DESIGN AND OPTIMIZATION PROGRAM FOR INTERNAL DIFFUSER HYDRAULICS

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KEYWORDS

diffuser geometry, discharge distribution, design optimization, continuity and energy equations

ABSTRACT

A computer program for the calculation of the internal hydraulics of outfalls equipped with multiport diffusers is developed and applied to different geometric configurations. The program calculates the velocities, pressures, head losses and flow rates inside the diffuser pipe and especially at the diffuser port orifices. Possible geometries consider simple ports, high risers and more complex discharge configurations for the openings, as well as various supply pipe configurations. The calculation is based on the application of the continuity and work-energy equations between the ambient fluid at the discharge point and the effluent inside the diffuser pipe. Preliminary calculations show the sensitivity of the geometric manifold features. Further calculations may aim at the design and optimization of the diffuser structure under different ambient and discharge conditions. The overall design objective is a balanced flow distribution under most of the operational conditions with minimized energy losses.

INTRODUCTION

Large flows of waste effluents are commonly discharged through outfalls with multiport diffusers. An ‘outfall’ is the entirety of hydraulic structures between the dry land and the receiving body of water, which consists of three components (fig. 1): the *onshore headwork* (*e.g.* gravity or pumping basin), the *feeder pipeline* which conveys the effluent to the disposal area, and the *diffuser section* (fig. 2) where a set of ports releases and disperses the effluent into the environment so as to minimize the impairment to the quality of the receiving waters. Moreover, diffusers dispose the effluent through either port orifices on the wall of the diffuser (simple-port configuration, fig. 3*a*) or attached pipes (riser/port configuration, fig. 3*b*) which may carry additional elements like elastic valves (variable area orifices, fig. 3*c*) or rosette-like port arrangements (similar to gas burner devices, fig. 3*d*).

On designing an outfall system, the hydraulics occurring both outside and inside of a diffuser must be carefully considered: the former affects the effluent mixing with the ambient fluid downstream the ports, the latter affects the flow partitioning within the manifold and the resulting discharge profile. This paper focuses on topics relevant with the latter area.

The outfall design data usually available involve the construction technique (pipe on seabed, in trench or tunneled) and geometric and hydraulic features relevant to both pipe (manifold specifications and discharges) and ambient (bathymetry and velocity/density fields). A diffuser is ideally designed to discharge equally through all ports over a wide range of total discharges, but this target can only be achieved with a diffuser operating at high pipe pressure and with small port sizes. Since such an operational mode is impractical due to the energy demand at the onshore headwork, an outfall diffuser can be designed to discharge uniformly only over a small range of flows, and a design compromise is generally necessary.

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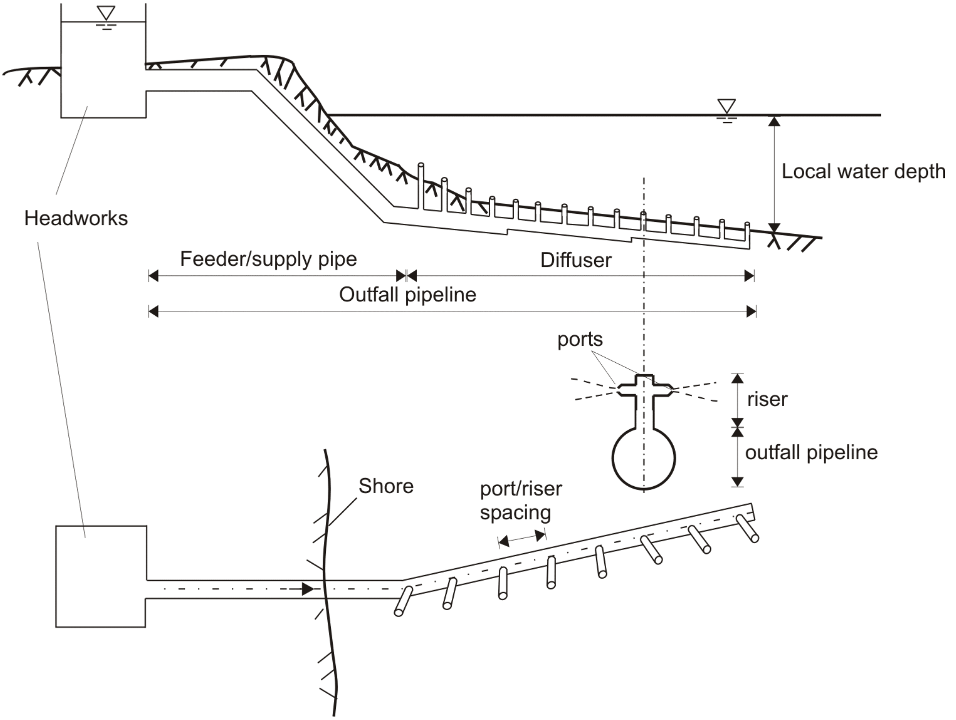

Figure 1: Outfall discharge configuration showing feeder pipe and diffuser from side view and top view, defining the pipelines and port/riser configurations.

Figure 2: Diffuser configuration example (here floating before installation on the bottom). The risers are bended sideward and the ports are still closed.

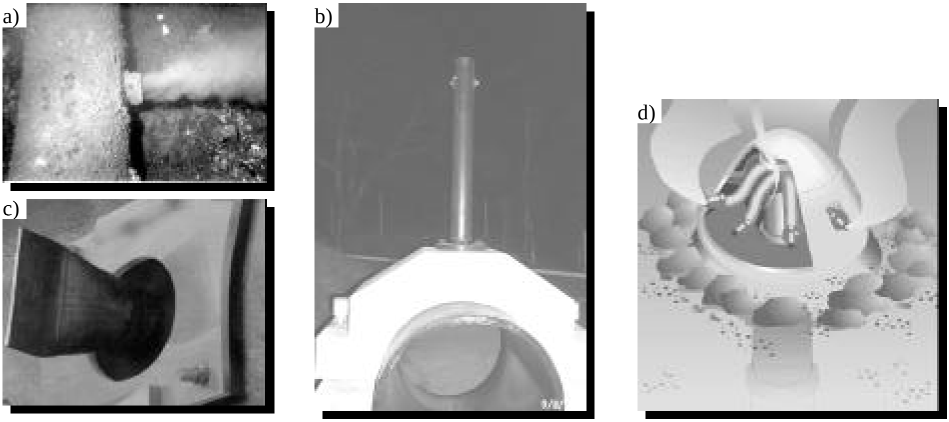

Figure 3: *a)* simple port configuration (source: Carlo Avanzini), *b)* riser/port configuration (Guarajá outfall, Sao Paulo State coast, Brazil), *c)* Variable-area orifices (VAO or 'duckbill valves'. Image source: Red Valve Company), *d)* rosette like port arrangement (Boston Outfall, Image source: Massachusetts Water Resources Authority, Boston, USA)

Despite of its simplicity if compared to the water-supply network systems, the hydraulic behavior of outfalls is most sensitive to geometric details and dynamic specifications at the boundaries. Geometrical details may be meant as the set of pipe diameters, lengths and roughness', number of ports, type and arrangement (single- or multiport discharges, either 'short' or 'long' riser/port configurations, variable area orifices, etc.). All of them may much vary in time according to natural obsolescence, maintenance or even accidents. The dynamic specification may be further distinguished in those at the trailing *disposal boundaries*, where the effluent physical properties differ from the ambient fluid and the ambient itself undergoes some complex hydrodynamics (density and velocity non-uniformities, phenomena like external and internal waves); then, in that at the *entrance boundary*, where the flow rate is seldom steady and a pumping station may dictate a non obvious relationship between pumping head and discharge rate (also highlighting the risk of water-hammer occurrences).

The discharge at the entrance boundary, in particular, may vary on a daylong scale considerably when from a sewage treatment plant. Moreover, during rainy periods, massive overloads may occur as long as the run-off enters the collection system either directly (like in combined sanitary- and storm-sewers) or indirectly through infiltration (leakages at pipe joints and manhole covers). During either events, if the outfall system is not properly designed, the incoming discharge can rise dramatically and the effluent backflow and flooding may take place at the onshore facilities. Moreover, when the hydraulic head difference between the ocean and the outfall headwork is minimal, consideration must be given to the use of pump stations or combined use of gravity- and pump-systems, where the discharge may be not only time-varying but also intermittent.

Apparently a *good designing, monitoring and management practice* should take care of – or at least be aware of – such a wide variety of scenarios, some of which are difficult or impossible to predict and control. The response of outfalls to the interplay of such factors is accordingly not trivial and clearly influences the subsequent effluent mixing in the receiving fluid. An optimal design should:

1. provide a balanced flow distribution among the orifices in order to meet dilution and mixing requirements under varying external conditions (i.e. tides or flow-rate variations);
2. minimize costs with respect to both construction and operation which demand a trade-off on the pipe diameter, minimal pumping heads, short riser heights and pipeline lengths much so as possible;

3. prevent off-design operational problems like excessive head losses, particle deposition, salt water intrusion and low discharge velocities (resulting in decreased effluent dilution);
4. test the outfall performance against unsteady operations (on purging and starting-up), temporal and spatial varying boundary conditions for both static heads and flow rates, manifold amplifications and modifications (extensions, attachment of variable area orifices) or damages and accidents (water-hammers, plugged ports, broken risers).

Two methodologies for the analysis of the internal hydraulics have been adopted by various authors. The first involves a port-to-port analysis while the second involves design by discretizing a fictitious porous conduit. A port-to-port analysis will be adopted herein and the second methodology will not be considered. A review of the pertinent literature and contacts with different research organizations and engineering design companies have shown that different design algorithms ("diffuser programs") are used in practice. However, all these codes seem to stem from two main sources: 1) the work of R.C.Y. Koh as summarized in Chapter 10 of Fischer *et al.* (1979) and released as the design code PLUMEHYD; and 2) the work of I.R. Wood (Wood *et al.*, 1993) in form of the design code DIFF. Both codes have considerable deficiencies for the computation of diffuser details and operating conditions as they can occur in practice. These are the assumptions of simple local-loss formulations just for uniformly spaced ports/risers, non-tapered diffuser pipes and continuous discharge. Furthermore, in the case of riser/port disposal, two possibilities are usually distinguished: *a*) 'short' risers with negligible friction losses and static head differences; *b*) 'long' risers (like in deep-tunneled outfalls) with meaningful frictional losses and static head differences due to the elevation differences. These static head effects arise because of the density difference between the effluent water (typically wastewater) ρ_0 and the ambient water (typically saltwater) ρ_a that might be a function of the elevation (*e.g.* density variations and stratifications due to seasonal temperature variations). Most of the existing programs and algorithms only consider possibility *a*).

Despite of large uncertainties inherent in the topic, it is possible to extend the scope of the technical background on paying more attention to how far some of these factors influence the outfall behavior. This paper is a first attempt to perform a rational investigation into the internal hydraulics in an outfall equipped with a multiport diffuser (hereafter, shortly *internal diffuser hydraulics*); herein the major emphasis will be put onto the sensitivity of the diffuser discharge profile to some manifold specifications. Moreover, only steady state scenarios will be considered here. The tool under development for performing the intended study, is a computer code which is meant to encapsulate, at the highest possible extent, the available technical knowledge relevant to the internal diffuser hydraulics. On a longer term, it aims at supporting those engineering demands related to the design and optimization of newly planned outfalls, as well as the monitoring and analysis of existing manifolds.

GOVERNING EQUATIONS

An outfall system with a single diffuser and an alignment of n diffuser ports may be treated as an open pipe network whose characterizing elements are:

a) n+1 'external nodes' (*i.e.* outfall boundary sections) with no flow division, namely the n diffuser port orifices and the feeder pipe entrance. This is still a simplification with respect to more complex port arrangements like rosette-like ports, that may be overcome by considering adequate expressions for the local losses and corresponding port diameters;

b) n–1 'internal nodes' belonging to the diffuser, where the flow undergoes division;

c) 2n–1'sides' (*i.e.* pipe segments with constant discharge), namely the feeder pipe, the n risers and n–2 diffuser segments between each pair of internal nodes; the number of meaningful sides reduces to n–1 in case of disposal through ports only (*i.e.* risers with zero length).

The number of *physical variables* specifying the outfall hydraulic behavior is as high as 4n–1, being:

A) n+1 static heads at the external nodes;

B) n–1 static heads at the internal nodes;

C) $2n-1$ discharges along each side. Discharges are positive or negative in sign according to whether they flow along or against the direction they are supposed to in a properly working outfall.

The number of *equations* available for the solution is $3n-2$, namely $n-1$ continuity equations at the internal nodes and $2n-1$ equations of motion along the sides.

Therefore, the governing system is ∞^{n+1} and requires the specification of $n+1$ boundary conditions given by n static heads at the port orifices and either the flow rate or the entrance head to the feeder pipe (the excluded one being treated as an unknown). Subsequently, that system may be solved for the n port discharges and either the entrance head or the flow rate to the feeder. Moreover, if the feeder discharge is acted on by a pumping station, the pump H-Q curve also establishes a further relationship between the discharge and entrance head in the feeder pipe and the n static heads at the ports provide enough boundary conditions for solving the problem.

The adopted equation of motion is the work-energy equation in pressure units applied to each side with discharge Q:

$$(\gamma z + p)_i - (\gamma z + p)_{i+1} = 8\rho/\pi^2\{1/D^4_{i+1} - 1/D^4_i + \Sigma_j\, l_j\lambda_j/D_j^5 + \Sigma_k\, \xi_k/D_k^4\}|Q|Q \qquad (1)$$

where the indices i and $i+1$ label the leading and trailing (internal or external) nodes to the side; the index j spans over the side segments with an unique set of length (l), diameter (D) and roughness (ε); finally k spans over the number of local loss occurrences within a side. The symbols ρ, γ and λ stay for the density, specific weight and friction factor respectively.

At the left-hand side of (1), the specification of the head at external nodes must be tuned accordingly to the ambient density field. At the right-hand side of (1), the first two contributions denote the dynamic pressures at the boundary nodes; the contribution from the first summation represents the energy losses due to friction according to the Darcy-Weisbach formula; finally, the contribution from the second summation represents the energy losses due to flow separations (caused by exceptions to a straight and single-diameter pipe, like sudden contractions, bends, etc). The first summation may also be regarded to as the total-head loss along the side due to the frictional effects from the unit squared-discharge and will be termed *frictional resistance*. The second summation represents the analogous total-head loss per unit squared-discharge on account of flow irregularities at locations with geometric changes and will be termed *local resistance*.

The friction factor is calculated with the Colebrook-White formula which well suits the entire range of pipe Reynolds numbers (symbol Re):

$$1/\sqrt{\lambda} = -2\log\,[2.51/(Re\sqrt{\lambda}) + \varepsilon/(3.71D)] \qquad (2)$$

The local loss specification depends on the value of ξ_k coefficient, for which suitable expressions in case of entrance, bends, sudden or gradual contractions and expansions are readily available from the literature (for instance, see Idelchik, 1986). If the ports are more than three port diameters apart, loss coefficients for isolated dividing junctions can be used (Miller, 1990). Moreover, ports might be equipped with elastic variable-area orifices (VAOs) as shown in fig. 2c, in order to prevent intrusion of debris, sediment, saltwater and aquatic life. Lee *et al.* (1998) showed that the jet velocity and the opening area for VAOs vary nonlinearly with port discharge flow and presented experimental diagrams that can be used to determine the flow coefficient ξ_k for a given port discharge.

NUMERICAL SOLUTION

The code developed for the solution of the governing equations is divided in two modules. The first is concerned with the specification of the topographic profile of, and pipe allocation along, the outfall axis. This module allows the uploading of the data of an outfall with any geometric features (bottom slope, tapered diffusers, risers with different diameters and bends). The second module is concerned with the solution of the governing system whose implementation concepts will be briefly described hereafter.

Many algorithms are possible to solve the non-linear algebraic governing system given by the energy and continuity equations. A simple iterative upstream-marching technique has been adopted in the present applications. Figure 4 supports the algorithm description.

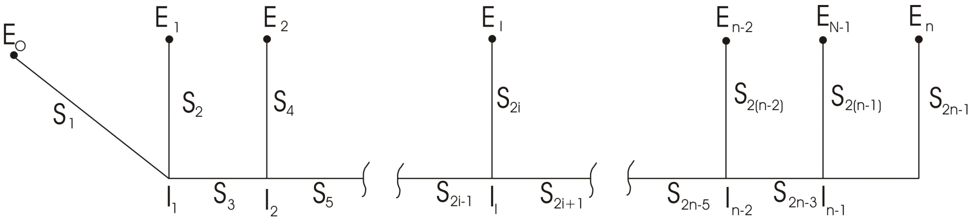

Figure 4: Numbering convention for the implemented algorithm, where I: internal nodes; E: external nodes; S: sides. It can be noted that, with the exception of the most offshore riser, all sides with odd label belong to the diffuser or feeder pipe, while those with even label belong to risers.

The algorithm consists of two nested loops. The *inner cycle* performs the system solution with a three-step algorithm. Firstly, after guessing the discharge rate along the farthest seaward diffuser port (side S_{2n-1}) and given the static head at the corresponding orifice (external node E_n), the energy equation is solved for the head at the next upstream internal node I_{n-1}. Secondly, the flow rate along the next upstream riser (side $S_{2(n-1)}$) is calculated from the head difference between the internal node I_{n-1} and the relevant orifice (external node E_{n-1}). Thirdly, the enforcement of the continuity equation at the internal node I_{n-1} allows the calculation of the flow rate in the upstream side S_{2n-3} in the diffuser. Within this cycle, the code assembles the resistance terms of equation (1) and estimates the Reynolds number from the discharges at the previous outer cycle, when available. This three-stepped procedure marches upstream the outfall until the feeder pipe is reached and the corresponding entrance head/flow rate is computed; if correct, the computed value should equate the boundary condition assigned there.

The implicitness of the friction law (2) is overcome on calculating the friction factor efficiently by a Newton-Raphson algorithm which shrinks the residual of the Colebrook-White formula to zero; the fully rough turbulent friction factor provides the best first guess. The local resistances were calculated only when suitable formulae were available.

The *outer cycle* establishes the ‘seed’ for the guessed port discharge at the first inner step (as high as the average outflow discharge), checks the consistency between the inner cycle results and input data, and proposes a better discharge guess for the following iteration until a relative error on the L_2 norm of all the governing equations is warranted (10^{-16} in the present applications, thus achieving machine accuracy).

The code has been verified on solving simpler configurations and comparing the numerical results with paper-and-pencil calculations and, whenever available, analytical or graphical results.

MODELING CONCEPTS

Three general applications are planned:

1. *Diagnosis* of existing outfalls in order to evaluate the performance of the manifold upon certain operational conditions (*e.g.* changed roughness’ due to slime, clogged ports due to accidents, increased discharges due to new settlements). These applications can already be carried out by using the code. A user-friendly graphic interface has also been developed (Bleninger *et al.*, 2003);
2. *Sensitivity analysis,* in order to check and evaluate all parameters as far their influences on discharge distribution, total head at the headwork or velocities at the ports are concerned. Such an analysis will provide the user with a deeper insight into the internal hydraulics for a supported planning and optimization process. Early sensitivity analyses have been presented in a successive work (Bleninger *et al.*, 2003);
3. *Optimization and hydraulic coupling,* in order to provide an automized optimization in the design stage. A consistent optimization algorithm will be developed for this purpose. Due to the interaction with the ambient water, it is necessary to take into account environmental impacts during design optimization. An optimization process has to consider internal *and* external hydraulics. Therefore, it is planned to couple the internal

hydraulics code and optimization code with the Cornell Mixing Zone Expert System (CORMIX), which is able to predict especially the near-field impacts of most of the possible outfall configurations.

As to the first two purposes, results including sensitivity analysis are presented in the following. As to the third application, first recommendations for design and optimization are drawn in a next section.

APPLICATION AND SENSITIVITY ANALYSIS

Two test cases are observed: firstly, a simple diffuser with globally-changing parameters, meaning that just a single diffuser diameter and the same port diameter everywhere are applied; secondly, a tapered diffuser with changing parameters along the diffuser pipe (namely, diffuser pipe diameter and port diameters are allowed to change).

I) Simple diffuser with globally changing parameters

We first considered a fictitious 'base' diffuser whose pipe is 150m long and 1.50m of diameter, which disposes a discharge of 1.5m^3/s under a 15m water column head. The roughness was presumed to $3{\cdot}10^{-5}$m. The diffuser is horizontally laid. The flow velocity in the 1.50m diameter pipe is 0.88m/s. We compared its hydraulic performances when equipped with a small/large number of short/long risers. Thus, as shown in Table 1, there result four exemplary configurations which are supposed to highlight the influence of port spacing and risers length on the friction losses and discharge distribution. Higher riser lengths under the same static head imply that the whole diffuser pipe is tunneled and the riser length are partly built below the seabed.

Configuration	Number of risers	Spacing (m)	Riser length (m)
a) few short risers	20	~7.9	1.5
b) few long risers			15
c) many short risers	60	~2.5	1.5
d) many long risers			15

Table 1: Parameters of the exemplary diffuser configurations

Figures 5*a*)-*d*) display the discharge profile along the diffuser pipe for a set of three diameter ports (0.10m, 0.15m and 0.20m) in each configuration. The gross features of a discharge profile may be described qualitatively by its tendencies to keep somewhat close to the average discharge (*i.e.* without excessive deviations) and the shape of the discharge distribution along the diffuser (*i.e.* without discharging more or less shoreward than seawards). We deemed useful to distinguish and term these properties 'homogeneity' and 'evenness'.

The former (hereafter, HI: homogeneity index) has been simply estimated by the standard deviation of the local discharges from the average outflow-rate, which is as high as Q_0/n for continuity reasons, being Q_0 the inflow-rate and n the number of risers. The latter (hereafter, EI: evenness index) has been estimated by the formula:

$$\sum \frac{Q_i}{Q_0} \frac{(x_i - x_{\mathrm{L/2}})^3}{L^3} \tag{3}$$

that is the third moment of the discharge profile with respect to the mid-diffuser location ($x_{\mathrm{L/2}}$), non-dimensionalized by the third power of the diffuser length and the average discharge. The negative sign of EI denotes a larger disposal shoreward and *vice versa*. The better behaved is the diffuser, the closer are both HI and EI to 0.

Furthermore, the head loss along the diffuser is observed. Recalling (1), the frictional resistance in the risers increases on account of the increasing number of terms in the summation (*i.e.* a larger number of risers), longer pipes/risers and smaller diameters. A larger number of risers also affects the resistance in the diffuser on account of more local losses at divisions (by increasing) and port-spacing shortening (by decreasing). After the discharge profiles from Fig. 5 and results summarized in Table 2, the following remarks are in order.

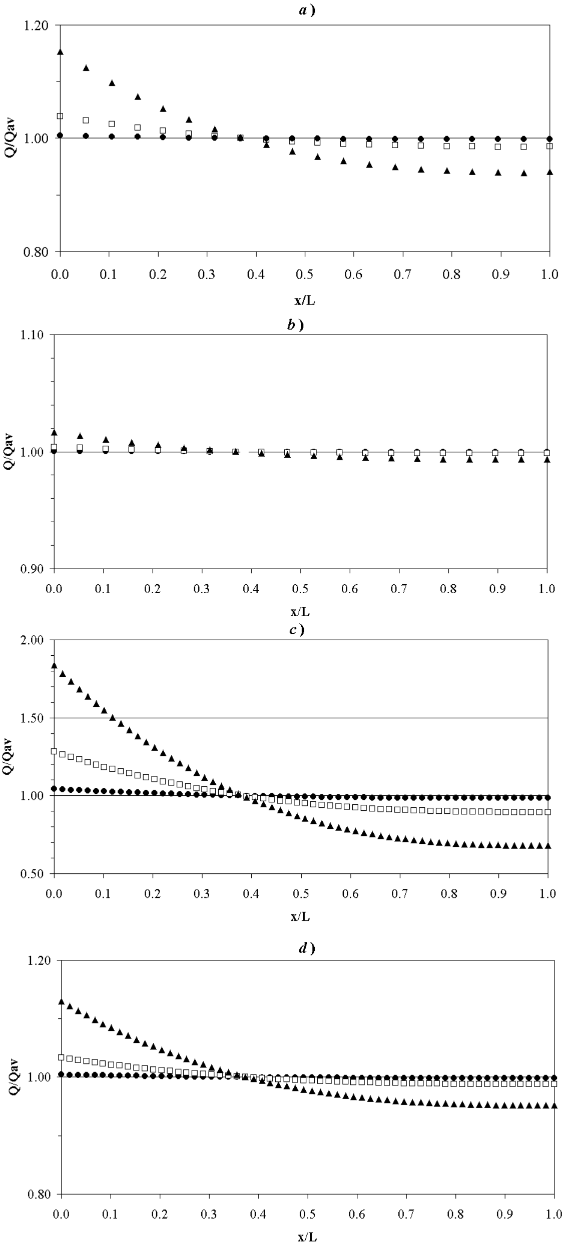

Figure 5:
Dimensionless discharge profiles in the diffuser for different riser numbers (*a*, *b*: 20 risers; *c*, *d*: 60 risers), riser lengths (*a*, *c*: 1.5m; *b*, *d*: 15m) and port diameters (*circles*: D = 0.10m; *squares*: D = 0.15m; *triangles*: D = 0.20m. The *a*)-*d*) labeling follows Table 1. Please note the scale difference in the ordinate axis.

On one hand, when the number of risers is fixed, increasing riser length (resulting in an increase of frictional resistance) always brings about a more homogeneous discharge profile; the most homogeneous profiles were observed with long risers and small diameters, as apparent from configurations *b*) and *d*). On the other hand the discharge homogeneity is reduced on increasing the number of risers: in configuration *a*), the uppermost and lowest deviations from the average are +15% and –6% with the smallest diameter, whilst the corresponding values are +84% and –32% in the configuration *c*) again with the smallest diameter. As an aside, it must be noted that the average discharge is as smaller as higher is the number of risers: in this case the average to configuration *c*) is 2/3 of that to configuration *a*).

A design rule for achieving discharge homogeneity, often mentioned in literature, recommends to keep the ratio between the cumulative port areas a_p and diffuser pipe area A_d within the range $0.33 < \Sigma_n(a_{p,i})/A_d < 0.66$ (Fischer *et al.* 1979, p.419), where *n* here denotes the number of ports downstream a particular pipe section. This suggestion is very restrictive and causes high costs for the discharge structure on account of too large diameters. Checking these ratios from our computations for the 0.10m diameters, we receive 0.09 (20 risers) and 0.27 (60 risers): both results are smaller than the proposed values although the discharges could be defined as homogeneously distributed. For the 0.15m diameters, the values are 0.2 (20 risers) and 0.6 (60 risers): only the second one respects the proposed interval despite of the discharge being not homogeneously distributed (*i.e.* for the short riser configurations). For the 0.2m diameters, we receive 0.36 (20 risers) and 1.07 (60 risers): only the few riser configuration is within the proposed range along with a discharge that might be considered nearly homogeneously distributed; the many riser configuration, which exceeds the proposed bounds, shows a strongly inhomogeneous distribution wherefore the criterion seems to be valid. Further tests for this criterion will be carried out to analyze and assess its general validity. We may conclude already here that the criterion does not consider long riser configurations which do have a certain influence on the discharge distribution.

configuration		d=0.100 m	d=0.150 m	d=0.200 m
a) 20 risers, length 1.5m	H.I.	$1.58\cdot10^{-4}$	$1.24\cdot10^{-3}$	$4.94\cdot10^{-3}$
	E.I.	$-2.00\cdot10^{-2}$	$-1.57\cdot10^{-2}$	$-6.27\cdot10^{-2}$
	H.L.	$1.47\cdot10^{-2}$	$1.45\cdot10^{-2}$	$1.38\cdot10^{-2}$
	Q^+/Q_0	0.401	0.407	0.428
b) 20 risers length 15m	H.I.	$1.16\cdot10^{-4}$	$1.04\cdot10^{-4}$	$4.60\cdot10^{-3}$
	E.I.	$-1.61\cdot10^{-4}$	$-1.32\cdot10^{-3}$	$-5.83\cdot10^{-3}$
	H.L.	1.16	1.16	1.15
	Q^+/Q_0	0.400	0.351	0.353
c) 60 risers length 1.5m	H.I.	$4.27\cdot10^{-4}$	$2.86\cdot10^{-3}$	$8.53\cdot10^{-3}$
	E.I.	$-4.43\cdot10^{-2}$	$-2.97\cdot10^{-1}$	$-8.86\cdot10^{-1}$
	H.L.	$1.47\cdot10^{-2}$	$1.35\cdot10^{-2}$	$1.09\cdot10^{-2}$
	Q^+/Q_0	0.390	0.432	0.527
d) 60 risers length 15m	H.I.	$3.66\cdot10^{-4}$	$2.95\cdot10^{-3}$	$1.23\cdot10^{-2}$
	E.I.	$-3.79\cdot10^{-3}$	$-3.05\cdot10^{-2}$	$-1.27\cdot10^{-1}$
	H.L.	1.17	1.16	1.13
	Q^+/Q_0	0.367	0.372	0.404

Table 2: Index results of the exemplary diffuser configurations for different port diameters. H.I.: homogeneity index; E.I.: evenness index; H.L.: diffuser head loss; Q^+/Q_0: fraction of the total discharge disposed through the ports with local discharge larger than the average Q_0/n. The case of configuration c) with d=0.200m is also used for comparison in the ensuing taper-diffuser analyisis.

As to the evenness of the discharge profile, it must be noted that the third power adopted in the EI definition (3) exaggerates the weight of the ports farthest from the mid-diffuser section purposely. Port discharges larger than the average value always take place in the upstream part of the diffuser and *vice versa*, and the discharge distribution is unbalanced towards the leading diffuser section (wherefrom the negative sign in all EI results). The decreasing-discharge pattern may be thought of as the natural hydraulic response of the adopted diffuser; it is worthwhile noticing that the port discharge equates the average discharge in the riser somewhat close to the location x=0.365L in all configurations, where L is the diffuser length. Shifting this position may be achieved on changing conveniently some geometric features within the diffuser (*e.g.* by tapering the diffuser or varying port diameters locally along the diffuser). Table 2 also shows the fraction of the inflowing discharge released through the ports where the local discharge exceeds the average (*i.e.* those on the upstream diffuser segment): this fraction apparently varies around the 40% and seldom exceeds 50%.

As to the diffuser head loss, on one hand it increases on lengthening the risers on account of a proportional increase of the frictional resistances – contrast configurations *a*) to *b*), and *c*) to *d*). On the other hand, comparing pairs of configurations *a*) and *c*) with the same port diameters shows that the few-riser arrangement head loss is up to +21% larger than the many-riser arrangement. In fact, despite of the increased number of terms in the frictional resistance summation, the average discharge is lower and the squared port discharge decreases far faster in the largest-diameter configuration *c*) than in largest-diameter configuration *a*), yielding lower overall head losses according to (1).

II) Tapered diffuser with locally-changing parameters along the diffuser pipe

After those computations regarding a very regular diffuser (on account of even manifold specifications), we investigated some discharge profiles modified by tapering the diffuser (reducing the diameter to 1.2m in half the diffuser length), varying the port diameter along the diffuser (0.18m, 0.20m. 0.22m each in a third of its length) and combining tapering with port diameter change (1.5m diffuser diameter with 0.18m diameter ports along half diffuser, and 1.2m diffuser diameter with 0.22m diameter port along the remaining part). We aimed at understanding at which extent the ‘toughest’ discharge profile previously calculated – configuration *c*) with 0.2m port diameter – may exemplarily benefit from such adjustments. The chosen values are meant to display some trends of the hydraulic response after tuning geometrical parameters. Results are summarized in Fig. 6.

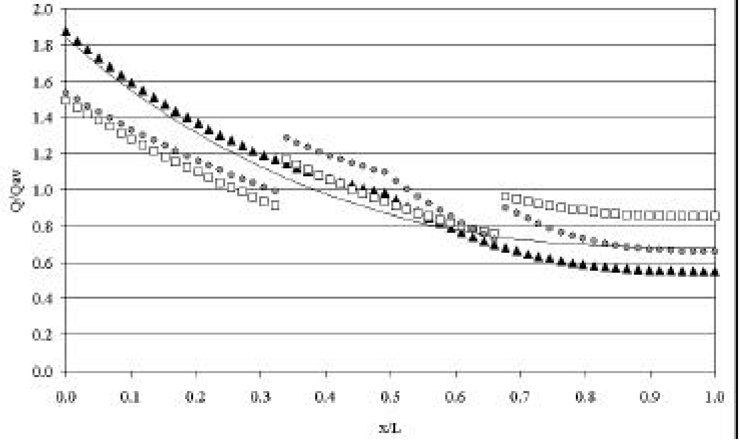

Figure 6: Dimensionless discharge profiles in the diffuser after tapering, varying port diameters and combining tapering with varying port diameters along the diffuser for different riser numbers, riser lengths and port diameters. The line reproduces the 0.2m port diameter configuration *c*) from Fig. 5. *Solid triangles*: just tapering; *open s*quares: just varying port diameters; *gray circles*: both.

It is obvious that simple tapering proves an unadvisable choice if a more homogenous discharge profile is looked for; indeed there result HI = $9.89 \cdot 10^{-3}$ (without taper: $8.53 \cdot 10^{-3}$) and EI = –1.03 (-0.886) from Table 2. This worsening of the general performance results from the 'squeezing effect' on the diffuser diameter, which increases the frictional resistance in the most downstream diffuser sides and enhances the disposal through the most upstream ports. Tapering is used only for increasing the diffuser velocities for scouring purposes and should not affect the homogeneity. On the contrary, varying port diameter smoothes the excess discharge in the upstream diffuser half-length and rises the discharge profile in the downstream half-length: indeed, HI = $1.28 \cdot 10^{-3}$ (without port diameter changes: $8.53 \cdot 10^{-3}$) and EI = -1.32 (-0.886). Finally, adopting a set of three decreasing port diameters (ranging around 0.2m) together with tapering rises HI = $6.38 \cdot 10^{-3}$ (against $8.53 \cdot 10^{-3}$ without local changes) and decreases EI = -0.657 (-0.886).

The last option is the most demanding one in terms of energy on account of the increased side resistance due to both riser and diffuser diameter reduction: the head loss increases here to HL = $1.44 \cdot 10^{-2}$ (Table 2 HL = $1.09 \cdot 10^{-2}$) is nearly 25% higher than the case with uniform diameter settings, whereas the tapering requires a head loss which is 10% larger and the port diameter reduction for this configuration even reduced the head loss to HL = $9.25 \cdot 10^{-3}$.

It might be recognized that these examples are not sufficient to achieve an overall sensitivity analysis of the involved parameters. Further calculations are indeed planned in order to consider the complete influences of all parameters on the aforementioned (and new) indices. We especially will consider parameter changes in between the ranges applied in existing diffuser constructions, modifications and temporal changes. Beside the understanding of the influences and interactions of the parameters, the sensitivity analysis will help to develop an automized design optimization.

DESIGN STEPS AND OPTIMISATION

After fixing the environmental parameters (usually given by the authorities), a first 'sketch' outfall with single pipeline diameter and single-sized port diameters should be defined and checked with a near-field mixing program (*e.g.* CORMIX) in order to evaluate whether the required dilution is achieved. Then, such parameters should be optimized considering both the dilution requirements and internal hydraulic requirements. The optimization may be divided into steady- and unsteady state parameter optimization. Necessary inputs are generally those given by the first design ideas or derived from scaling arguments (diffuser length, riser heights, riser/port configurations, port diameter, pipe diameter), like the (maximum) total discharge rate of the diffuser and the discharge rate per unit length of the diffuser.

Following are some basic recommendations for these parameters, presented under steady- and unsteady state observations.

I) Design parameters - steady state conditions

Riser/port spacing

Recommended spacing between adjacent ports is 25% of the depth of the receiving water body if plume interference is to be avoided (Wilkinson and Wareham, 1996). Equally spaced ports are usually applied since the effects of plume interaction are more than offset by reducing discharges and increasing depth along the diffuser for constant port diameters. Optimizations of port spacing can mainly be performed with CORMIX in order to obtain the minimum spacing.

Port diameter

Uniform port sizing is usually applied in small outfalls for expediency of fabrication, although it is far from as optimal as when port size is adjusted to achieve a uniform dilution along the diffuser. A 50mm minimum port size for secondary- or tertiary-level treated effluent and stormwater inflow is suggested by Wilkinson and Wareham (1996), thus avoiding the risk of blockage; they recommend a minimum port size of 70 through 100mm for primary treatment plants (just screening and sedimentation). The choice of port diameters also affect the value of the limiting minimum discharge before seawater intrusion takes place. Finally, for any given port size there is a diffuser depth which yields the minimum outfall length for a required dilution.

Number of ports

The number of ports required should be determined by the initial dilution requirements (see WRc GUIDE) and defined with CORMIX (or any equivalent program) in order to minimize the outfall length.

Diffuser pipeline diameter

It is one of the most expensive factors since the bigger the diameter, the more the outfall will cost. There are upper diameter restrictions related to the deposition velocity of particles and lower restrictions on account of the available head losses and total head. The pipeline diameter is usually set so large as self-scouring discharge velocities (in excess of 0.7m/s) are achieved on a daily basis (Wilkinson and Wareham, 1996). The diffuser pipe is tapered in some cases in order to achieve higher scouring velocities. As seen, this reduces the pressure and affects the port flow distribution. The local head losses at the contractions must also be considered. Charlton and Neville-Jones (1988) recommend to introduce a taper upstream of the diffuser so as to prevent a drop in the flushing velocity.

Diffuser length

The length is simply a result from the analysis on the number of ports and port spacing.

Overall length of pipeline

The length (and cost) to the majority of outfalls is primarily determined by initial dilution requirements. Design flexibility is such that diffuser configuration and depth have a much greater impact on total dilution than on far field dilution. For example, a 30% increase of the diffuser depth may result in a doubling of the initial dilution, but may only increase far-field dilution by a third of that amount (Wilkinson & Wareham, 1996). The length of the pipeline should be minimized for cost saving.

The internal hydraulic code presented here should be used for design and optimization purposes after certain runs with CORMIX, in order to evaluate the outfall discharge profile and necessary total head. Then, internal hydraulic optimizations should be done in order to define the final design, ideally without changing the external hydraulic behavior. Finally, the determined final design should be contrasted with off-design and unsteady state conditions, which are considered in the following.

II) Off-design behavior and unsteady state conditions

Diffusers still have to operate properly if flowrates other than the design ones are applied (*i.e.* no discharge should harm the operation of a restarted system). This may be the case during dry seasons, where wastewater reuse is practiced, during stormwater events, and also on account of the variation of population and industry connected to the sewer (as typical as in tourist areas). Under low-discharge conditions we are confronted especially with issues of scouring and/or intrusion of seawater. Seawater may also remain inside the diffuser due to the commissioning after construction (start-up), shutdown events and , even, reduction of effluent flow with previous saltwater intrusion.

Just after building, the risers and diffuser pipes are filled with stagnant seawater, with a hydrostatic pressure distribution, and the start-up condition has to be addressed in order to achieve a saline wedge purging by using, for example, some velocity criterion (Wilkinson, 1984). The start-up criterion after Brooks (1988) for port/riser purging recommends that the diffuser pipe pressure exceeds the salt water hydrostatic value at pipe level $(\Delta\rho/\rho)H$, where H denotes the riser height. This shows that the purging parameter to a flooded riser is determined by the height of the riser, but such condition does not actually consider the details of the interface between fresh- and saltwater in the tunnel. Furthermore, the diffuser pipe itself needs to be purged. Brooks (1988) sets the critical flow rate for tunnel purging to: $Q_{purg} = A_d\ (2g' D_d S/f)^{0.5}$ with S the diffuser pipe slope. Therefore, two discharge values may be defined: the first for purging the diffuser pipe and the second for purging the riser/port configurations.

The time required to reach steady state once purging was initiated must also be determined (see Wilkinson und Nittim, 1992) and then, after the discharge port is flowing full, intrusion can be prevented by requiring the port densimetric Froude numbers to exceed unity: $F_p = V_j/(\Delta\rho/\rho g D_j)^{0,5} > 1$ (Wilkinson, 1988), where V_j denotes the port exit velocity at the jet centerline.

Because of the difference in water density, the rate of pressure increase with depth will be larger in risers filled with seawater than in risers filled with wastewater. As a result, there can develop a flow configuration in which seawater would actually be sucked in through some risers, and discharged out with the wastewater through some others (Wilkinson, 1984). This shows that the control of seawater intrusion depends on port geometry and that the flow at which intrusion will occur in a purged outfall is only a small fraction of that required to initially purge the system from a totally flooded state. The previous mentioned criteria are only conservative estimates, and usage of such criteria for investigating the detailed purging sequence of a particular sequence was not recommended by the authors (Wilkinson and Nittim, 1992). Where more detailed information on the sequence in which risers purge is required, physical model studies of the complete riser section of the outfall are recommended.

Finally, wave-induced oscillations occur if large waves are passing over a diffuser section in shallow water. Resonance effects and internal density-induced circulations are possible (Wilkinson, 1985) which have to be analyzed and optimized during the design procedures.

OPEN QUESTIONS AND FURTHER DEVELOPMENTS

Four main developments are planned for continuing work:

1. *Outfall diagnostics*: we wish to improve the program capabilities of calculating and evaluating existing outfall performances. The numerical algorithm adopted here depends also on the aligned arrangement of the diffuser. A certain amount of reformulation may be requested as soon as more complex manifold must be modeled (*e.g.* several diffusers branching from the feeder pipe). Local losses can only be implemented in a numerical code when the corresponding mathematical formulae are available, whereas several expressions for ξ_k coefficients (see Eq.2) are provided in form of plots (Idelchick, 1986; Miller, 1990; Lee *et al.*, 1998). This stymies their implementation except that suitable interpolation formulae are obtained from experimental graphs. Building such a database for local losses may be needed in the future and further research on this topic should take in account such a demand arising from automatic computation. Finally, the code improvement goes along with the development of the input/output interface.
2. *Sensitivity analysis*: we wish to work on the already mentioned fuller sensitivity analysis so as to evaluate the involved parameters and their interactions. This will help to evaluate the importance of assumptions which are made in designing and optimizing outfalls. Thereafter, the user will be supported by information on which best parameter to tune for reaching a certain design aim.
3. *Optimization and coupling:* a design optimization code for outfalls is to be built under user given limits for the geometries. This will be followed by coupling the program with CORMIX (Cornell Mixing Zone Expert System) in order to merge in a consistent frame the effects of manifold specification on both internal and external hydraulics.
4. *Unsteady state behavior*: further extension in order to cope with unsteady behavior can be divided in those which can be tackled on considering the evolution in time as a sequence of steady frames (*e.g.* variable incoming discharge or static heads at the ports) and those which require the amplification of the governing equations like (1). It is the latter case when either different density fluids are present within the outfall piping (*e.g.* in issues like intrusion, purging and start-up) or water-hammers take place (then taking into account the fluid compressibility).

CONCLUSIONS

The outfall behavior is sensitive to both ambient and manifold factors in a rather complex fashion on account of both natural and/or operational variability of boundary conditions (*i.e.* incoming discharge and/or static heads) and geometric piping specifications. Understanding and awareness of the outfall manifold hydraulic response to such factors is important for correct engineering practice in that it may affect considerably the subsequent mixing processes.

In the present paper, the numerical solution of the governing steady state equations for the manifold hydraulics has shown that the natural response of outfalls with a ‘simple’ multiport diffuser (one global diffuser pipe diameter and risers with equal lengths and diameters along the diffuser) consists in higher port discharges in the upstream part of the diffuser. This pattern may take place at different extents according to the choice of number of risers, lengths and diameters, even resulting in strongly distorted distributions which are furthermore prone to intrusion issues (because of low port velocities) and heavy malfunctioning (because of the drop in the disposal efficiency). The deficiencies can be corrected, or at least optimized, using 'complex' multiport diffuser (diffuser pipe diameter changing along the diffuser and varying port diameters along the diffuser pipe). The early calculations for developing an optimization algorithm have been analyzed and it was shown that a proper final design depends strongly on the awareness of the interaction of the involved parameters (*e.g.* total pumping head necessary to drive a homogeneously discharging system might be unacceptable high). First steps for a sensitivity analysis evaluating the importance of the diffuser parameters on optimizing the manifold system, have shown that the number of ports applied, port and diffuser pipe diameters, riser heights and friction losses demand attention.

The applications presented hererelease some assumptions of previous 'diffuser programs' by considering more flexible geometry specifications. The effects of tapering and/or varying port diameters as expedients for regularized undesired discharge profile were also shown thanks to the diagnostic capabilities of the code.

The major concepts that should lead the design of a diffuser in view of the coupling between 'external' and 'internal' hydraulics have also been presented. The design has to be optimized hydraulically to achieve balanced flow distribution and dilution requirements, and furthermore economically to achieve minimized head losses under minimized geometric dimensions; all this in the most of the operational conditions and expectable boundary conditions. Design criteria and diagnostic indices in order to achieve this optimization are based on the 'homogeneity' and 'evenness' of the discharge distributions along a diffuser.

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