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HEAD LOSSES IN SEWER JUNCTION

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ABSTRACT

The functionality of sewer networks is strongly affected by the correct operation of their appurtenances; the dendritic structure of urban drainage systems implies that junction manholes represent a crucial hydraulic structure, allowing two conduits merging into one. Hydraulic features of combining flows become quite complex when supercritical flows are involved, as in the case of steep urban context, with consequent formation of shockwaves and surging phenomena. Former studies conducted by Gisonni and Hager resulted in an optimized layout of sewer junctions operated under supercritical approach flow conditions. Recently, an extensive experimental campaign was performed on a physical model with generalized geometrical conditions, including various conduit diameters. Furthermore, physical model tests have been used to implement and validate a numerical model, aiming to explore a wider range of junction angles, which were limited to 45° and 90° for the physical model. In particular, the numerical model focused on the flow condition where both approach flows are supercritical. Based on the dataset constituted from both physical and numerical model results, comprehensive equations are proposed for the prediction of energy losses at junction manholes with different upstream and lateral conduit diameters, with particular reference to supercritical combining flows.

Keywords: Capacity; Choking; Junction manhole; Sewer hydraulics; Supercritical flows

1. INTRODUCTION

Sewer junctions represent a crucial hydraulic structure for urban drainage systems. Sewer systems must guarantee free surface flow through junctions, in order to prevent surge phenomena and abrupt transitions from free surface to pressurized flow. A correct operation of any urban drainage system must accomplish a twofold task, i.e. to securely convey (i) dry-weather flows, which may originate waterborne diseases, and (ii) stormwater runoff in order to prevent flooding of urban areas and threatens for public health and safety.

However, junctions with combining flows are very frequent in hydraulic structures, irrigation and drainage systems. An analysis of this hydraulic structure is particularly complicated if supercritical approaching flows combined with shock waves occur.

The hydraulic features of a junction flow are governed by a large set of geometric and hydraulic parameters, so that it is impossible to formulate a precise general approach for the analytical description and evaluation of this phenomenon.

The hydraulic features of subcritical combining flow have been thoroughly investigated, with particular reference to rectangular cross sections which are prone to theoretical approaches. In general, the usual assumptions of nearly uniform flow and negligible boundary friction within the control volumes are accepted (Ramamurthy et al 1988). More recently, the peculiar condition of surcharged junction manholes has been investigated for circular pipes (Zhao et al. 2006). One of the main issues of these researches was to establish the maximum free surface elevation within a surcharged manhole, in order to prevent blown-off manhole covers, sewer geysering, urban flooding, and structural failures of conduits.

A larger amount of experimental data is available for the estimation of local head losses in pressurized conduit flow, also with particular reference to combining flows (Idel'cik 1986, Oka and Ito 2005). However, pressurized flow can be considered as a special case of free-surface flow, as long as the Froude number is $F<0.7$; the estimation of local energy losses for free surface flows can thus be based, under certain conditions, on the coefficients specifically obtained for local head loss in pressurized flows (Hager 2010, Gisonni and Hager 2012).

When dealing with hilly contexts, bottom slopes usually exceed some per mille units, thus originating supercritical flow approaching junction manholes. For such flow conditions shockwaves occur, similarly to other hydraulic singularities with local perturbations such as contractions, expansions, bends or even changes of roughness and bottom slope. Despite of the challenging phenomenon (Chow 1959) few systematic studies are available from the literature, due to the highly complex flow features, including 3-D effects and presence of air-water mixture flow.

Supercritical flows at junction manholes have been mainly investigated via physical modeling. Del Giudice and Hager (2001) and Gisonni and Hager (2002b) analyzed the shockwaves geometry and manhole choking for circular sewers aiming to propose a design procedure for junction manholes with supercritical approaching flow. However, no systematic investigation on head losses in supercritical combining flows seems to be available, so far. This circumstance is probably due to the fact that energy losses in supercritical flows are generally considered a minor concern for practical problems as compared to discharge capacity. However, energy losses evaluation is definitely important for an adequate modeling of open channel systems, such as sewer networks (Yen 1986).

This contribution resumes the major findings of a generalized approach proposed by Pfister and Gisonni (2014) to formulate the energy losses at junction manholes, for both subcritical and supercritical flow conditions.

2. PHYSICAL MODEL

The experimental campaign was based on two new physical models at the Laboratory of Hydraulic Constructions (LCH) of Ecole Polytechnique Fédérale de Lausanne (EPFL) (Simos 2012, Gökok 2013, Niedermann 2013), in order to investigate 45° and 90° junction manholes. The main issue of the new models consisted in the presence of varying diameters for the combining conduits, all having circular sections, as represented by the scheme of Fig. 1.

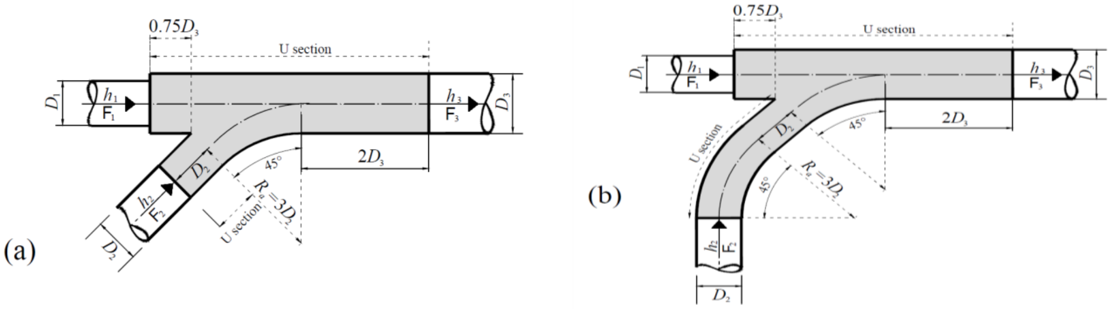

Figure 1. Scheme of junction manhole, (a) plan view for θ=45°, (b) plan view for θ=90°. Grey: U-shaped portion; white: circular conduit portion.

The outlet diameter was fixed equal to D_3=0.240 m, with the approach diameters D_1 and D_2 assuming different values according to all the possible combinations of pipe diameters equal to 0.123, 0.190 and 0.240 m (Fig. 2). Here the subscripts 1, 2 and 3 indicate the upstream straight, the lateral and the outlet branch of the junction, respectively (Fig. 1).

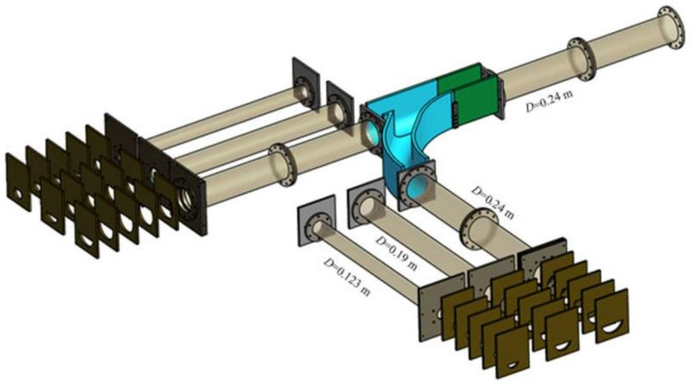

Figure 2. Overview of model elements including jet-boxes, conduits and junction (Note that the junction geometry is shown only for D_2=0.24 m).

Here following the main geometrical features of the physical models are resumed:

- a straight U-shaped portion of length $2\cdot D_3$ is installed upstream of the manhole outlet (Fig. 1), in order to improve the capacity of the junction manhole, according to previous observations (Gisonni and Hager 2002a);
- across the junction, the manhole section is U-shaped, with $1.5\cdot D_3$ high benches;
- the lateral conduit has an axial curvature radius $R_a=3\cdot D_2$, with a straight portion of length $1\cdot D_2$, upstream of the junction point, ending with a junction angle of 45° (Fig. 1).

The experimental set up allowed to impose independent variations of the approach velocity V and the filling ratio y in both combining channels, also for supercritical conditions with large Froude numbers. In total, more than 600 experiments were recorded, aiming to characterize the main features of manhole junction flow and, particularly, the head losses. Further details of the physical model are illustrated by Pfister and Gisonni (2014).

The flow process is basically governed by the following parameters: filling ratios $y_i=h_i/D_i$, Froude numbers F_i and diameter ratios $\beta_i=D_i/D_3$ of the two approach branches, i.e. i=1, 2. Experimental runs covered a wide range of the main parameters, such as $0.10\leq y_i\leq 1.0$ and $0.2\leq \mathsf{F}_i\leq 15.7$; details are provided in Table 1.

It has to be remarked that, for a given discharge Q, the Froude number can be approximated as $\mathsf{F}=Q/(gDh^4)^{1/2}$, with an accuracy of some ±3% for $0.20\leq y\leq 0.90$ (Hager 2010, Gisonni and Hager 2012).

Table 1. Experimental range of main parameters.

Junction angle	β_1	y_1	F_1	β_2	y_2	F_2
45°	0.51, 0.79, 1.00	0.17 to 0.92	0.2 to 10.6	0.51, 1.00	0.10 to 0.94	$0.2^{(*)}$ to 10.3
90°	0.51, 0.79, 1.00	0.19 to 1.00	0.2 to 15.7	0.51, 0.79, 1.00	0.10 to 1.00	$0.2^{(*)}$ to 6.5

The extended experimental campaign allowed for a detailed description of the main hydraulic features, including free surface profiles and discharge capacity; hereafter the attention will be focused on junction head losses.

2.1 Basic features of junction flow

Junction manholes may present various flow conditions (Del Giudice and Hager 2001, Gisonni and Hager 2002b), among which the following are the most important in practice:

- Supercritical approach flow in both branches.
- Subcritical flow in lateral, and supercritical flow in straight branch.
- Supercritical flow in lateral, and subcritical flow in straight branch.
- Subcritical flow in both branches.

Two further flow conditions may be considered, with zero discharge in one of the two upstream conduits (F_i=0 for i=1 or 2), which are less frequent in real open channel systems and are not included within the synoptic outline of the experimental conditions (Table 1). All of the above mentioned conditions were tested during the experimental investigation.

Figure 3 shows typical features for supercritical combining flows at a 90° junction manhole. It is possible to distinguish several types of shockwaves, as described by Gisonni and Hager (2002b). Three relevant waves are:

- The first type of shockwave develops along the curved portion of the lateral branch (Fig. 3a) and has similar features to that formed within a bend manhole.
- The second type is located on the wall opposite of the lateral branch, due to flow impingement (Fig. 3b); generally, this is the highest wave developing within a junction manhole.
- The swell generated by the flow impacting the outlet section of the manhole is visible in Fig. 3b. Whenever the swell height is too large, the combined flow may choke, thus causing abrupt transition from free surface flow to pressurized flow.

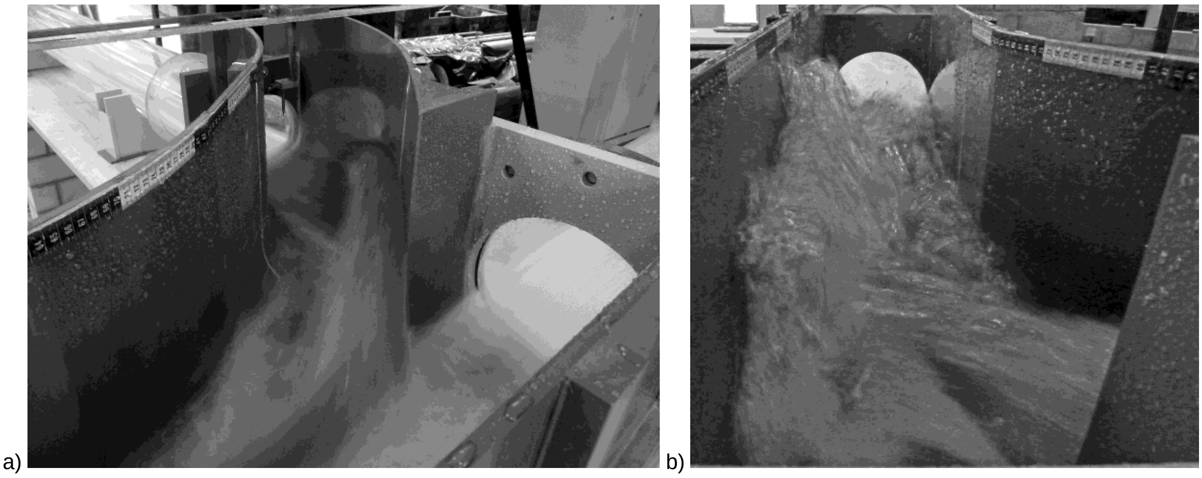

Figure 3 – Flow pattern in 90° junction manhole: y_1=0.28, F_1=5.0, β_1=1.0, y_2=0.37, F_2=3.4, β_2=0.8. Junction point (a) and downstream (b) views.

Flow patterns for supercritical conditions within a 90° junction manhole, are substantially similar to the 45° junction manhole, except for some peculiar details which are illustrated by Pfister and Gisonni (2014).

3. HEAD LOSS COEFFICIENTS

Combining or dividing flows at junctions are governed by the conservation principles of mass, energy and momentum. Based on these equations it is possible to develop analytical expressions for the local energy losses and corresponding coefficients.

The head loss coefficients ξ are conventionally defined as

$$\xi_{1,3} = \frac{H_1 - H_3}{V_3^2 / 2g} \qquad [1]$$
$$\xi_{2,3} = \frac{H_2 - H_3}{V_3^2 / 2g}$$

where H_i and V_i are the total head and average velocity at the reference section i (Fig. 1), respectively.

In principle, it is possible to deduce generalized equations for combining flows by linking the energy, momentum and continuity equations. The main complexity is constituted by the evaluation of the pressure forces components (i.e. momentum conservation), depending on manhole geometry and flow conditions.

Furthermore, for the sake of simplicity, the cross sectional area A and the Froude number F of circular channels may be approximated as (Hager 2010, Gisonni and Hager 2012)

$$A = D^2\left(\frac{h}{D}\right)^{1.5} = D^2 y^{1.5} \qquad [2]$$
$$\mathsf{F} = \frac{Q}{\sqrt{gDh^4}} = \frac{Q}{\sqrt{gD^5 y^4}}$$

Based on the abovementioned procedure, Pfister and Gisonni (2014) presented the following expression for the head loss coefficients ξ

$$\xi_{1,3} = c_{1,3} + a_{1,3}\left[1 - 2\frac{\mathsf{F}_1^2 y_1^{2.5}\beta_1^3 + \mathsf{F}_2^2 y_2^{2.5}\beta_2^3\cos\theta}{\mathsf{F}_1^2 y_3^{2.5}} + \beta_1\frac{\mathsf{F}_1^2 y_1}{\mathsf{F}_3^2 y_3}\right] \qquad [3a]$$

$$\xi_{2,3} = c_{2,3} + a_{2,3}\left[1 - 2\frac{\mathsf{F}_1^2 y_1^{2.5}\beta_1^3 + \mathsf{F}_2^2 y_2^{2.5}\beta_2^3\cos\theta}{\mathsf{F}_1^2 y_3^{2.5}} + \beta_2\frac{\mathsf{F}_2^2 y_2}{\mathsf{F}_3^2 y_3}\right] \qquad [3b]$$

In Figs. 4a and 4b the head loss coefficients $\xi_{1,3\text{exp}}$ and $\xi_{2,3\text{exp}}$ (for sub- and supercritical flows) at the *45° junction manhole* as derived from model measurements (subscript exp) are plotted against the theoretical (subscript th) $\xi_{1,3\text{th}}$ and $\xi_{2,3\text{th}}$ values resulting from Eqs. (3a) and (3b). The values of the coefficients $a_{1,3}$, $c_{1,3}$, $a_{2,3}$ and $c_{2,3}$ are listed in Table 2 for both, sub- and supercritical approach flow conditions. Note that the head loss coefficients for subcritical flow conditions were never larger than $\xi_{1,3}$=0.25 and $\xi_{2,3}$=0.35. The coefficients of determination were larger than 0.95, despite of the macro-turbulent nature of combining supercritical flows (e.g. occurrence of shockwaves, air entrainment, etc.).

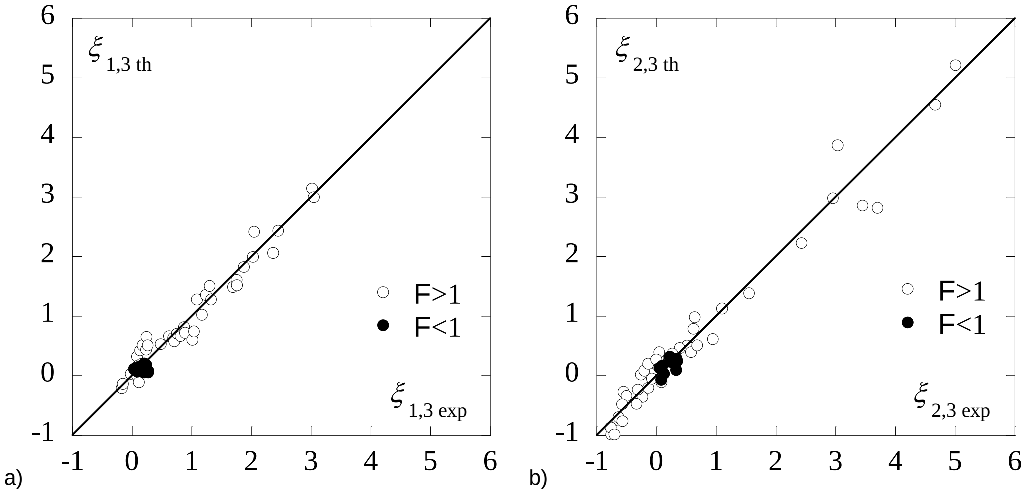

Figure 4 – Comparison of experimental and theoretical ξ values for the 45° junction manhole referring to the (a) main, and (b) lateral branch.

Similar results were obtained for the *90° junction manhole* and the corresponding values of $a_{1,3}$, $c_{1,3}$, $a_{2,3}$ and $c_{2,3}$ are also listed in Table 2. Note that an effective inflow angle δ had to be accounted for within the momentum Eq. (5), as discussed by Hager (1987). According to the junction geometry (Fig. 1) the lateral flow is influenced by the straight extension of length $1{\cdot}D_2$. For the 90° junction manhole, the data analysis confirmed that an effective lateral inflow angle of δ=45° had to be assumed in Eqs. (3a) and (3b), instead of the “geometric” junction angle θ=90°.

Table 2 – Empirical coefficients of Eqs. (3a) and (3b).

		$a_{1,3}$	$c_{1,3}$	$a_{2,3}$	$c_{2,3}$
45°	Supercritical flow	0.72	0.27	0.83	0.16
	Subcritical flow	0.91	-0.30	0.75	-0.16
90°	Supercritical flow	0.70	0.15	0.68	0.16
	Subcritical flow	0.8	-0.13	0.54	-0.08

The coefficients in Table 2 allow for some remarks:

- For any flow condition, the absolute values of the coefficients for the 45° junction manhole are systematically larger than for the 90° junction manhole.
- For the 90° junction manhole, with supercritical flow condition, it is possible to assume $a_{1,3}=a_{2,3}=0.70$ and $c_{1,3}=c_{2,3}=0.15$, without introducing significant error in the evaluation of $\xi_{1,3}$ and $\xi_{2,3}$.
- For both 45° and 90° junction manhole, with subcritical flow condition, $c_{1,3}$ and $c_{2,3}$ are negative, but with almost the same absolute values for the supercritical flow condition.

4. CONCLUSIONS

A comprehensive experimental campaign was conducted to investigate the flow features of combining flows at 45° and 90° junction manholes on circular conduits, with various diameters. In particular, the paper illustrates the results obtained for the local head losses in presence of both subcritical and supercritical flows.

The analysis of the experimental results, along with the application of the basic principles of mass, energy and momentum conservation, provided theoretical expressions for the head loss coefficients.

The expressions of the head loss coefficients provide an important tool for the numerical modeling of open channel flows in sewer systems and drainage networks, according to the classical computation procedures outlined for supercritical and subcritical flow by Yen (1986) and Hager (2010).

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