# Filter nozzle and underdrain systems used in rapid gravity filtration

**HK Lombard[1]* and J Haarhoff[2]**
[1] *Otto Langenegger & Partners, PO Box 72937, Lynnwood Ridge 0040, South Africa*
[2] *Rand Afrikaans University, PO Box 524, Auckland Park 2006, South Africa*

## Abstract

Inadequate understanding of the basic hydraulic principles is often the cause of malfunctioning filter underfloor systems, which will eventually lead to inefficient filtration. To achieve a successful end result, it is imperative that certain fundamental principles are considered and adhered to in the planning and construction of filtration systems. Therefore, this paper:

- Provides the theoretical background to enable designers to check the adequacy of water and air flow distribution.
- Contrasts the essential differences between filtration systems, to assist clients and process designers in the selection of an appropriate filtration system.
- Provides practical guidance to supervisors on the pitfalls and precautions to be heeded during construction and commissioning.

The following aspects contribute towards an efficient filtration system:

- Fundamental hydraulic principles are essential towards understanding the behaviour of underfloor systems.
- Even distribution of air and water is ideal, but variations in water and air discharge will inevitably be encountered in filter underfloor manifolds. Careful manifold design and analysis are essential to limit these variations to within acceptable limits.
- Diligent care in design, manufacture, installation and supervision together with rigorously controlled testing is of decisive importance.
- Correct operational procedures by operators are critical.

## Introduction

Rapid sand filtration is encountered at the vast majority of water treatment plants in South Africa. Despite the impressive track record of this old and well-established unit process, problems with filtration systems are routinely encountered. In the majority of the cases, the problems can be traced to malfunctioning underfloor and media support systems. In the authors' opinion, many of these problems could be avoided if the relatively simple hydraulic principles of water and air distribution, as well as the numerous practical constructional pitfalls were recognised by designers, contractors and operators. This paper, therefore, deals with the following:

- The elements of filter nozzle design and specification
- Flow of water and air through nozzles
- Flow of water and air through manifolds
- The merits of different backwash systems
- Precautions to be heeded to ensure an effective filtration system, illustrated by numerous practical examples of failures encountered by the authors.

## Underfloor systems

### Nozzle support systems

There are two common nozzle support systems in use in South Africa; the false floor system and the pipe lateral system. Hydraulically, the essential differences are:

- In the case of the false floor system, rectangular slabs with an evenly spaced matrix of nozzles overlie the underfloor plenum. As a result, the flow of water in the underfloor plenum is directionally unrestricted.
- In the case of the pipe lateral system, nozzles are evenly spaced on the lateral pipes, and the pipes are laid out parallel to each other. This causes unidirectional flow along the lateral pipes, and also increases the flow velocity in the underfloor volume compared to the false floor system due to the smaller underfloor volume.

  This pipe lateral system thus requires more stringent hydraulic analysis than the false floor system in terms of the underfloor flow, but otherwise the systems are identical in terms of all other requirements.

Filter backwash rates (and the resulting underfloor flow velocities) are considerably higher than filtration rates. Nozzles and their support systems are therefore designed for effective distribution during backwash.

### General hydraulic relationships

The discharge per nozzle is calculated from the following:

$$q = \frac{v}{3600.n} \qquad (1)$$

where:

$q$ = flow per nozzle ($m^3 \cdot s^{-1}$)
$v$ = backwash rate ($m \cdot h^{-1}$)
$n$ = nozzle density ($\# \cdot m^{-2}$)
$\#$ = number of nozzles

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* To whom all correspondence should be addressed.
☎(012) 807-0125; Fax: (012) 807-0129
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This discharge through a single orifice is given by:

$$q = A.C_D.\sqrt{2.g.h} \qquad (2)$$

where:

$A$ = orifice area (m²)
$C_D$ = orifice constant (-)
$h$ = pressure drop across orifice (m)

Typical nozzle configurations, such as shown in Fig. 1, preclude the application of the single orifice formula given above, due to partially obscured orifices or the tortuous flow path close to orifice inlets and outlets. For practical application, Eq. (2) is consequently simplified to:

$$q = K_n.\sqrt{h} \qquad (3)$$

where:

$K_n$ = nozzle coefficient ($m^{5/2}.s^{-1}$)

Equations (1) and (3) provide a convenient formula for calculating the head loss through the nozzles:

$$h = \left( \frac{v}{3600.Kn.n} \right)^2 \qquad (4)$$

## Nozzle types

Apart from their obvious role to keep media out of the underfloor volume, the primary function of nozzles is to act as hydraulic control mechanisms to ensure even distribution of water and air. A number of fundamental nozzle characteristics need to be considered.

Due to the difference between air and water viscosity and density, an orifice will pass about thirty times more air than water for the same pressure differential across the orifice. It follows that a filter nozzle cannot distribute air and water evenly with the same single set of orifices. For this reason, filter nozzles have two sets of orifices; one set for the distribution of air, and the other, larger set for the distribution of water. An air release orifice must also be present at the highest point of the underfloor system to allow underfloor air to escape after the air scour cycle is terminated. A few typical filter nozzles, used for the dual purpose of air and water distribution, which are commonly used in South Africa, are schematically shown in Fig. 1.

The following comments apply to Fig. 1:

- In Nozzle 1a, the coarse dome slots are much larger than the orifices (C) in the top of the stem, and the water discharge rate is controlled by these orifices in the stem.
- In Nozzle 1b, the water flow is controlled by the narrow dome slots (D). These dome slots must therefore be sized for proper flow control, as well as for keeping the media out of the underfloor system. The bulk of the air is discharged through the large slot (B) in the nozzle stem - the small orifice (A) is predominantly for air release.
- In Nozzle 1c, the need for a nozzle stem is obviated by discharging directly out of the pipe lateral (B&C), rather than into a nozzle stem and then out of the pipe lateral. There is only one air release orifice (A) at the top for every pipe lateral, usually placed at the end of the lateral which is furthest away from the manifold.

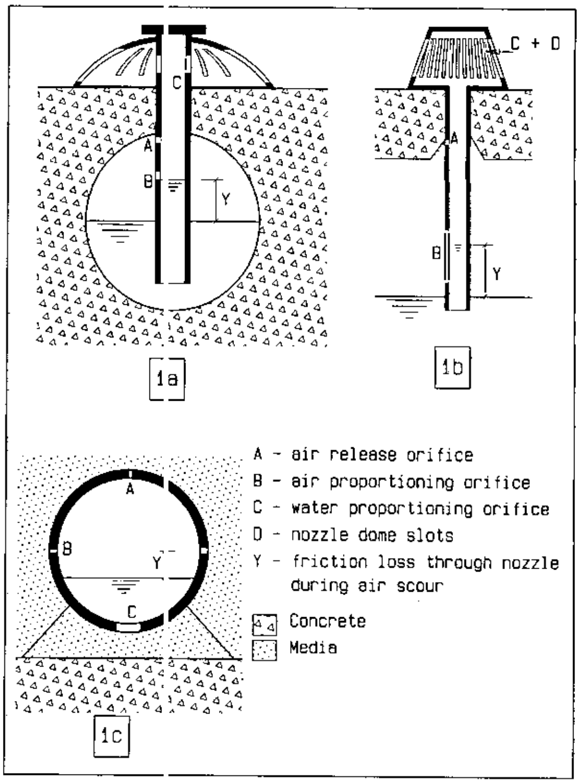

***Figure 1***
*Transverse sections of typical filter nozzles*

## Distribution of water

### Pressure drop across nozzles

The pressure drop across a filter nozzle is calculated with Eq. (4). There is no reliable way of theoretically estimating the nozzle coefficient $K_n$; this has to be determined experimentally or obtained from the nozzle suppliers. Typical coefficients for nozzles installed in South Africa range from $2.5x10^{-4}$ to $4.5x10^{-4}$ $m^{5/2}.s^{-1}$. For the backwash rates commonly used, this translates into a pressure drop of 1 000 mm to 2 000 mm.

What are the consequences of nozzle misalignment on washwater distribution? Nothing at all. For a nozzle installed $\Delta h$ higher than the rest, there will be $\rho.g.\Delta h$ less back pressure, but also $\rho.g.\Delta h$ less upstream pressure. This is analogous to placing an orifice plate in a pipeline; the flow rate through the pipeline is the same regardless of the position of the orifice plate.

### Pressure drop along manifold - Theory

In filter underfloor systems, manifolds are pipes or ducts with the purpose of distributing water flow to uniformly spaced secondary fittings. In a pipe lateral, the secondary fittings would be the filter nozzles whilst in a header pipe the secondary fittings would be the lateral pipes. Hydraulically, they are analysed similarly.

Perfectly even manifold distribution with uniform secondary fittings is impossible. Some pressure difference along the manifold between the first and the last secondary fittings will always be found - this has to be calculated.

The pressure in a manifold will be affected by two factors. Firstly, pressure energy will be lost due to wall friction, which will decrease the pressure as the water moves down the manifold.

Secondly, the velocity head in the manifold will decrease in a downstream direction, as a part of the flow is lost to every secondary fitting. As the total energy consists of the sum of pressure and velocity head, the pressure will increase in a downstream direction.

The effect of wall friction is estimated with a useful relationship for pressure drop along a manifold, namely that the manifold pressure drop is one-third of what it would be during uniform flow, i.e. when the flow rate is not decreasing in the pipe. This relationship can be derived by integrating the pressure drop along a pipe with linearly decreasing flow, and is also given in standard textbooks (Fair et al., 1958). Friction losses are seldom a major factor in underfloor systems due to the short lengths and smooth walls involved. Moreover, as it has the opposite effect of the much more important velocity head effect, it can be safely ignored for practical computations (Hudson, 1981).

Hudson (1981) developed an iterative technique to estimate the flows in each lateral and orifice of a manifold system. The following empirical equation was adopted for the lateral entry, after review of data from a number of studies:

$$h_f = \left[\phi\left(\frac{V_m}{V_l}\right)^2 + \theta\right] \cdot \frac{V_l^2}{2.g} \tag{5}$$

where:

$h_f$ = lateral entry loss [m]
$V_l$ = average velocity in lateral [m·s$^{-1}$]
$V_m$ = average velocity in manifold [m·s$^{-1}$]
$g$ = gravitational acceleration [m·s$^{-2}$]
$\phi$ = 0.9 for long laterals or 1.67 for short laterals
$\theta$ = 0.4 for long laterals or 0.9 for short laterals.

(Laterals are considered short when the length of the lateral is smaller than three times the dia. of the lateral)

The final solution is obtained by assuming perfect distribution as a starting point, and adjusting the flows with each iteration until the required level of iterative closure is reached. This rather laborious method is fully detailed in Hudson (1981).

Chaudhry and Reis (1992) used the same mathematical model as Hudson (1981), but greatly simplified its application by rewriting the equations in dimensionless form in order to solve them directly with a forward difference solution method. An equation is finally derived which gives the discharge at each successive lateral/orifice:

$$\begin{aligned} Q'_k &= Q'_{k-1} - \sqrt{\Delta H' - K_r . Q'^{\,2}_{k-1}} \\ Kr &= \frac{\phi}{1-\theta} \cdot \left(\frac{A}{A_m}\right)^2 \end{aligned} \tag{6}$$

where:

$\Delta H'$ = dimensionless path headloss
$Q'$ = *dimensionless discharge in main*
$A_m$ = cross-sectional area of the manifold pipe (m$^2$)
$A_l$ = cross-sectional area of the lateral pipe (m$^2$)

The definitions of the symbols used in Eq. (7) are indicated in Fig. 2. The method is fully detailed in Chaudhry and Reis (1992).

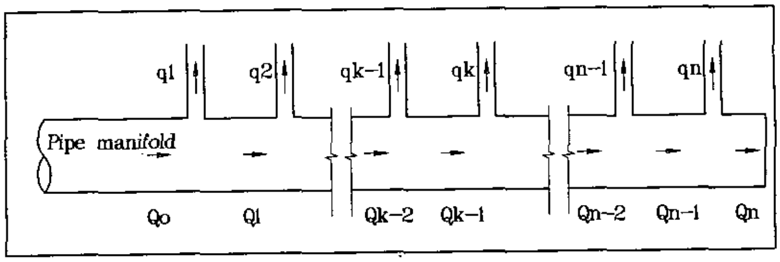

***Figure 2***
***Analysis of a manifold according to the notation of Chaudhry and Reis (1992)***

## Pressure drop along manifold - Application

For pipe lateral systems, the methods presented above must be applied twice; first to calculate the pressure differences along the main header pipe or channel (into which the pipe laterals connect), and secondly to calculate the pressure differences along the pipe laterals themselves.

The pressure differences along the main header are directly calculated with Eq. (7), assuming the coefficients for long laterals. Such a calculation was carried through for a few typical cases, to demonstrate the effects of header length and header dia. The ideal is, firstly, to achieve a relatively small difference in flow between the first and the last lateral, and secondly, a small variation in nozzle discharge along the lateral. A summary of the calculations is shown in Table 1, with the discharge variation shown in Fig. 3.

Equation (7) could be similarly applied to pipe laterals where the flow distribution is simply done through orifices in the wall of the pipe lateral (see Fig. 1). The application of Eq. (7) to filter nozzles protruding into a pipe lateral has, to the authors' knowledge, not yet been experimentally verified. Until such time, Eq. (7) should be used cautiously but could serve as an indicator for preliminary checking of adequate distribution amongst nozzles in pipe laterals.

The important parameters in the design of a pipe lateral filter floor are header dia. (Dh), lateral dia. (De) and orifice dia. (Do). Calculated results showed that influence of a drainage in the length of the header or lateral is insignificant.

Figure 3 illustrates the percentage variation in calculated nozzle discharge along nozzles number one to twenty of the first and last (20th) lateral. Figure 3A shows the variation in nozzle discharge in a typical well-designed filter floor with a 4% variation. The results of changing the said parameters (Dh, De and Do), one at a time, are shown in Figs. 3B, 3C and 3D.

## Interpretation of design guidelines

Fair et al. (1958) recommended the following ratios as a rule of thumb for the design of filter manifold systems:

- Ratio of area of lateral to area of orifices served - (2 to 4):1
- Ratio of area of manifold to area of laterals served - (1.5 to 3):1.

These suggested ratios were applied to the underfloor system (as in the above example) maintaining the same lateral dia. and analysed with the calculation procedure of Chaudhry and Reis (1992). The results are shown in Table 2. From Table 2 it is clear that:

- The 25% variation in orifice discharge obtained from the previous practical example (Ratio A = 2.55 and Ratio B = 0.51 - Table 1) compares unfavourably to even the worst results obtained when adhering to the suggested ratios in Table 2. However, this result could be improved from 25% to 8% variation by changing the manifold dia. from 0.319 m to 0.548 m (Ratio A = 2.55 and Ratio B = 1.5). Both ratios would

## TABLE 1
## RELATIVE FLOWS IN TYPICAL UNDERFLOOR SYSTEM DETERMINED ACCORDING TO METHOD DEVELOPED BY CHAUDHRY AND REIS (1992)

A. Relative flows from header into lateral pipes:

| Input | |
|---|---|
| Header dia. Dh = [m] | 0.750 |
| Lateral dia. Dl = [m] | 0.100 |
| Header length Lh = [m] | 6.000 |
| Lateral length Ll = [m] | 8.000 |
| Number of laterals N = | 20.000 |
| Double/Single laterals ? (D/S) | s |

| Output | |
|---|---|
| K1 = | 2.35E-01 |
| K2 = | 1.16E+03 |
| Kr = | 1.28E-05 |
| Phi = | 0.900 |
| Theta = | 0.400 |

DH' = (Fig. 3) 2.5000E-03

| Header | | Lateral discharge | |
|---|---|---|---|
| Number | Q' | Calculated | Adjusted |
| | 1.000 | | |
| 20 | 0.950 | 0.050 | 0.0499 |
| 19 | 0.900 | 0.050 | 0.0499 |
| 18 | 0.850 | 0.050 | 0.0499 |
| 17 | 0.800 | 0.050 | 0.0500 |
| 16 | 0.751 | 0.050 | 0.0500 |
| 15 | 0.701 | 0.050 | 0.0500 |
| 14 | 0.651 | 0.050 | 0.0500 |
| 13 | 0.601 | 0.050 | 0.0500 |
| 12 | 0.551 | 0.050 | 0.0500 |
| 11 | 0.501 | 0.050 | 0.0500 |
| 10 | 0.451 | 0.050 | 0.0500 |
| 9 | 0.401 | 0.050 | 0.0500 |
| 8 | 0.351 | 0.050 | 0.0500 |
| 7 | 0.301 | 0.050 | 0.0500 |
| 6 | 0.251 | 0.050 | 0.0500 |
| 5 | 0.201 | 0.050 | 0.0500 |
| 4 | 0.151 | 0.050 | 0.0500 |
| 3 | 0.101 | 0.050 | 0.0500 |
| 2 | 0.051 | 0.050 | 0.0500 |
| 1 | 0.001 | 0.050 | 0.0500 |
| | | 0.999 | 1.000 |

**Maximum variation in orifice discharge :**

={Qmax(Orifice)×Qmax(lateral) + Qmin(Orifice)×Qmin(lateral) } - 1

4%

B. Relative flows from laterals through orifices:

| Input | |
|---|---|
| Orifice dia. Do = | 0.012 |
| Lateral dia. Dl = | 0.100 |
| Orifice length Lo = | 0.001 |
| Lateral length Ll = | 8.000 |
| Number of orifices X = | 20 |
| Double/Single laterals ? (D/S) | s |

| Output | |
|---|---|
| Ko1 = | 1.38E+03 |
| Ko2 = | 6.77E+06 |
| Kro = | 2.04E-04 |
| Phi o= | 1.67 |
| Theta o = | 0.70 |

DH' = (Fig. 3) 2.5370E-03

Lateral no :

| Orifice Number | Lateral | Orifice discharge | |
|---|---|---|---|
| | Q' | Calculated | Adjusted |
| | 1 | | |
| 20 | 0.952 | 0.0483 | 0.0487 |
| 19 | 0.903 | 0.0485 | 0.0489 |
| 18 | 0.855 | 0.0487 | 0.0491 |
| 17 | 0.806 | 0.0489 | 0.0492 |
| 16 | 0.757 | 0.0490 | 0.0494 |
| 15 | 0.707 | 0.0492 | 0.0496 |
| 14 | 0.658 | 0.0493 | 0.0497 |
| 13 | 0.609 | 0.0495 | 0.0499 |
| 12 | 0.559 | 0.0496 | 0.0500 |
| 11 | 0.509 | 0.0497 | 0.0501 |
| 10 | 0.459 | 0.0498 | 0.0502 |
| 9 | 0.409 | 0.0499 | 0.0503 |
| 8 | 0.359 | 0.0500 | 0.0504 |
| 7 | 0.309 | 0.0501 | 0.0505 |
| 6 | 0.259 | 0.0502 | 0.0506 |
| 5 | 0.209 | 0.0502 | 0.0506 |
| 4 | 0.159 | 0.0503 | 0.0507 |
| 3 | 0.108 | 0.0503 | 0.0507 |
| 2 | 0.058 | 0.0503 | 0.0507 |
| 1 | 0.008 | 0.0504 | 0.0507 |
| | | 0.9924 | 1.000 |

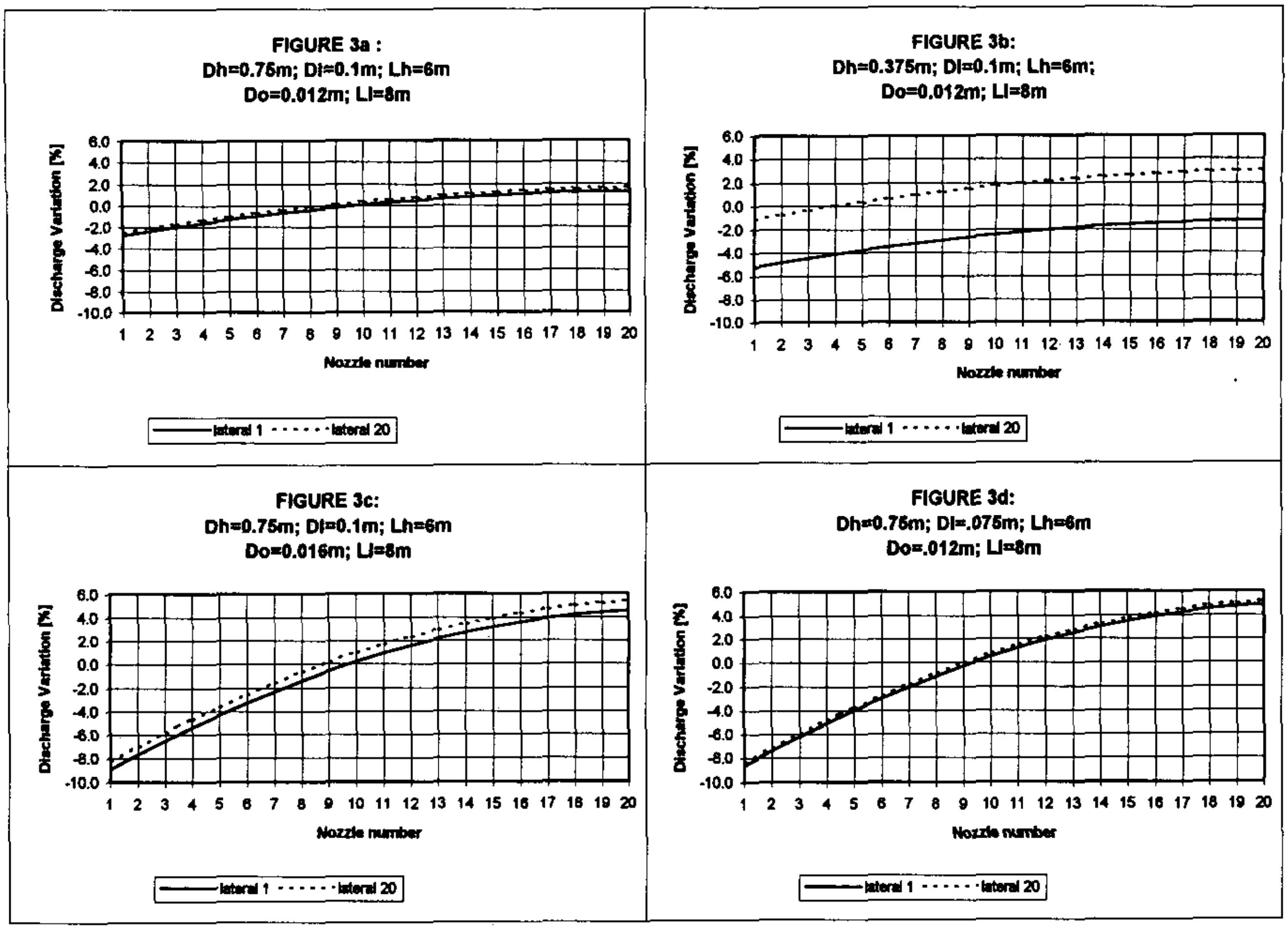

*Figure 3*
*Variation in nozzle discharge changing parameters, Dh, Di or Do one at a time, calculated with the method of Chaudhry and Reis (1992)*

TABLE 2
VARIATIONS IN ORIFICE DISCHARGE IN THE EXAMPLE CALCULATED ACCORDING TO CHAUDHRY'S METHOD FOR RATIO VALUES AS SUGGESTED BY FAIR ET AL. (1958)

| | | Ratio B | | |
|---|---|---|---|---|
| | | 1.5 | 2.25 | 3 |
| **Ratio A** | 2 | 16.5% | 15.1% | 14.5% |
| | 3 | 7.0% | 6.3% | 6.0% |
| | 4 | 3.9% | 3.5% | 3.3% |

Ratio A = Ratio of area of lateral to area of orifices served
Ratio B = Ratio of area of manifold to area of laterals served
Lateral dia. constant

be within the suggested parameters.

- If adhering to the suggested parameters the influence of Ratio A is the more important one.
- The minimal variation (most favourable result) is obtained when applying maximum ratio values; however, cost-effectiveness will also have to be considered.

## Distribution of air

### Pressure drop across nozzles

The driving force for discharging air through the air orifices is considered next. Figure 4 shows a sketch of a nozzle stem during air discharge only.

Knowing that the pressure at X is equal inside and outside the stem, it is readily seen that the pressure difference between B and Z, for the ideal situation shown, is:

$$p_{orifice} = \rho_w \cdot g \cdot \Delta y \qquad (7)$$

where:

$p_{orifice}$ = pressure drop (Pa)
$\rho_w$ = unit mass of water (kg·m$^{-3}$)
$\Delta y$ = water level depression measured from the water level to the bottom of the air orifice (m)

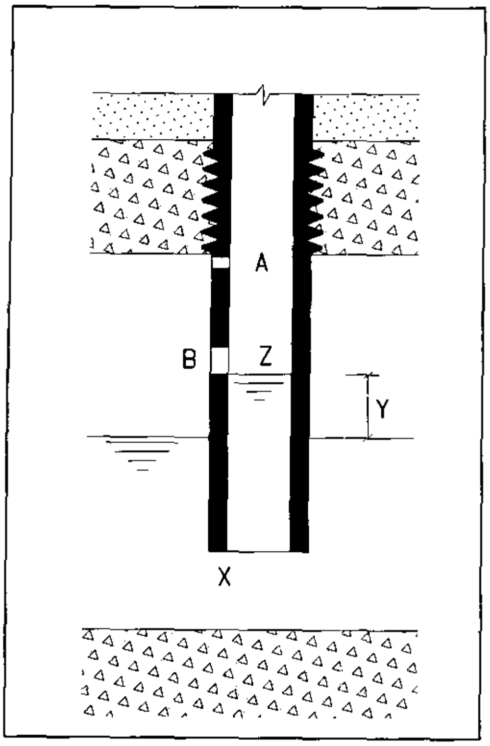

*Figure 4*
*Water levels in nozzle stem during air discharge*

The following points are noted:

- The pressure drop ($p_{orifice}$) through the air orifice B, as roughly estimated by Eq. (7), is typically very small in comparison to the underfloor pressure.
- The water level in the pipe lateral during air discharge is directly controlled by the position of the air proportioning orifice B. If it were drilled say 10 mm lower, the water level would also have been 10 mm lower (assuming the air discharge through the air release orifice A is negligible).
- It is, therefore, of great importance to keep the level of the air proportioning orifices B within strict tolerance. This important point is often not understood. To demonstrate, the following unreferenced example comes from the promotional literature of a prominent manufacturer: "...air introduced beneath the floor forms a cushion over the lower surface and escapes through the holes in the nozzles. As these holes are situated in a layer of air at uniform pressure, all discharge the same flow of air without any need for regulating them or making sure that the floor of the filter is perfectly horizontal..."
- For air discharge, a typical value of the water level depression below the air proportioning orifice is about 20 mm (Haarhoff, 1982). If a nozzle is installed say 5 mm out of horizontal alignment compared with the other nozzles, the pressure drop across that nozzle will be 25%, and the air discharge about 10% from the ideal value.
- The air discharge is directly proportional to the area of the air proportioning orifice B, but only proportional to the square root of the height $\Delta y$. Level control is therefore important, and manufacturing control of the orifices in the nozzle stems even more so.
- There is no free flow of air through the air proportioning orifice B, due to water inside the stem which partially blocks the orifice with oscillating flow. This is especially so when the air is discharged through a slot in the nozzle stem which remains partially submerged. It is therefore not possible to accurately predict the height $\Delta y$ with conventional formulae for orifice flow.
- The pressure drop across both air orifices (between A and Z in Fig. 4) should be the same, if there is no water in the nozzle stem between A and Z. In practice, however, not all the water between A and Z is blown out. This can be seen in Fig. 5, which was taken during experiments with a transparent nozzle stem (Haarhoff, 1982). The pressure drop across the air release orifice A will therefore be slightly higher than the air proportioning orifice B.
- It stands to reason that the bottom of the nozzle stems must always be immersed in water during air scour. If the air is allowed to enter the nozzle through the bottom of the nozzle stem, it will encounter almost no resistance resulting in a most uneven air distribution. It points to a danger of having the air proportioning orifices (B) too low in the nozzle stem. If the water level is momentarily disturbed, as happens during the transient condition when water is being displaced by incoming air (Haarhoff and Malan, 1983), the air could indeed find its way around the bottom of the nozzle stem.
- For analysis of the air distribution, the water level in the lateral during air discharge is required. This cannot be calculated with satisfactory precision, and the water level depression as a function of air discharge rate has to be determined experimentally.

## Backwash systems

For a filtration system to be effective it is imperative that the basic hydraulic principles already dealt with, be adhered to in order to ensure efficient cleaning of the media over the full filter media bed. To achieve this, various backwash systems are used (AWWA, 1990b):

- Backwashing with water only
- Backwashing with air and water consecutively
- Backwashing with air and water simultaneously.

These systems will be briefly described individually before they are compared in terms of cleaning efficiency.

### Backwash with water only

Backwashing with water only is a cleaning method widely practised in the USA, and is often referred to as the "American" system. The authors found this method to be rarely used in South Africa, with the exception of the backwashing of some pressure filters mostly used in swimming pools. Even in the USA, the original system has since been enhanced by backwash auxiliary systems such as surface wash (AWWA, 1990a).

Typically, the backwash rate into the filter underfloor system is gradually increased until the final backwash rate of 35 to 50 $m \cdot h^{-1}$ is reached after about 30 s. The filter media gradually assume a fluidised state as the backwash flow rate is increased and the bed is expanded. It is a very simple method which only requires a single wash-water distribution system. Two variants of the process exist:

- Low-rate backwash with rates causing less than 10% expansion of the filter media
- High-rate backwash where the wash rate is sufficient to expand the filter media by 10% to 50%, or even higher.

Both these options tend to stratify the granular media (the second option faster than the first), with a resulting thin layer of fine grains at the top of the bed after backwashing, which could lead to shorter filter runs and higher headloss through the media.

It has been conclusively demonstrated by eminent workers in this field that particle collisions in a bed fluidised by water alone do not occur to any significant extent, and that abrasion as a cleaning mechanism is thus of negligible importance (Amirtharajah, 1971; Baylis, 1959; Cleasby and Lorence, 1978). Backwashing with water alone is therefore an inherently weak cleaning process, as fluid shear is not very effective. Amirtharajah (1971) showed that maximum hydraulic shear in a fluidised bed occurs at porosities of 0.68 to 0.71 for typically sized silica sand, which corresponds to bed expansion of 80 to 100%.

To improve media cleaning in a bed, it is necessary to introduce more energy into the media bed which will lead to abrasion between grains and higher hydraulic shear forces in the bed. High-rate backwash may still be adequate when filtering solids with weak adhesive forces holding the deposits on the grains such as filtration without chemical treatment or with $Al^{3+}$ or $Fe^{3+}$ coagulation. There is little doubt that air scour or surface wash becomes indispensable for effective cleaning when filtering waste water or water with polyelectrolytes or whenever the solids become attached to the filter grains with stronger adhesion forces (Amirtharajah, 1980).

Surface wash is a common backwash auxiliary in the USA and is accomplished either with a grid of fixed pipes placed above the granular medium, or with rotary water distribution arms, containing orifices or nozzles that supply high pressure jets of water above the fixed-bed surface prior to the backwash and into the upper layers of the media during part of the bed expansion. It is relatively simple since it only comprises a system of distribution nozzles injecting high-pressure water into the bed.

### Backwash with air and water consecutively

This type of backwash operation, often called the "British" system, is in common use in South Africa and has proved itself over many years as an effective system when correctly designed and constructed. The air scour first abrades the deposit from the media grains and is followed by the water backwash to flush the deposits out of the bed. Air is introduced through the bed at rates of 18 to 36 $m \cdot h^{-1}$, followed by water backwash just above the point of incipient fluidisation at 12 to 30 $m \cdot h^{-1}$. The duration of the air scour is usually between 2 to 3 min and the water backwash is continued until the wash-water is clear.

When air is introduced at the bottom of the filter, bubbles travel upward carrying some water and dirt particles as they pass through the bed and burst at the surface, where the maximum scouring action appears to be produced. Substantial agitation of the medium near the bed surface occurs and it is this action that provides the basis for air-scour use in sand filters where minimum solids penetration occurs. Deeper agitation is also observed during the first minute or so of air scour. Thereafter, the bed begins to settle down, and the air becomes more channelised as it passes through the bed. The continuation of air scouring after the bed has settled (after about 2 to 3 min of air scouring) serves no purpose (Cleasby et al., 1977).

***Figure 5***

*Actual conditions in a nozzle stem during air discharge. Photograph from Haarhoff (1982)*

Figure 6 shows the variations in air flow, water flow, and underfloor pressure during a typical backwash sequence. Although the backwash system is designed not to use air and water simultaneously, such conditions do occur during the initial stages of the air-scour cycle (between points C and D in Fig. 6). Although only momentarily, this short period is nevertheless enough to seriously disturb the gravel-supporting layers at a high enough air-scour rate (Haarhoff and Malan, 1983). If the air-scour rate is high enough so that the water displaced will fluidise the media it would be necessary to bleed off some air until all the nozzle stems are exposed to air.

One of the drawbacks of this system is the fact that the sand compacts during air scour and that the period of useful agitation is limited to a minute or two. New, automated backwash sequencing systems make it possible to partially eliminate this problem by sequencing two or even three backwash cycles instead of only one, in such a way that the same or less backwash water is used than for a single cycle. This method allows consecutive air and water to approach the efficiency of simultaneous air and water.

### Backwash with air and water simultaneously

This system, sometimes called the "French" system, is also common in South Africa. During the first step of the backwash process, air scour (at 50 to 60 $m \cdot h^{-1}$) and water backwash (at 10 to 15 $m \cdot h^{-1}$) are used simultaneously for coarse sand single media (effective size typically larger than 0.9 mm).

This water rate is well below the fluidisation velocity of the sand. After a period of 5 to 10 min. of simultaneous air and water backwash, the airflow is terminated. During the second step, the water continues to expel some of the air from the bed and to flush the remaining dirt from the water above the filter medium. The

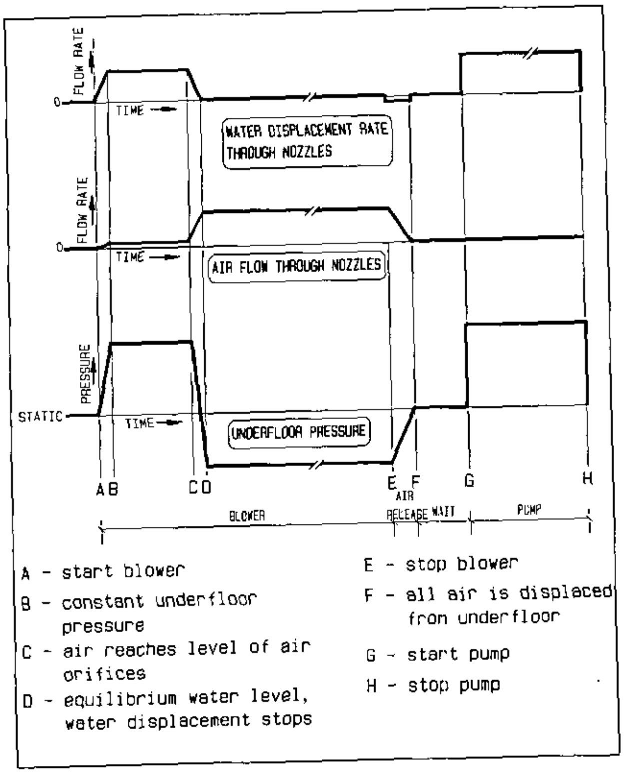

**Figure 6**

*Variations in flow rates and pressure during a filter backwash cycle when using air and water consecutively*

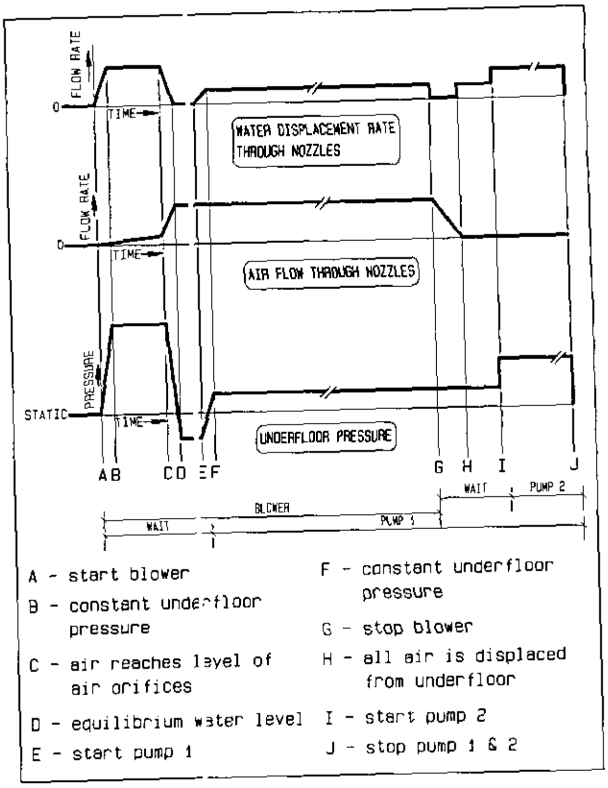

**Figure 7**

*Variations in flow rates and pressure during a filter backwash cycle when using air and water simultaneously*

flow rate may be increased (up to 15 to 25 m·h$^{-1}$) but should remain below the fluidisation velocity of the sand to avoid the loss of sand (Degremónt, no date).

It has been demonstrated (Amirtharajah, 1993) that this method of backwashing is most effective when the ratio of the air and water flow rates is such that collapse-pulsing of the bed occurs. Collapse-pulsing conditions can be created at combinations of air and subfluidisation water flow rates where cavities larger than the media grains form and collapse. This process repeats itself throughout the depth of the bed. The greatest amount of abrasion among the media grains is achieved during collapse-pulsing conditions. This is the optimum condition for removal of particles during the backwashing of media beds with water and air simultaneously.

The danger exists that the filter media may be lost with simultaneous air-and-water backwash during overflow because of violent fluid motion above the bed if this backwash method is not applied correctly. Figure 7 shows the variations in air flow, water flow and underfloor pressure during a typical backwash sequence.

## Comparison of backwash systems

Every commercial backwash system has its own unique practical features which make it more or less desirable. These practical matters will be discussed in the following section. The emphasis of this section is on the inherent strengths and weaknesses of the different systems.

Cleasby et al. (1977) made a comprehensive pilot-plant comparison amongst different backwash systems, namely water alone, water enhanced by surface wash, consecutive air and water (below media fluidisation). Using municipal waste water as a suspension, they ranked the systems as follows:

- The simultaneous air and water system was the most effective.
- Water enhanced by surface wash, and consecutive air and water were comparable in efficiency.
- Water alone was least efficient.

These findings do not imply that simultaneous air and water should necessarily be used for all applications. It very much depends on the nature of the particles captured in the filter bed. If media grains are easily cleaned, less efficient systems may be perfectly acceptable. Cleasby et al. (1977) concluded that:

- When physical mechanisms are responsible for retaining floc particles in the bed (e.g. iron removal), water fluidisation alone can be as good as air scour or surface wash.
- If the raw-water quality is such that the film around the media grains is firmly attached (e.g. waste water or lime-softened water), air scour or surface wash is essential.
- Polyelectrolytes increase the "adhesiveness" of the film around the grains and in such instances a backwash system with the best efficiency (backwashing with air and water simultaneously) would be advisable

The implications of these findings for South Africa, where polymeric filtration aids are seldom used, are that consecutive air and water, as well as simultaneous air and water, can be considered on equal technical footing for most applications.

## Causes of underdrain problems

### Design problems

A number of design errors, relating to the underfloor system, could conceivably be made. Normally, when a complete system is supplied by a reputable, experienced manufacturer, these errors are not likely to occur. These errors have, however, indeed been observed in practice by the authors and were usually traced to well-meant attempts to "fix" or "rehabilitate" filters that perform below expectation. Without a thorough understanding of filter underfloor systems, these attempts often lead to replacement of supporting layers and filter nozzles which are not compatible with the original design.

An underfloor system will not perform well if the water and air distribution is unevenly distributed to the filter nozzles. The preceding section on manifold hydraulics and its application to filter underfloor systems provides the theoretical tools to evaluate the uniformity of air and water supply to individual filter nozzles.

The design of the filter-supporting layers is critical in two respects:

- If the supporting layers are too coarse relative to the media size, the media will penetrate into the voids in the supporting layers and eventually reach the filter nozzles. As a rule of thumb it is recommended that the fine size of the coarser layer should be less than or equal to two times the fine size of the adjacent fine layer (AWWA,1990b).
- If the supporting layer, on the other hand, is too thick, it could lead to poor distribution of water through the media bed. Although the water may be distributed perfectly evenly through the nozzles, a too thick layer could allow the water to redistribute itself in the supporting layers before entering the sand. A lump of compacted sand, under these conditions, will not be broken up (Langenegger, 1993). Systems successfully used in South Africa have layer thicknesses of about 15 to 30 times the median grain dia.

The dome slot width must be selected in conjunction with the media or the supporting layer directly above the nozzles. If there are no supporting layers, the slot width should be fine enough to retain the finest media grains. If there are supporting layers, the slot width could obviously be larger, provided that the hydraulic resistance is controlled by an internal water measuring orifice.

A frequent design error relates to the air inlets into the underfloor system. If these inlets are close to (or even below) the water surface, the water surface in that area will be disturbed. If some filter nozzle stems or pipe lateral inlets are in close proximity, the even air distribution will be disturbed due to the varying water level. In the worst case, the underside of the stems could be uncovered.

### Nozzle problems

Filter nozzles are generally of good quality and design. Problems are consequently rare. Two manufacturing problems, however, have been encountered by the authors:

- Air orifices or air slots in nozzle stems are usually very small or narrow (minimum dimension 1 to 3 mm) and small imperfections of these orifices can have a sizeable effect on air flow rate. This is especially so when orifices are partially blocked by burrs or when the orifice is not fully pressed through the stem.
- In the case where dome slots are glued onto a base, the bond may be broken by poor workmanship, prolonged exposure to the sun or to heavy traffic during media loading. In this case, the dome comes off, media are free to enter the underfloor volume and even distribution of air and water is disrupted. Figure 8(a) shows one nozzle from which the dome has disappeared. Nozzle designs, where the dome is screwed down with the nozzle stem rather than being glued to the rest of the assembly, obviously do not have this problem.

Inexperienced operators do not always appreciate the importance of equal air distribution, and damaged or broken nozzles were found to be replaced with nozzles not identical to the original ones. The manufacturer's colour coding distinguishing between nozzles with different air and water design flow rates should be adhered to when nozzles are replaced.

### Installation problems

Installation problems are the most common reason for the failure of filters and backwash systems and can cause the best filter backwash system to fail. Typical installation problems are:

- Uneven air distribution caused by
    - imperfect levelling of the false floor slabs or pipe laterals,
    - imperfect levelling of the nozzles,
    - imperfect levelling of the media supporting layers or
    - nozzles not properly tightened as clearly noticeable in Figs. 8(b) and 8(c).
- Overtightening of nozzles can strip the plastic threads, which will eventually lead to nozzle blow-out.
- Direct sunlight and high temperatures can lead to cracked nozzles due to thermal stress. Figure 8(d) shows a "funnel" visible on the media surface. This was caused by a broken nozzle which allowed sand ingress into the filter underfloor system. Uneven air distribution due to a broken nozzle during air-scour is clearly noticeable in Fig. 8(e).
- Joints between false floor panels not properly sealed where more air could escape during air scour than through a nozzle.
- Insufficient cleaning of the underfloor volume or pipe laterals after construction. This can be detrimental if a number of nozzles are blocked and structural failure is possible. Isolated blocked nozzles will result in dead areas in the bed and uneven backwash patterns.

However simple and obvious these problems may appear, they do occur in practice and can only be prevented by careful construction and meticulous supervision.

## Symptoms of faulty underfloor systems

The filter underfloor system is invisible after media placement, which makes the direct observation or measurement of underfloor errors impossible. Commissioning and operational personnel fortunately can rely on a number of indirect methods to find and diagnose problems with the underfloor system.

### Uneven air/water backwash pattern

An initial assessment of the condition of an underfloor system can be made by observation of the air-scour pattern during a backwash cycle. During the air-scour pattern, zones of "dead" nozzles can normally be identified at those positions where no air is bubbling

***Figure 8(a)***
*Missing nozzle and structural failure of false floor*

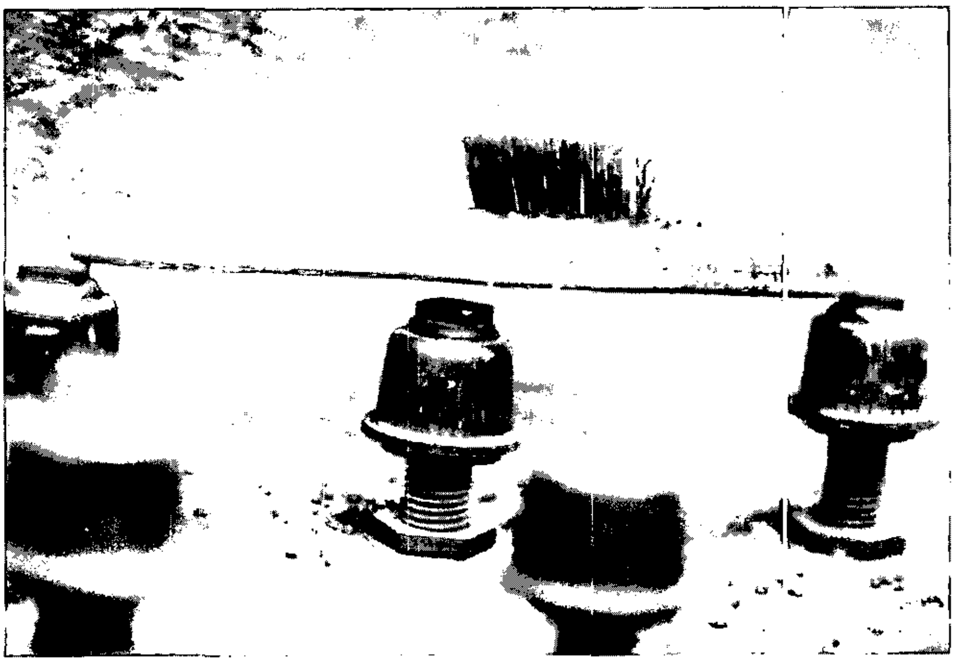

***Figure 8(b)***
*Imperfect installation and levelling of nozzles*

through the bed, but it is difficult to detect a single "dead" nozzle. A much more reliable observational test can be done before the media are loaded into the filter. The nozzles are then covered with less than 100 mm of water, in which case problems with individual nozzles can be easily and accurately identified. It is essential that such "test blows" or "bubble tests" are performed as a routine measure before the supporting layers and the filter media are loaded.

Figure 8(f) shows a filter during a test blow, where the air flow through individual nozzles can be clearly distinguished. In this case, there were a number of underfloor restrictions which inhibited the flow of air and caused continuous, random surging of the underfloor water level. The resulting air pattern was consequently disrupted, as can be seen on the photograph. Figure 8(g) shows an extremely poor air pattern for a filter fully loaded with media, after many years of operation. In this case, it is obvious that a substantial portion of the bed is totally "dead".

Observation of the water pattern will also show areas where the water flow is excessively high (indicated by "boiling") or low (indicated by a lack of sand movement). For these effects to be clearly visible, the backwash period should be extended until the water on top of the media is clear enough to observe the trouble spots.

***Figure 8(c)***
*Imperfect installation and levelling of nozzles*

***Figure 8(d)***
*Broken nozzle caused sand ingression into filter underfloor system*

### Filter media

An ineffective backwash system will certainly result in one or more of the following:

- The formation of considerable gaps where the media are drawn away from the filter walls as seen in Figs. 8(h) and 8(i), causing short-circuiting and filtrate of a poor quality.
- The formation of considerable cracks in the media bed, as seen in Fig. 8(j).
- Mudballs can form which are not easily removed. The media become progressively dirty. Figure 8(k) illustrates the appearance of dirty media.

### Supporting layers

Additional information on the condition of the underdrain system can be gained by digging down into the filter supporting layers. The exposure of the supporting layers is a tedious task which should be done with extreme care, as significant damage can be inflicted on the supporting layers by careless excavation and backfilling.

The top level of the gravel should be horizontal. If not, it indicates disruption by an excessive combination of air and water flow through the nozzles. This problem can occur under certain circumstances when air and water is used either consecutively, or simultaneously. The exact mechanism of disruption, and the

***Figure 8(e)***
*Uneven air distribution due to broken nozzle*

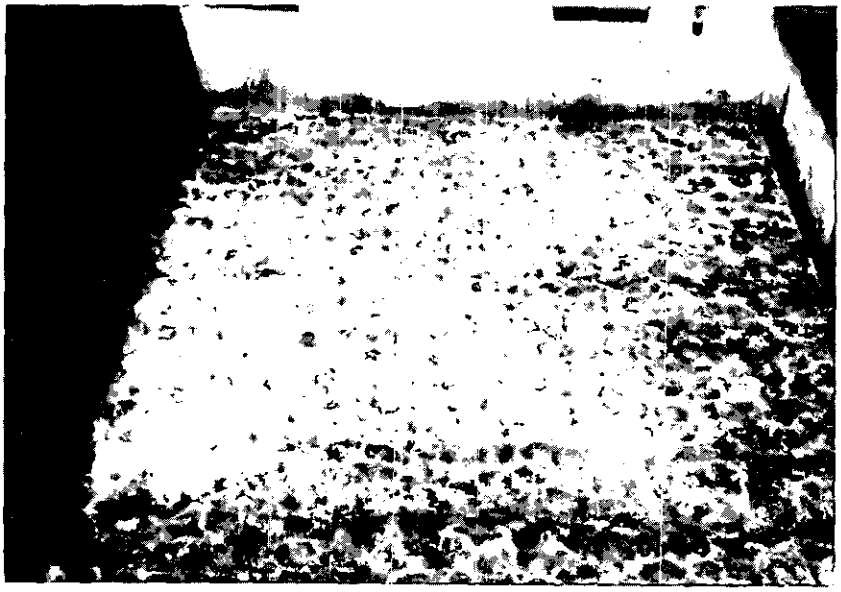

***Figure 8(f)***
*Uneven air distribution pattern (no media)*

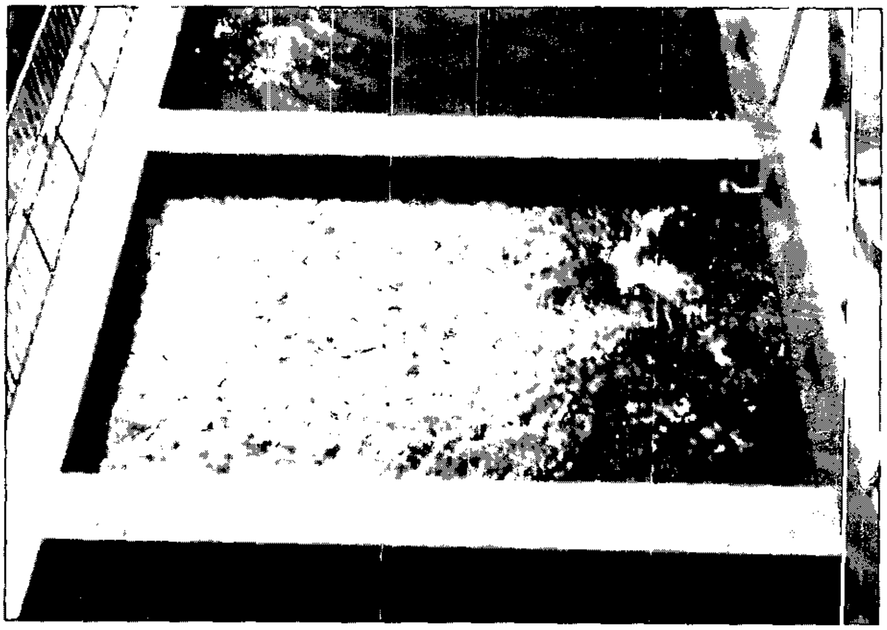

***Figure 8(g)***
*Uneven air distribution pattern (media in place)*

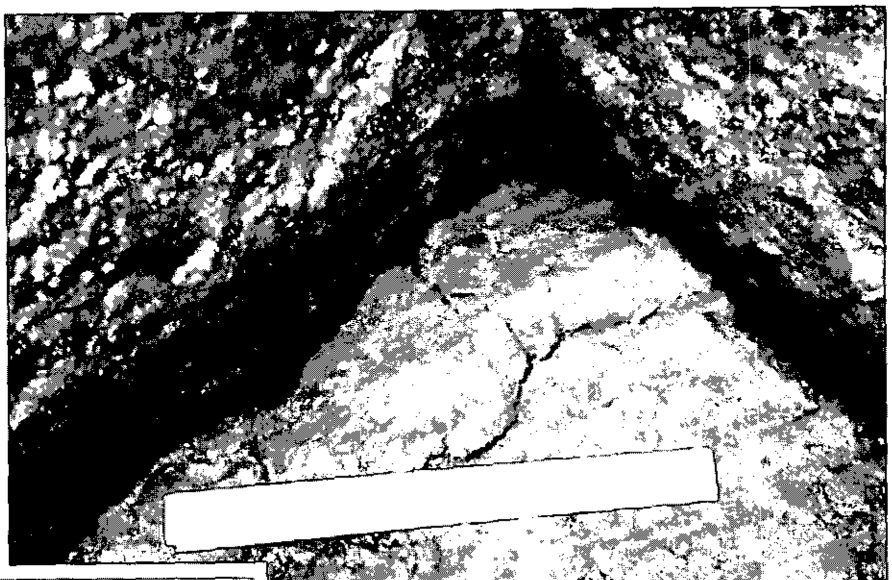

**Figure 8(h)**
*Crack between media and wall*

**Figure 8(i)**
*Crack between media and wall*

**Figure 8(j)**
*Media cracks*

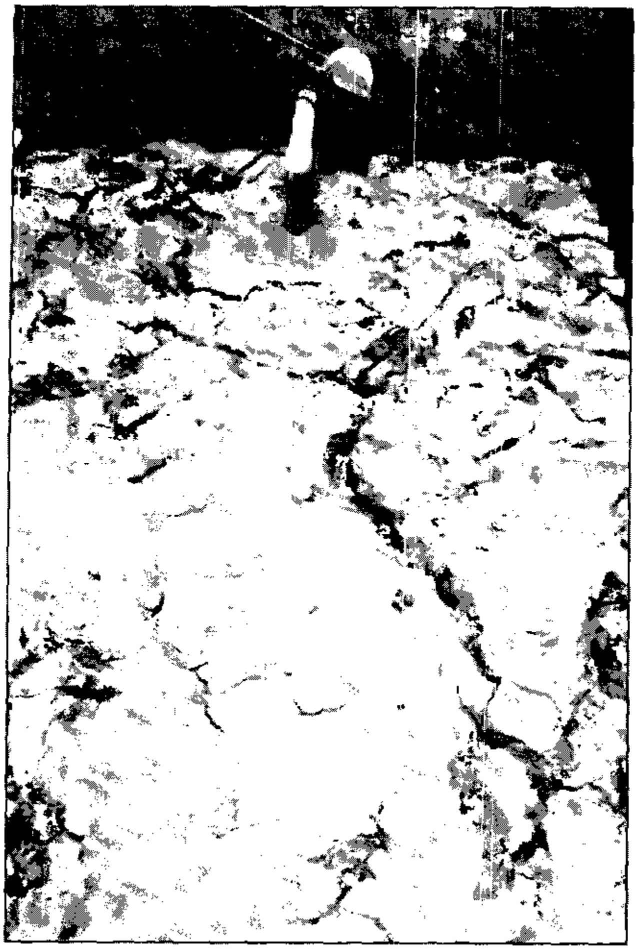

*Figure 8(k)*
*Dirty media*

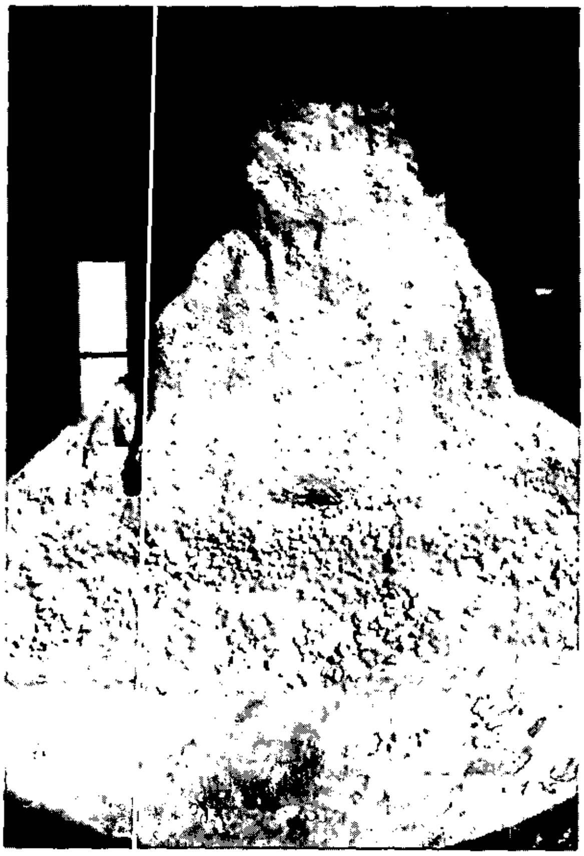

*Figure 8(l)*
*Sand ingress in supporting layer*

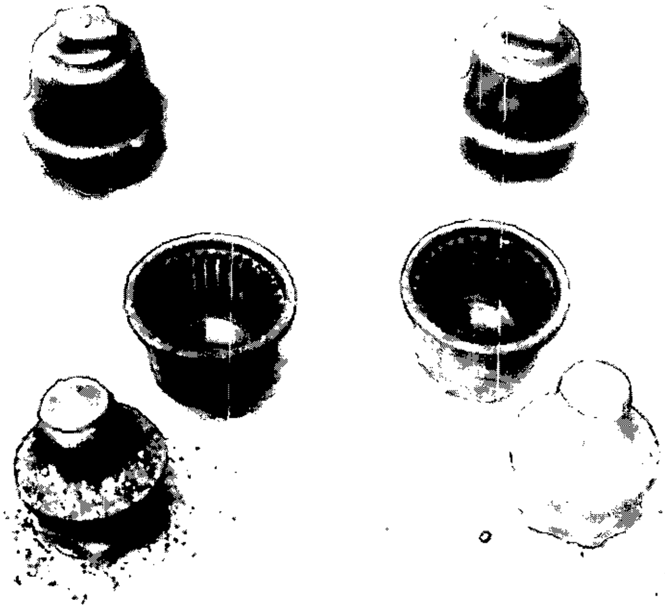

*Figure 8(m)*
*Sand trapped in filter nozzle*

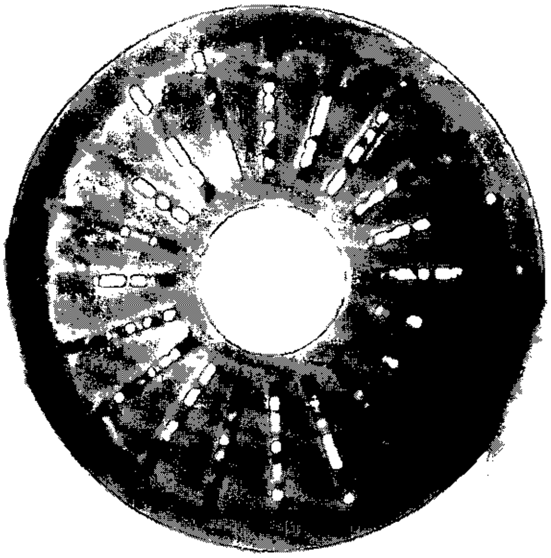

***Figure 8(n)***
*Dome slots of filter nozzles blocked*

***Figure 8(o)***
*Nozzle stem totally blocked with media*

options for prevention were described elsewhere (Haarhoff and Malan, 1983).

The supporting layers, if operating properly, should be clean and free of filter media. If filter media have leaked into the supporting layers, it indicates either too fine media in relation to the supporting layers, or disruption of the interface by excessive air and water rates. Figure 8(l) shows a partially demolished pressure filter, which had been performing very poorly. It is evident how sand has leaked into the gravel layer, presumably because of incorrect sizing of the supporting layer.

## Sand ingress into underfloor volume

Once sand has entered the underfloor volume, it leaves evidence of its presence in all the different underfloor components. Figure 8(m) shows how sand accumulated in the nozzle dome after it was blown from below into the dome, but could not pass through the narrow dome slots. Figure 8(n) shows to what extent the dome slots can be blocked. The dome slots are wedge-shaped with the narrow end on the outside, so once the media grains are lodged in the slots, they cannot be removed hydraulically. Figure 8(o) shows an example of a nozzle stem totally blocked with sand which will not pass air or water in any direction. Figures 8(p) and 8(q) show

*Figure 8(p)*
*Pipe laterals totally blocked with media*

*Figure 8(q)*
*Pipe lateral partly blocked with media*

cases where pipe laterals are partly or totally blocked.

It is good practice to design filters with human access to the underfloor volume. If the underfloor volume can be periodically inspected, it will be easy to detect the ingress of sand at an early stage before conditions have deteriorated to the extent as shown in the figures. Sand accumulation is first seen in the corners and at the low points of the underfloor system.

## Structural failure

The ultimate symptom of a faulty underfloor system is structural failure or filter floor "blow-up". False floor panels are structurally designed to withstand the differential pressure under normal conditions of water discharge. As the nozzles block, the flow decreases and the differential pressure rises. In the extreme case of total nozzle blockage, the underfloor pressure is determined by the static height of the backwash tank or the shut-valve pressure of the backwash pump, whichever is applicable. Calculations will show that these pressures will exert enormous forces on the underside of the false floor panels - in excess of what they were designed for. Figure 8(r) shows a filter after structural failure and in the process of the false floor panels being demolished, while Fig. 8(s) shows a filter (at another plant) after removal of the false floor panels.

Pipe lateral systems present no large exposed areas upon which water pressure can act, and are consequently less prone to structural failure in the case of underfloor pressure build-up. Pipe lateral systems, however, provide no guarantee against structural failure. A case is known to the authors where pressure did increase and water eventually penetrated the horizontal

*Figure 8(s)*
*Demolished false floor system after structure failure*

*Figure 8(r)*
*Structural failure of false floor system*

construction joint between the structural floor (below the pipe laterals), and the infill concrete (around the pipe laterals). The pressure eventually lifted the laterals and the filter floor had to be rebuilt. This specific problem is normally pre-empted by the judicious placing of a special water bar ensuring a water-tight construction joint.

An early indication of nozzle blockage and build-up of underfloor pressure is given when a vertical release pipe is connected into the underfloor system, with its top just above the hydraulic gradient during a normal backwash. When water starts to spill from this pipe, operators are warned that the underfloor pressure is increasing.

## Conclusions

The exact hydraulic principles and practical pitfalls of filter underfloor systems are, generally speaking, not very well understood by managers and operators of water treatment plants. Unfortunately, this uncertainty is often ruthlessly exploited by some manufacturers of underfloor systems which claim that their particular system is "superior to" or "better than" those of their competitors. This paper provides the theoretical background and practical examples to show that:

- Different nozzle support and backwash systems, despite their differences, are able to effectively perform the same functions, namely even distribution of water and air, and maintaining the media in a clean, satisfactory condition. This presents a challenge to designers to structure their tenders so that different systems can be offered, while being specific enough in the key aspects to ensure that all offers provide a technically sound solution.
- Filter underfloor systems operate according to relatively simple hydraulic principles and are therefore amenable to rational analysis.
- Variations in discharge rate amongst different nozzles are inevitable for all floor systems, but especially so for pipe lateral systems. These variations can, however, be kept within specification by proper manifold design.
- It is, ultimately, the care and diligence of manufacture and installation which determine the success of an underfloor system. A perfectly designed underfloor system, but poorly constructed, will be no better than a poorly designed underfloor system.
- Errors during installation or manufacture can be detected and corrected by a rigorous testing and commissioning programme.

- Operators can, by careful observation of how their filters operate and backwash, pinpoint underfloor problems at an early stage.
- It was demonstrated that filter underfloor systems are sensitive to a wide range of factors which could undermine their efficiency. It takes the combined commitment and experience of designer, contractor and operator alike to build and maintain the vitally important filter underfloor system.

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