. However, if the ratio s/D_{out} between drop height and outlet diameter is smaller than 3 to 5, choking may even occur in regime R2. In special cases, as the water discharge increases, it is possible to observe the following sequence in regime R2:

- First transition from free surface to pressurized flow (choking),
- Subsequent transition from pressurized flow to free surface flow (opening), and
- Finally, a second transition from free surface to pressurized flow.

Experimentation indicates that downstream flow choking is also affected by the approach flow Froude number $\mathsf{F}_o = Q/(gDh_o^4)^{0.5}$ (Hager, 1999), and the approach flow filling $y_o = h_o/D$. A data analysis demonstrates that choking is governed by the combined parameter

$$\psi = y_o[\mathsf{F}_{och} - (h_p/D_{out})] \tag{4}$$

where F_{och} = approach flow Froude number for choking inception (subscript ch). Choking onset points are fitted for $0.3 < y_o < 0.75$ by (Fig. 9)

$$\psi_{ch} = -5.9 \cdot y_o + 3.5 \tag{5}$$

Equation (5) splits the plane (y_o,ψ) into a "choking zone" and a "no choking zone" (Fig. 9), provided aerated manhole flow is considered.

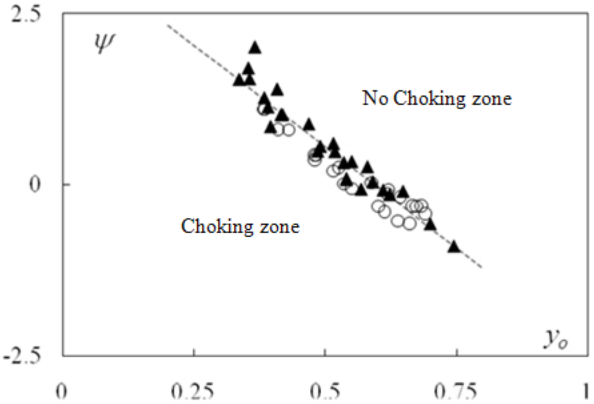


Fig. 9 - Choking inception from (▲) Model 1, (○) Model 2, Eq. (4) (- - -)

Equation (5) allows to verify the choking risk of a sewer placed downstream of a drop manhole. First, determine the approach flow filling ratio y_o and the Froude number F_o. Then, evaluate h_p/D_{out} from Eq. (3) or Eq. (2), and subsequently determine the parameter $\psi' = y_o[\mathsf{F}_{och} - (h_p/D_{out})]$. Finally, the value of ψ' is compared with ψ_{ch} as given by Eq. (5): if $\psi' > \psi$, choking condition does not occur. A safety factor is recommended.

CONCLUSIONS

A laboratory study has been conducted at University of Cassino to investigate the choking features of drop manholes in sewer systems. Choking of pipe flow is a complex phenomenon and depends on various effects. One of the most relevant factor is the height of the manhole pool. A data analysis has indicated that both hydraulic and geometric parameters affect the pool depth differently in terms of the manhole flow regimes. In regimes R1 and R2 the pool height depends on water discharge, jet shape, inlet and outlet diameters, and the ratio between drop height and manhole diameter. In regime R3, for which the drop manhole outflow is often similar to orifice flow, the pool depth is affected by the water discharge and the diameters of the manhole and the up- and downstream pipes, but it does not depend on the jet shape and the drop height. The downstream pipe slope does not seem to affect the pool depth. Empirical equations for the estimation of the pool depth in various operating conditions are provided.

Experimentation indicates that the downstream flow choking is also affected by the approach flow Froude number and the approach flow filling ratio y_o. A novel parameter ψ characterizes choking inception. This parameter allows to define a *choking zone* only in terms of y_o to allow definition of the choking risk in the downstream pipe of a drop manhole.

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