SUPERCRITICAL FLOW IN SEWER MANHOLES

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Parole chiave: choking, design, hydraulics, sewer, shockwave, wastewater

ABSTRACT

The breakdown of supercritical flow in sewer manholes may be dangerous when designed according to current practice. This issue is particularly relevant for drainage systems conveying stormwater discharges in both stormwater and combined sewers. Based on detailed hydraulic experimentation, the main features of three manhole types were observed, including the through-flow, the bend and the junction manholes. Using systematic laboratory observations and a hydraulic approach, the large data sets allowed to present a modified and generalized design for such hydraulic structures, thereby accounting for Froude similitude. Both the hydraulic flow patterns along with design guidelines are presented to allow for a safe and straightforward design of manholes in these sewer networks. The design relates particularly to freeboard requirements and to the discharge capacity of sewer manholes. It is demonstrated that the dimensionless discharge capacity of the junction and the through-flow manholes is roughly twice and three times larger than for bend manholes, respectively.

1. INTRODUCTION

Sewers are a significant infrastructural component of the modern society because waters used in private and public life are safely diverted. Whereas the wastewater sewer collects only used fluid wastes, the combined sewer in addition receives rainwater and may unintentionally collect parasite waters from groundwater infiltration. The following relates to combined and stormwater sewers only, where a safe design is important to prevent flooding of urban areas.

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A basic principle of sewer design is free surface flow in normally circular-shaped pipes of diameter D. Pressurized sewer flow may occur in sanitary sewers serving depressed regions where the sewage has to be pumped, but usually is irrelevant for stormwater management (ASCE 1992, ATV 2000, CSDU 1997, Pecher et al. 1991). A sewer manhole allows access to a sewer system; generally, manholes must be added to a sewer system with a maximum spacing of 100 m to: (1) Aerate the sewer, (2) Control defective or clogged sewer reaches, and (3) Change any of the sewer parameters, such as diameter, direction or discharge. The sewer manhole represents a significant element of all urban drainage networks, therefore.

The hydraulics of sewers involves two distinctly different elements, namely the sewer reach between two manholes with a gradually varied flow regime, and the sewer manhole with a spatially varied flow regime. Whereas the flow between two manholes may be accounted for by backwater and drawdown curves, the manhole structure requires a more thorough investigation because of locally variable manhole geometry and a spatially variable discharge due to lateral branch flow.

Open channel hydraulics as occur in partially filled sewers depends essentially on the Froude number. For subcritical flow, any disturbance propagates into the upstream direction, such that these flows must be computed against the flow direction. In contrast, the computational and the flow directions are identical for supercritical flows, for which the average flow velocity V is larger than the wave celerity c. The Froude number is defined as the ratio of fluid velocity V and wave celerity c, therefore. Partially-filled sewers in circular conduits involve a relatively complex geometry, resulting in a complicated expression for the Froude number. Hager (1999) proposed a simplification for the Froude number F in terms of discharge Q, gravitational acceleration g, sewer diameter D and flow depth h for a sewer filling $y=h/D$ between 20% and 95% as

$$\mathrm{F} = Q/(\mathrm{g}Dh^4)^{1/2} \tag{1}$$

This is similar to the expression in the rectangular channel, yet with a larger effect of flow depth, or relative sewer filling y. For complete sewer filling, i.e. the transition from free surface to pressurized pipe flow (y=1), (1) degenerates to the so-called pipe (subscript D) Froude number $\mathrm{F}_D=Q/(\mathrm{g}D^5)^{1/2}$.

Open channel flow may easily be characterized with the Froude number, provided viscous effects are negligible. According to Hager (1999), one mai distinguish between:

(1)	$0<\mathrm{F}<0.7$	*Weakly subcritical flow* with a nearly plane surface pattern and small dynamic effect; these flows behave nearly as pressurized flow, for which F=0;
(2)	$0.7<\mathrm{F}<1.5$	*Transitional flow* typically prone to standing free surface waves such as undular hydraulic jumps;
(3)	$1.5<\mathrm{F}<3$	Supercritical flow with a characteristic dynamic flow behavior; and

(4) $3<F$ *Hypercritical flow* involving strong flow dynamics and a large stability with a potential damage if the flow is disturbed.

The following relates exclusively to flows in which the Froude number is larger than 1.5, as occur in sewer networks of hilly and mountainous areas for which flow velocities are typically larger than 3 m/s. Disturbing such flows may result in two distinctly different effects, namely:

1. *Shockwaves* as a reaction to any alteration of a flow in a straight prismatic channel, and
2. *Hydraulic jump* when the flow disturbance is too large to maintain supercritical flow.

Whereas shockwaves involve mainly a medium increase of flow depth beyond the shock front, a hydraulic jump results in the collapse of the supercritical flow regime and a backwater effect. The latter may be a significant problem in sewers, because the flow may rapidly change from free surface to pressurized two-phase conduit flow, associated with water hammer, decrease of discharge capacity up to geysering of wastewater off the manhole shaft onto public space (Figure 1), with consequent threats to public safety and hygienic conditions. That latter aspect may be described as a breakdown of the sewer system, and must be avoided in any case (ATV 1996, 2000). The present research was mainly conducted to inhibit these phenomena, associated with a better understanding of manhole flow and an improved design of existing manhole structures.

The following intends to review the most recent observations relating to supercritical flow across combined sewer manholes conducted during the past decade at *Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie* VAW of ETH Zurich. Reference is given to a recent book by Hager (1999), because little other information is available, and because that book summarizes the main findings of works published in the literature. The purpose of this paper is thus twofold: (1) Review of past research in the subject matter, and (2) Offering a design basis for improved sewer design.

Figure 1 - Geysering of a combined sewer (Storm event in Ischia, Italy, on September 22, Gisonni, private archives).

2. THROUGH-FLOW MANHOLE

A through-flow manhole or inspection manhole is the simplest arrangement of a sewer for control and maintenance purposes. According to European standards, inspection manholes must be properly spaced to guarantee a complete surveying; obviously, smaller pipes have more inspection manholes to ease the control of buried pipes. The through-flow manhole is connected to an equal upstream and downstream sewer of diameter *D* and has U-shaped cross-section of the same diameter across the manhole length *L*.

Figure 2 shows a definition sketch involving the approach (subscript *o*) flow depth h_o and velocity V_o. For $y_o=h_o/D\leq0.50$, the flow remains in the lower half of the identical circular and U-shaped cross-sections. For $y_o>0.50$, the flow may abruptly expand at the manhole entrance resulting in a side depression followed by shockwaves of height h_i shortly downstream because of the flow impact onto the side walls. More dramatically, the flow undergoes a significant change at the manhole end because it impacts sideways onto the downstream manhole wall resulting in a shaft (subscript *s*) flow depth h_s that is either small enough to maintain supercritical flow in the downstream sewer, or too large such that a hydraulic jump occurs. The latter results in choking of the manhole outlet because the air transport is cut (Figure 3); a surface disturbance may propagate upstream to choke also the upstream sewer. If the discharge increases within a short period, the choking phenomenon proceeds so fast that geysering results, as previously described.

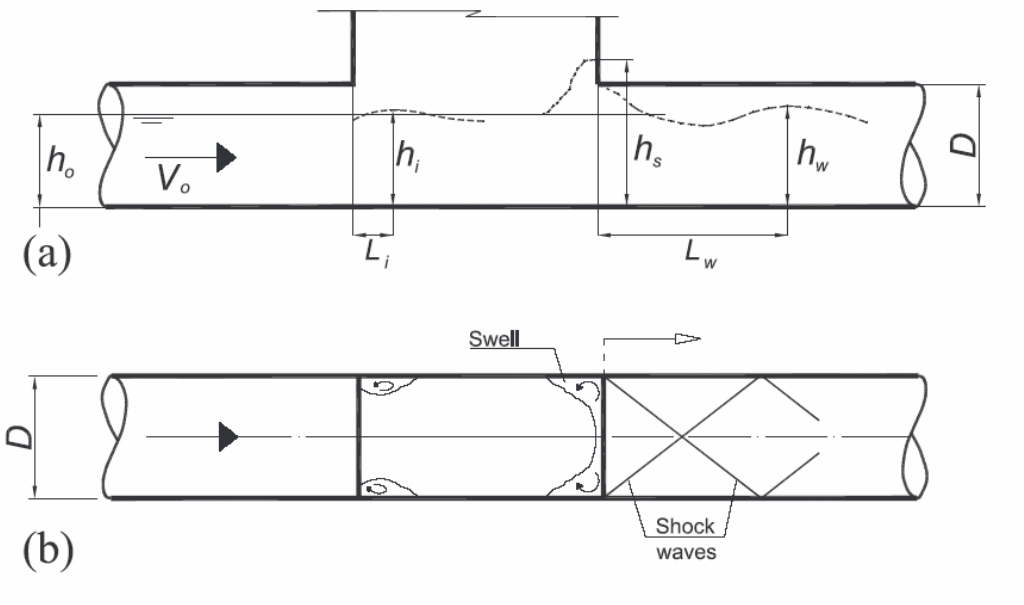

Figure 2 - Through-flow manhole (a) Section, (b) Plan.

Given that the highly-filled U-shaped profile is similar to a rectangle, the determining Froude number of manhole flows is $F_U=Q/(gD^2h_o^3)^{1/2}$ instead of (1). The flow depth h_s relative to the approach flow depth h_o was experimentally found as (Gargano and Hager 2002)

$$h_s/h_o = 1 + (1/3)(F_U y_o)^2 \tag{2}$$

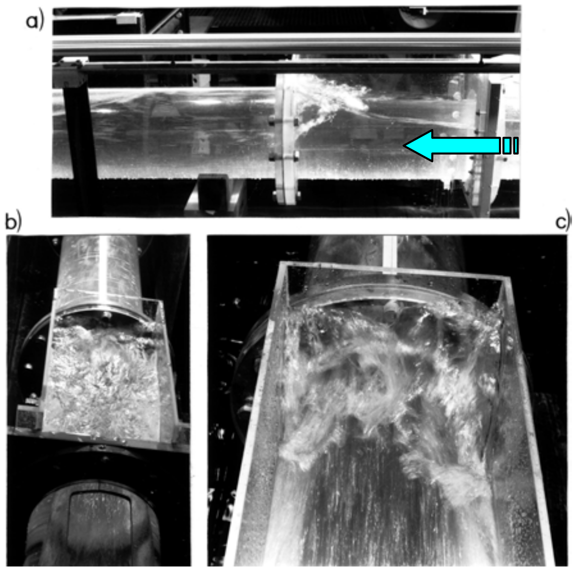

Figure 3 - Choking flow at manhole outlet for yo=0.75 and Fo=1.30 (a) Section, (b) Upstream view and (c) Detail of impact flow.

Accordingly, the relative wave amplitude $[(h_s-h_o)/h_o]$ increases quadratically as both the relative sewer filling y_o and the approach Froude number increase. More interestingly, the ratio $[(h_s-h_o)/D]$ depends exclusively on the pipe Froude number F_D.

The discharge capacity (subscript *C*) Q_C of a through-flow manhole for free surface flow is of design interest. According to (2) it depends on the sewer diameter *D*. The transition from free surface to pressurized pipe flow is associated with the capacity pipe Froude number $F_C=Q_C/(gD^5)^{1/2}$, therefore. According to Gargano and Hager (2002)

$$F_C = 14.6 - 17.3y_o, \quad \text{for } 0.70<y_o<0.75 \tag{3}$$

During the experiments, no free surface flow resulted whenever y_o was larger than 75%, whereas choking never occurred for $y_o<0.70$. Flow choking thus involves capacity Froude numbers F_C between 1.60 and 2.50, with an average of $F_C=2$.

The current design practice for sewers is based on a so-called full-flow approach occurring for a relative sewer filling of 85%, independent of the flow condition; this criterion applies exclusively for pipes with diameters in excess of 1m, to guarantee a sufficient freeboard of some 20 cm. The previous observations clearly demonstrate that the flow across all through-flow manholes then breaks down. This may hardly occur in practice because the design discharge is infrequent, depending on the design return period. However, for supercritical flow, the breakdown of flow must be expected in a through-flow manhole whenever the sewer filling exceeds 75% (Figure 3).

3. BEND MANHOLE

Given that sewers often run along public roads, a sewer bend manhole is a normal sewer element. Of particular interest are bends with a deflection angle of 45° and 90°. The average bend radius R_a is usually equal to three sewer diameters D, which was also used in the present research. One would think that the 90° bend manhole is more critical in terms of discharge capacity than the 45° bend manhole. Figure 4 shows a definition plot involving the approach flow depth h_o and the approach flow velocity V_o, the average radius of curvature R_a=3D and the deflection angle δ=45°.

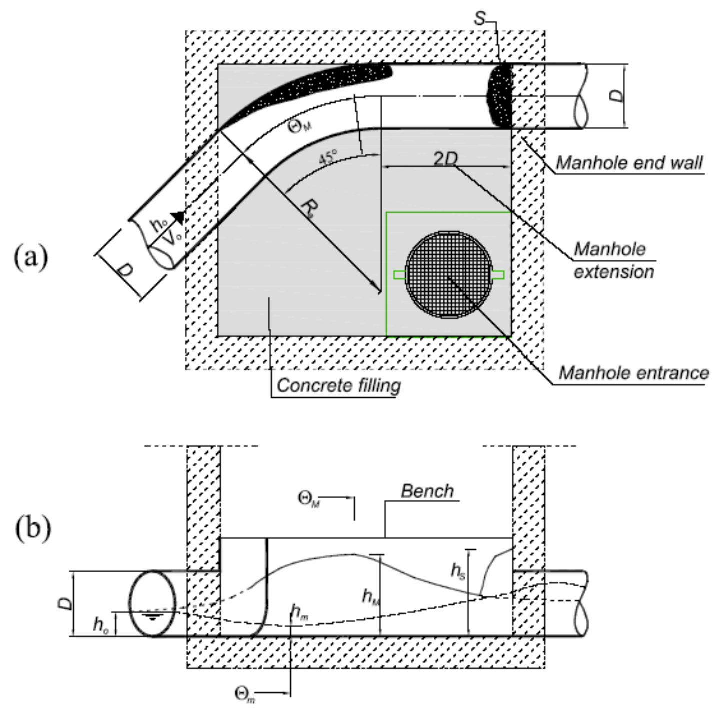

Figure 4 - Improved bend manhole with bend extension (a) Plan, (b) Section

Due to the bend, two shockwaves both along the inner and the outer bend walls develop, of which the maximum (subscript *M*) height along the outer wall is h_M, whereas the minimum (subscript *m*) flow depth along the inner wall is h_m. The latter is irrelevant for design, whereas the maximum height may be expressed with $F_U=Q/(gD^2h_o^3)^{1/2}$ as (Del Giudice, et al. 2000)

$$h_M/h_o = [1 + 0.50(D/R_a)F_U^2]^2 \quad (4)$$

Note that the angle Θ_M of maximum wave height is between 35° and 55 depending on the approach flow conditions and the manhole deflection angle (Gisonni and Hager 2002a). Using the standard manhole design for 45° deflection with the downstream manhole wall immediately at the deflection end thus reduces the discharge capacity of the structure significantly, because the wave along the outer manhole wall impinges onto the manhole end wall.

To improve the capacity of the 45° bend manhole a straight tailwater manhole extension of length 2*D* was added to the structure, as shown in Figure 4. Based on model experimentation, this manhole addition increases the manhole discharge capacity significantly because the shockwave along the outer bend wall reduces before entering the tailwater sewer. The discharge capacities of the modified 45°, and the 90° bend manholes were determined experimentally to (Gisonni and Hager 2002a)

$$F_C = (3 - 2y_o)y_o^{3/2}, \quad \text{for } y_o<2/3 \quad (5)$$

Bend manholes have thus a significantly smaller discharge capacity of up to F_{CM}=0.90 for y_o=67%, and only F_{CM}=0.80 for y_o=60%, as compared with an almost three times larger capacity of the through-flow manholes. Note also that the flow across a bend manhole breaks down whenever the approach flow depth is larger than (2/3)*D*, as compared to (3/4)*D* for the through-flow manhole. Figure 5 shows typical flow features prior to flow choking, as observed in a laboratory bend manhole. Note that the present design is independent from the manhole deflection angle: No special treatment is thus required for a bend manhole if the lateral branch is subdivided into two 45° deflections and if the 2*D* manhole extension is added upstream from the manhole end wall (Figure 4).

The discharge capacity may be increased by a downstream sewer of larger downstream (subscript d) diameter D_d. It is recommended to increase the diameter from *D* to D_d along the bend extension of length $2D_d$. So far, these experiments have not yet been conducted. Note that the tailwater sewer never choked during experimentation, but that choking was always associated with so-called gate flow, as is familiar with culverts. The flow may thus be compared with a supercritical open channel flow into which a gate is lowered. Up to a certain gate position, supercritical flow is maintained despite a local surface disturbance immediately upstream from the gate, whereas a hydraulic jump occurs when the gate is lowered slightly more (Hager 1994).

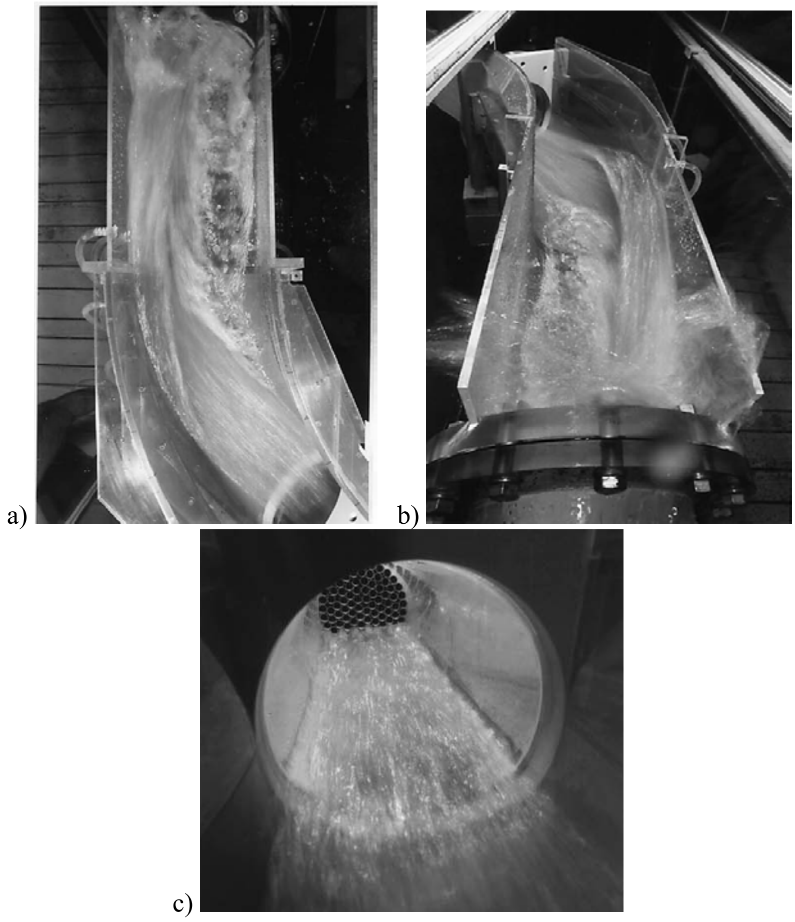

Figure 5 - Flow features in bend manhole with bend extension (a) Plan, (b) Upstream view, and (c) Intake section

4. JUNCTION MANHOLE

A junction manhole may be considered intermediate between the through-flow and the bend manholes. Due to the reduced lateral discharge portion, the capacity of a junction manhole is expected to be larger than for the bend manhole. However, the flow structure of the junction manhole is different from the two previous manholes. Figure 6 shows a definition sketch involving a junction manhole with equal branch diameters. The upstream (subscript *o*) branch has an approach flow depth h_o and an upstream velocity V_o, the lateral (subscript *L*) correspondingly h_L and V_L. The junction angle between the two branches is δ with a sharp-crested intersection at the junction point *P*.

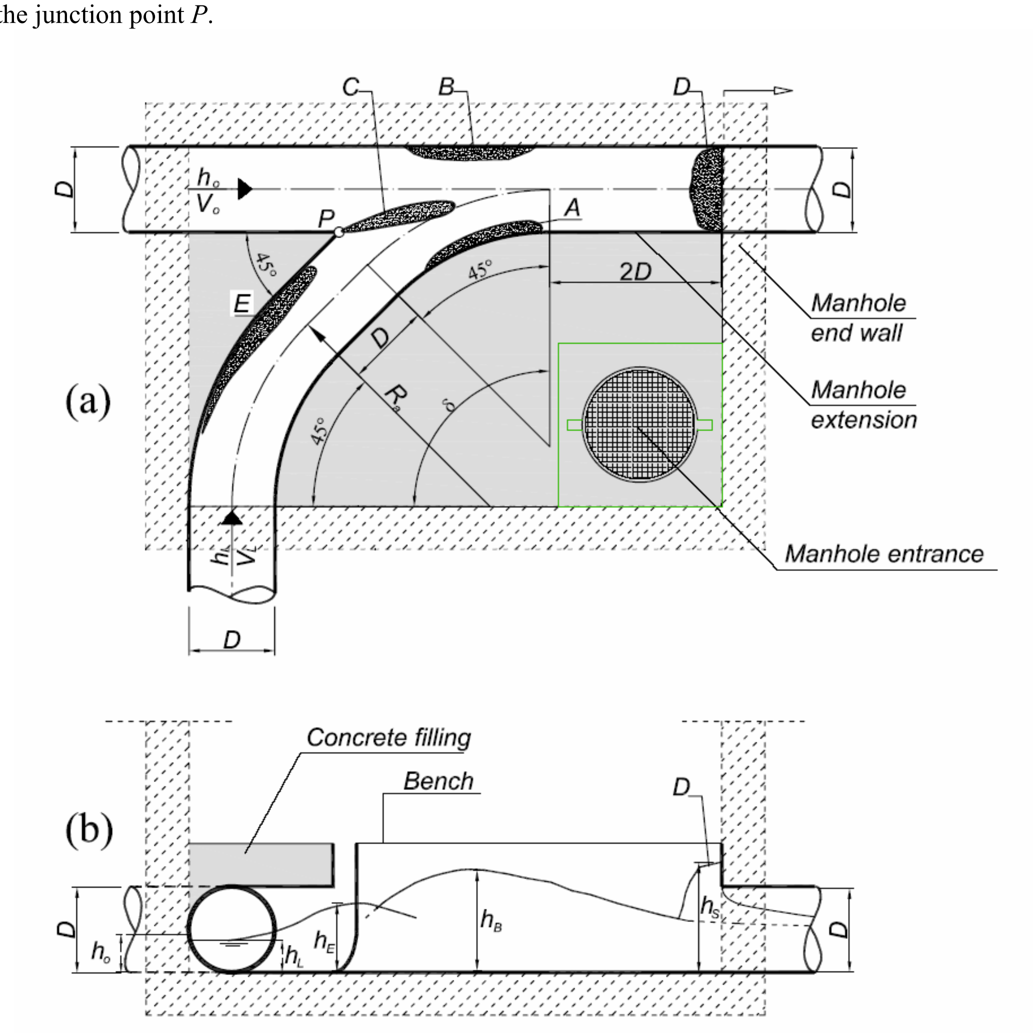

Figure 6 - Definition sketch of junction manhole (a) Plan with shock waves A, B, C, D and E, (b) Section.

Depending on the branch discharges, four waves may be observed in a junction manhole, namely: *Wave A* for small lateral discharge due to impact of the upstream flow onto the curved branch wall, *Wave B* due to the impact of flow onto the opposite straight manhole wall, comparable to the shockwave in a bend manhole, *Wave C* downstream from the junction point as the true junction shockwave due to the two branch flows, and *Wave D* due to the manhole end wall, comparable to the shaft waves of both the through-flow and the bend manholes. For junction manholes, *wave E* similar to the bend manhole may be observed along the outer wall of the lateral branch. Because waves A and C are always smaller than wave B, only the latter and wave D are relevant in design.

Both the 45° and the 90° bend manholes were experimentally investigated (Del Giudice and Hager 2001, Gisonni and Hager 2002 b). Four basic flow types were identified:

(1) Supercritical approach flows in both branches (Figure 7)
(2) Subcritical flow in the lateral branch, and supercritical flow in the through branch
(3) Supercritical flow in the lateral branch, and subcritical flow in the through branch
(4) Subcritical flow in both approach branches

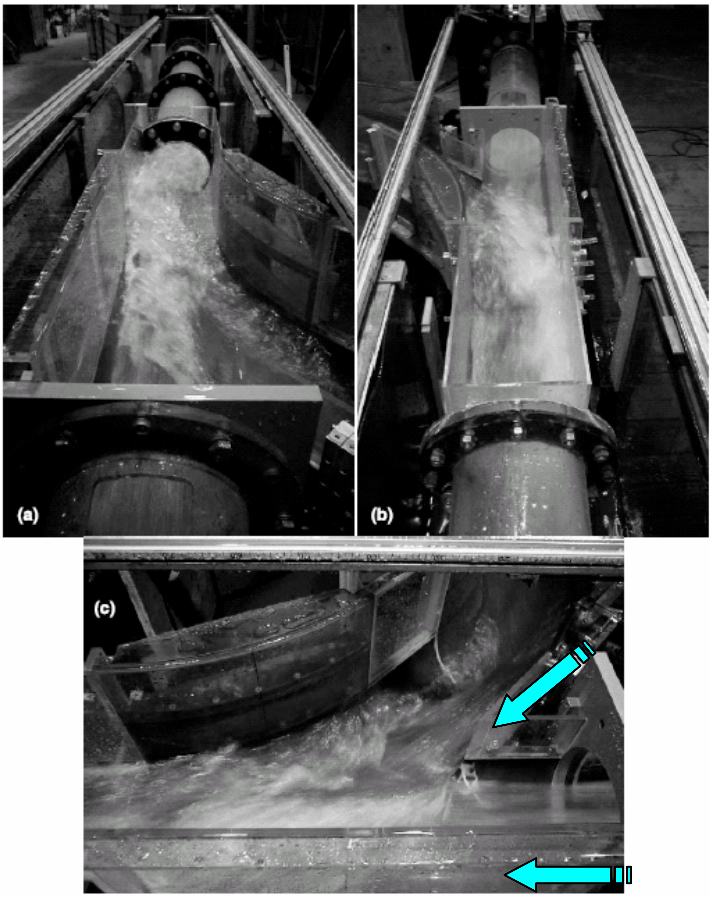

Figure 7 - Typical supercritical flow in junction manhole with both waves B and D for yo=yL=0.27, Fo=5.95 and FL=2.84 (a) Upstream view, (b) Downstream view, (c) Plan.

The following refers to cases (1) to (3). In contrast to both the through-flow and the bend manholes, the Froude number of the circular cross-section was relevant in junction manholes. Accordingly, $\mathsf{F}_L=Q_L/(gD_Lh_L^4)^{1/2}$ for the lateral branch flow, and $\mathsf{F}_o=Q_o/(gD_oh_o^4)^{1/2}$ for the through-flow branch.

The height h_B of wave B along the straight junction wall for the range of Froude numbers from 2 to 6 investigated was for both δ=45° and 90° independently of the Froude number F_o approximately as

$$h_B/h_L = 1 + (8/7)(\mathsf{F}_L - 1) \quad (6)$$

The impact (wave D) height h_S referred to as swell (subscript *S*) was determined for $\mathsf{F}_L>1$ as

$$h_S/h_L = 1 + C_\delta \mathsf{F}_L \quad (7)$$

where $C_\delta=1$ for $\delta=45°$, and $C_\delta=2/3$ for $\delta=90°$. The height of swell is thus of the order of wave B previously considered. The required height of the manhole chamber may thus be determined with the previous two relationships.

Of relevance is the (abrupt) transition from supercritical to subcritical manhole flows. Once the hydraulic capacity of a manhole is reached, two distinctly different phenomena may occur:

(1) Choking of downstream manhole outlet due to swell associated with an abrupt breakdown of the supercritical flow in the manhole first, possibly propagating in one or both branch pipes, or
(2) Choking in one or two branch pipes due to flow blockage. The lateral branch flow may be so dominant to cause breakdown of the through branch, resulting there in a hydraulic jump. This type of hydraulic breakdown was observed to be less abrupt, yet able to submerge either one or even both branches and result in undesirable backwater and pressurized sewer flow.

Figure 8 relates to choking type (1) showing both waves B and D and a highly turbulent flow pattern. Note that the flow in all the branches is free, and that choking occurs due to gate-type flow at the manhole outlet, as previously discussed for bend manholes.

The discharge capacity of a junction manhole depends on the number of branches in operation. For sewers, normally both branches must be considered. For supercritical flow in both branches, the capacity Froude number $\mathsf{F}_C=Q_C/(gD^5)^{1/2}$ varies essentially with the upstream Froude number and the upstream sewer filling, and slightly with the ratio of branch flow depths $\eta=h_o/h_L$.

The data follow for both the 45° and the 90° junction manholes (Gisonni and Hager 2002b)

$$\mathsf{F}_C = 0.60\mathsf{F}_o y_o \eta^{0.2}, \qquad \text{provided } y_L \le 0.075\mathsf{F}_o. \quad (8)$$

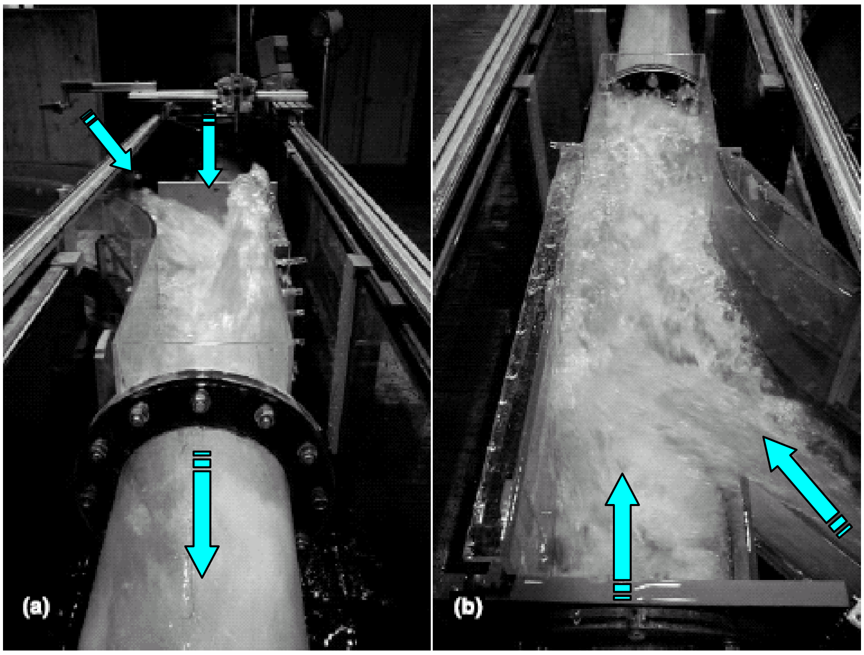

Figure 8 - Choking of manhole outlet for yo=yL=0.34, Fo=4.19, FL=4 (a) Downstream view, (b) Upstream view.

5. DISCUSSION OF RESULTS

The previous review allows comparison of results because of the simple parameter selection. It was found in particular that the 45° and the 90° bend manholes are controlled by the same mechanism provided that a 2*D* long bend extension is added to the 45° junction manhole. Moreover, the 45° and the 90° junction manholes are governed by a similar hydraulic behavior if a short straight intermediate piece one *D* long is added to the lateral branch of the 90° manhole (Figure 6a). Then, the height of the bend wave in the lateral branch is much smaller than for a complete 90° bend. The freeboard required in a manhole is imposed by the height of the junction wave according to (6), whereas the discharge capacity Q_C increases linearly with the upstream Froude number F_o, and over-proportionally with the approach flow depth h_o and the sewer diameter *D*.

To simplify results, consider the typical case $y_o \cong y_L$, for which $\mathrm{F}_C=0.60\mathrm{F}_o y_o$ from (8). Experiments indicated a maximum discharge capacity of $\mathrm{F}_C=1.4$; therefore, the main branch flow reduces the junction wave and increases the discharge capacity, as compared with a bend manhole.

Accordingly, the lateral branch flow disturbs the manhole flow, and junction manholes can be considered intermediate to the through-flow (Q_L=0) and the bend (Q_o=0) manholes. The capacities of these three basic manhole types may thus be roughly specified as F_C=0.80 for the bend manhole, F_C=1.4 for the junction manhole, and F_C=2 for the through-flow manhole. In parallel, the maximum approach flow depths associated with a fully supercritical manhole flow are y=0.65 for the bend, y=0.70 for the junction, and y=0.75 for the through-flow manholes. This contrasts current design practice for which the discharge capacity is governed essentially by uniform flow and the maximum sewer filling is usually set to y=0.85, according to the 'full-flow' assumption. Using these design guidelines may thus result in the breakdown of the supercritical flow across manholes, and in undesirable and dangerous flow conditions for which the sewer was not designed.

Consider finally also the impact of physical models on numerical application. Currently commercial software packages are available to evaluate the hydraulic performance of sewer systems, based on physically-based approaches, such as the SWMM, the HydroWorks, and the MOUSE packages (CSDU, 1997). Flood wave propagation through sewers is described by the De Saint-Venant equations based on the concept of one-dimensional gradually varied unsteady open channel flow. These packages simulate a sewer system with links (pipes) and nodes (manholes or other sewer appurtenances) and use various numerical algorithms to integrate the De Saint-Venant equations in order to assure numerical stability (Courant condition for explicit schemes); a special treatment for surcharge events is provided with the 'Preissmann slot' (Yen 1986). This model is inherently unable to properly account for the flow patterns in manholes previously described, because manhole flow is neither one-dimensional nor gradually varied; as a consequence, the essential hydraulic behavior of manholes cannot be correctly modelled, resulting in unreliable assumptions in case studies.

Therefore, the effects of sewer manholes on the performance of a sewer system may be simply assessed by the Froude number, the manhole capacity and the filling ratio. Such a procedure completes current software packages by including user-friendly information for manholes to verify their capacity with respect to the design assumptions.

6. PRACTICAL RECOMMENDATIONS

The following refers to manholes that are currently too small and should be improved. Modern sewers are normally circular-shaped, and the manhole cross-sectional profile is generally U-shaped, therefore.

Compared to current design practice, the bend and the junction manholes presented in Figures 4 and 6 involve no symmetrical benches on either side of the downstream manhole reach. Instead, the manhole wall opposite from the center of curvature is flush with the vertical side of the U-shaped channel, such that waves may not overtop. The manhole entrance is thus on the opposite side onto benches that have a height of 1.5*D*. Because the 45° bend and junction manholes have a manhole extension 2*D* long, there is enough space for maintenance and control of the sewer.

To the authors' knowledge, the flow in some 'difficult' manholes was controlled by (1) using air tightening manhole covers, and (2) using covers that are firmly screwed to the manhole structure, in order that the cover is not lifted during geysering. Both approaches are considered highly dangerous and point to a definite hydraulic problem, because: (1) Manholes are the only location where air is added to the sewer system required for both adequate hygienic and hydraulic performance, and (2) Geysering corresponds to a collapse of the sewer system. If it is suppressed, a sewer may fail due to large positive or negative pressure peaks and cause the complete failure of a sewage system. A sewer thus needs urgent consideration if geysering has occurred during storm runoff significantly smaller than the sewer design discharge.

7. CONCLUSIONS

The purpose of the present state-of-the-art paper was to review recent model observations collected at VAW, ETH Zurich on supercritical flow in sewer manholes. Three basic manhole types were considered, namely the through-flow, the bend and the junction manholes of constant sewer diameter across the manhole structure. It was found that the manholes should be designed such that the supercritical flow structure is maintained, from the upstream to the downstream branches; a breakdown of free surface flow into two-phase air-water flow results in complex and dangerous flow phenomena that currently cannot be numerically modelled. A sound hydraulic design of manhole structures should prevent the development of these undesirable phenomena, therefore.

Supercritical manhole flow is governed by the presence of shockwave due to any change of hydraulic and geometrical parameters, including (1) cross-sectional change from circular sewer to U-shaped manhole, (2) directional change from the lateral to the downstream branches, and (3) discharge addition for junction manholes by the lateral branch. These waves may become so large that they impact on the manhole end wall and cause a hydraulic jump blocking free surface flow along the manhole due to air-water flow obstruction. It was demonstrated that this adverse effect of shockwaves may be countered by the addition of the so-called manhole extension, a 2 diameter long U-shaped unit between the end of curvature and the manhole end section.

The second relevant issue with manhole design is the discharge capacity, which was demonstrated to depend essentially on the manhole type. According to the recommended design guidelines, the bend manhole has the lowest discharge capacity, followed by a double capacity of junction manholes, and even a three times larger capacity for the through-flow manhole. The effect of lateral flow deflection, either 45° or 90°, was found to be negligible for the present design proposal. Therefore, the bend manhole is the most critical manhole type in terms of discharge capacity and corresponds to the most crucial component of a sewer system. To increase the capacity of a sewer system with supercritical flow, bend manholes thus deserve a major attention. The present research may guide designers for the basic hydraulic design, and for an improved hydraulic performance of a sewer system, therefore.

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