Grain displacement during backwash of drinking water filters

Loren Ramsay, Feng Du, Majbritt Lund, Haiyan He and Ditte A. Søborg

ABSTRACT

Backwashing rapid sand filters causes inadvertent displacement of filter media grains from their previous depths. This displacement can affect the hydraulic function of filters by mixing or segregating media grains, and the function of biofilters through displacement of active biomass and coatings from proper depths. This study quantifies grain displacement in a pilot-scale filter using tracer grains of colored sand, glass beads, anthracite and garnet to determine the effect of grain size, density and shape on grain displacement. Statistical moments are used to describe the depth distributions resulting from displacement during backwashing. Results show that significant grain displacement occurs during backwash consisting of air scour, air-and-water wash and sub-fluidization water-only wash. Here, displacement is largely independent of grain size, density and shape. When fluidization backwash is used, greater displacement and more dependence on grain characteristics is seen. A variety of grain movement phenomena can be observed during the backwashing steps, indicating that grain movement and therefore the resulting displacement is highly inhomogeneous in four dimensions. These results have direct practical implications for the design of rapid sand filters and the optimization of backwashing procedures, while suggesting that the current widespread backwashing practice used in the case study country (Denmark) should be abandoned.

Key words | backwash, biofiltration, drinking water, grain displacement, rapid sand filtration

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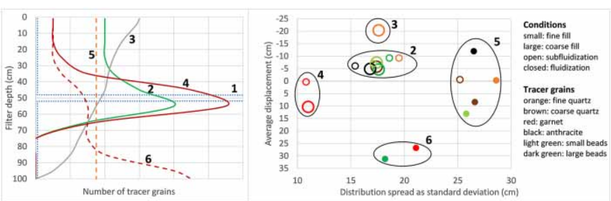
HIGHLIGHTS

- Filter media movement during 3-step backwashing is highly inhomogeneous.
- Significant displacement of tracer grains is seen in all backwash tests.
- During backwash with a final sub-fluidization step, displacement in the upper portion of the filter bed is significantly greater than lower portion.
- During backwash with a final fluidization step, mixing in the entire filter bed occurs with partial segregation due to grain shape and density.
- The hydraulic and biological function of filters may be affected by grain displacement.

GRAPHICAL ABSTRACT



doi: 10.2166/ws.2020.300

INTRODUCTION

The main purpose of the periodic backwashing of rapid sand filters is to restore their hydraulic function by removing clogging material through a process of elutriation. Inadvertently, however, backwashing may also cause displacement of filter media grains from their previous depths to new positions. This grain displacement – or change of position of individual media grains during backwash – may affect not only the subsequent permeability of the filter but also the ability of the filter media to remove unwanted substances from the source water. In the case of biofiltration, the stratification of the biofilm (Madoni *et al.* 2001; Tatari *et al.* 2016) may be disturbed.

Backwashing of rapid sand filters was introduced in the early 1900s (Baker 1934). Whereas slow sand filters can be hydraulically restored by scraping off the top few millimetres of the schmutzdecke (Ranjan & Prem 2018), rapid sand filters require backwashing. This requirement was a natural consequence of the introduction of coagulation/sedimentation processes that reduced the concentration of suspended solids and allowed for faster flows and deeper penetration of the remaining clogging substances into the filter media (Baker 1934). Today, backwashing provides the plant operator with an important opportunity to manipulate the water treatment process. However, successful manipulation requires insight into the full consequences of backwashing, whether intentional or inadvertent.

Since its inception, the backwashing process has been a frequent subject of investigation (Hulbert & Herring 1929; Baylis *et al.* 1959b; Cleasby *et al.* 1977; Slavik *et al.* 2013). Backwashing involves reversing the direction of flow from the typical top/down production mode to an upward flow of water and often air through the filter media. The most common backwashing steps are referred to here as air scour, concurrent air-and-water wash and water-only wash. While it is standard practice to conclude the backwash process with a water-only wash, the use of preceding steps as well as the flow and duration of each step varies according to regional traditions and situational demands such as source water quality, grain characteristics (size, density, shape), filter bed thickness and water temperature.

The water-only wash of rapid sand filters is often equated with a liquid fluidization process, where the upward flow of water is sufficiently high to suspend the solid granular media in a fluid-like state. An early use of liquid-fluidized beds or 'teetering' was the sizing (classification by size) and sorting (classification by density) of ores by mining engineers (Ozcan & Ergun 2017). When a flow exceeding the minimum fluidization velocity is used in backwashing rapid sand filters, filter bed expansion takes place, releasing the trapped particulate matter. An optimum bed expansion of around 20% has been suggested (Ikhlef 2016). Fluidization, however, displaces media grains from their original depth and can segregate grains by both size and density. Although density segregation (sorting) is desirable for drinking water filters with dual media such as anthracite and quartz, segregation by grain size (sizing) within a single medium is counterproductive, leaving the smallest grains at the top and contributing to the risk of early clogging and shorter run times. At higher backwashing flows, intermixing of two media types or even bed inversion may occur in dual media filters (Cleasby & Woods 1975; Epstein 2005).

Fluidization, however, is not always the aim of the water-only wash of rapid sand filters. In Denmark, fluidization is often avoided entirely, allowing operators to escape the need for large flows and volumes of backwash water. When fluidization is not the goal of the water-only wash, treatment plant designers are freed to utilize larger grain sizes. This extends filter run times, which is especially important when the raw water contains high concentrations of iron or when biofilters depend on slow-growing bacteria. Another example of the use of sub-fluidization flows is the so-called Extended Terminal Sub-fluidization Wash (Amburgey & Brouckaert 2005). The idea here is to replace the particle-laden backwash water remaining in the filter media pores with clean water without causing the further release of particulate matter from the media.

As water-only wash constitutes only a weak cleaning process (Cleasby & Woods 1975), many treatment plants precede this step with an air scour step to cause additional agitation of the filter medium. However, since bed expansion is minimal during air scour, loosened particulate matter is not necessarily released to the surface. Air scour forms localized airlift pumps, raising water in narrow columns of partially interconnected megapores, while causing downward flow of water between these columns. The result may be slight compaction of the filter bed (Cleasby *et al.* 1977).

Concurrent air-and-water wash is considered the most aggressive form of backwash for cleaning filter media (Amirtharajah 1993). The combined upward forces of air and water lift the filter media locally, resulting in improved cleaning through greater sheer forces during grain collisions. It should be noted that this method increases the risk of media loss by lifting grains through the freeboard and into the backwash trough. At certain combinations of air and water flows, a special movement phenomenon dubbed the collapse-pulse condition has been described in rapid sand filters (Amirtharajah 1993).

Although the motion pathway of individual media grains during backwash has been tracked in several studies (Ives 1989; Fitzpatrick 1993; Duris *et al.* 2013), the authors were unable to find backwashing studies quantifying the final displacement of filter media grains from their original position. Therefore, it was unknown which, if any, backwashing procedures cause the greatest displacement or whether this displacement occurs at a rate that exceeds the formation of new biofilm and coating more suited to the new location.

In this experimental investigation, full-scale rapid sand biofilters with dual media (anthracite overlaying quartz) were investigated to determine whether media mixing had occurred over time. A pilot-scale filter with thin layers of colored sand, anthracite, garnet and glass beads as tracers was used to quantify grain displacement during backwash due to variations of size, density and shape. The pilot filter was equipped with a plexiglass window for direct observation of grain movement phenomena. It should be noted that this investigation focuses solely on the grain displacement rather than on the effect of grain displacement on drinking water treatment quality (Miltner *et al.* 1995; Ikhlef & Basu 2016).

METHODS

Full-scale waterworks

Eight operating waterworks in Denmark using aeration/biofiltration treatment and groundwater sources were investigated. Filters were all open, gravity filters containing dual media (anthracite overlaying quartz) ranging in media age from 3 to 34 years. Data regarding original grain sizes and bed thickness was available at most waterworks. Typically, anthracite properties were 2.0–4.0 mm (grain size, d_{10} -d_{90}), 1.6 (uniformity coefficient), while bed thickness ranged from 35 to 70 cm. Quartz properties were typically 1.4–1.8 mm (grain size, d_{10} -d_{90}), 1,2 (uniformity coefficient), while bed thickness ranged from 70 to 110 cm. These values clearly change over time due to the opposing tendencies of coating and attrition.

Backwash procedures included an initial air scour and a final water-only wash. In addition, six waterworks also included a concurrent air-and-water wash. The entire backwash procedure ranged from 12 to 42 minutes total per filter.

Estimations of the minimum fluidization velocity, V_{mf}, for the quartz sand were calculated by Equation (1) (Duris *et al.* 2016), where V is in m/h and d_{50} is the equivalent sphere mean sieve diameter in mm. This equation was selected due to its simplicity to provide a rough indication of the backwash velocity required to fluidize quartz media.

$$V_{mf} = 40 \cdot d_{50}^{1.38} \quad (1)$$

Pilot filter set-up

A stainless-steel pilot filter (50 cm diameter, 2.4 m height), as seen in Figure 1, was constructed by Vand & Teknik, Denmark. The filter was fitted with a plexiglass observation window (14 × 150 cm) and 10 sampling ports staggered at 10 cm intervals, a filter floor with seven nozzles (water for backwash) and an air harp (14 holes with 5 cm diameter on the underside of the pipes).

For various experiments, the gravel support layer was overlain by 100 cm single media containing fine or coarse quartz sand. Filter media was pre-treated by wet sieving to remove fines. Tracer grains of colored sand grains in two sizes, glass beads in two sizes, anthracite and garnet (see Table 1) were placed in 2 cm layers. Sand was supplied by Dansk Kvarts Industri, Denmark, colored sand (from the same gravel pit and sieving fraction) by Stonewalk, Denmark, glass beads by Sigmund Lindner, Germany, anthracite by Silhorko/Eurowater, Denmark and garnet by Meldgaard, Denmark. Production mode (top/down-flow) as well as backwash (bottom/up-flow) was carried out using tap water at approximately 15 °C, which was collected and recycled in a rigid IBC tank.

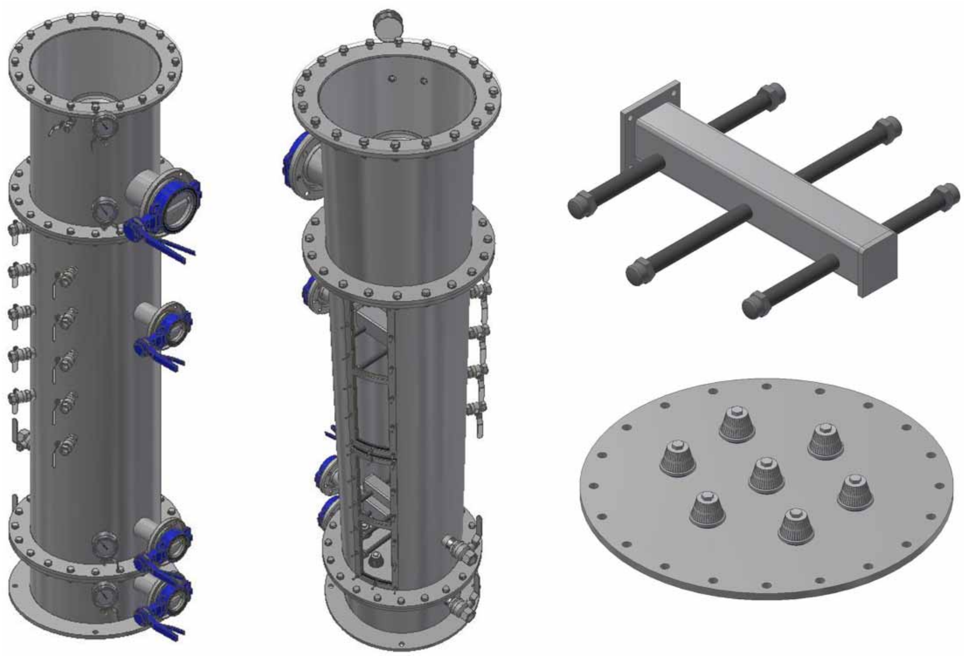


Figure 1 | Left: Stainless steel pilot filter seen from two angles showing sampling ports and observation window. Right: air harp and filter floor with nozzle placement.

Table 1 | Filter media used in the pilot filter

		Fill media		Tracer media					
Parameter	**Units**	**Fine quartz sand**	**Coarse quartz sand**	**Fine colored quartz sand**	**Coarse colored quartz sand**	**Small glass beads**	**Large glass beads**	**Anthracite**	**Garnet**
Grain size d_{10}	mm	0.76	1.23	0.81	1.17	1.61	2.87	1.39	0.88
d_{50}	mm	1.00	1.59	1.07	1.58	1.68	3.10	1.92	1.23
d_{60}	mm	1.05	1.66	1.13	1.67	1.70	3.15	2.03	1.31
d_{90}	mm	1.28	1.94	1.36	2.06	1.76	3.35	2.54	1.74
Particle density	kg/L	2.6	2.6	2.2	2.4	2.5	2.5	1.1	4.1
Bulk density, submerged	kg/L	1.6	1.5	1.5	1.5	1.5	1.5	0.5	2.3
Porosity	%	40	42	33	35	37	40	49	43
Uniformity coefficient	d_{60}/d_{10}	1.4	1.3	1.4	1.4	1.1	1.1	1.5	1.5
Sphericity	–	0.85	0.86	0.87	0.88	0.98	0.99	0.80	0.83
Number dry grains	−/g	724	194	686	190	153	24	317	253

Bed expansion

Measurements were performed for fine-grained sand (0.8–1.3 mm) and coarse-grained sand (1.2–1.9 mm). The results showed that bed expansion greater than one percent was achieved at flows of approximately 30 m/h for the fine-grained sand and 60 m/h for the coarse-grained sand. These results were the basis for selecting flows for the water-only backwash step during grain displacement studies.

Grain displacement tests

A total of 39 grain displacement tests were carried out. Each test had a unique combination of conditions with respect to (1) filter media fill (fine-grained, coarse grained), (2) type of tracer grains placed in a 2 cm thick layer (fine colored sand, coarse colored sand, small glass beads, large glass beads, anthracite, garnet), (3) placement of the tracer grain layer in the pilot filter (top, middle or bottom) and (4) final water-only backwash step (sub-fluidization, fluidization).

After placing the filter fill and the tracer grain layer in the pilot filter, the filter was backwashed and subsequently sampled to determine the displacement of the tracer grains. A set of three backwash steps (air scour, concurrent air-and-water wash and water-only wash) were used in succession. Thereafter, the filter was run in production mode for 15 minutes at approximately 4 m/h. The entire procedure of backwash and production was repeated 10 times for each test prior to filter media sampling.

Each backwash step had a duration of 5 minutes, preceded by 1 minute to slowly ramp up the flows to avoid sudden pulses disturbing the sand. Air flow was 60 m/h for the air scour and for the concurrent air-and-water wash. The water flow for concurrent air-and-water wash was 10 m/h for fine-grained fill and 15 m/h for coarse-grained fill. The water flow for water-only wash was 40 m/h for coarse-grained fill (sub-fluidization), 20 m/h for fine-grained fill (sub-fluidization), and 40 m/h for fine-grained fill (fluidization).

Filter media sampling

Pilot-scale: Ten discrete-depth samples of 120–150 g were collected from the entire diameter of the pilot filter using a 60 cm long, U-shaped, stainless-steel tool. Following draining of the pilot filter, the tool was inserted through the sampling ports, rotated 360° and withdrawn.

Full-scale: Filter media samples of about 500 g were collected at 20 cm depth intervals from filter beds following overnight draining. A sampling device was constructed with a 1.5 m long 50 mm PVC pipe and a shop vac to lift the sand through the pipe while pressing the pipe slowly into the filter bed. The media was captured in a 500 mL blue-cap flask after cyclonic separation of the filter media grains. To reduce the risk of carryover between depths, filled sampling flasks were replaced with new without raising the PVC pipe from the filter bed.

Physical measurements

Grain size distributions were determined by a photometric particle analyzer using dynamic imaging (Camsizer® 2006, Retsch Technology GmbH, Germany). Porosity was determined volumetrically and particle density was determined gravimetrically.

The number of tracer grains in media samples was counted manually with the help of a 5 diopter, illuminated magnifier with a lens diameter of 127 mm in samples dried overnight at 60 °C. Samples with a high number of tracer grains were divided before counting using a rotational sample divider (PT 100, Retsch Technology GmbH, Germany).

Filter media type (anthracite or quartz) in samples from full-scale waterworks was determined visually after first removing the media coating with a solution of 4M hydrochloric acid with 2 g/L oxalic acid. Gravimetric measurements before and after acid cleaning allowed for the determination of the coating weight.

Backwash air flow in the pilot-scale filter was measured using a direct read 2.5–25 m^3/h rotameter (Yuyao Kingtai Instrument Company, China) and water flow using a magnetic flowmeter (MAG 2500, Danfoss, Denmark). A bed expansion test was carried out in triplicate in the pilot filter during water-only wash. The position of the water/sand interface at the top of filter bed as a function of flow was determined with the help of a ruler and an endoscope.

Statistical moments

The depth distribution of tracer grains was described by the average displacement distance of the tracer grains from their original position (first moment in cm) and the spread of the tracer grain distribution (second moment expressed as standard deviation in cm). The third (skewness) and fourth (kurtosis) moments provided little additional practical insight and are not mentioned further. Equations (2)–(5) below were used, where d is the depth of the individual sand grain, n is the number of tracer grains in a sample from a discrete depth, and N is the total number of tracer grains in all the samples combined. The summation is taken over all 10 sample depths.

$$\textit{average final depth} = \frac{\sum (d \times n)}{N} \quad (2)$$

$$\textit{change in depth} = \textit{original depth} - \textit{average final depth} \quad (3)$$

$$\textit{variance}\ (\textit{var}) = \frac{\sum ((d - \textit{mean depth})^2 \times n)}{n} \quad (4)$$

$$\textit{standard deviation} = \sqrt{\textit{var}} \quad (5)$$

RESULTS AND DISCUSSION

Dual media mixing in full-scale

One of the most conspicuous and unfortunate consequences of grain displacement is the mixing of the two layers in dual media filters. Figure 2 shows selected results from media samples collected from eight operational waterworks.

The grain-size distributions from two operational waterworks (Figure 2(a) and 2(b)) are archetypes of the eight dual media filters. Figure 2(a) is a textbook example showing clear separation of the larger anthracite grains in the top 80 cm of the filter bed and the smaller quartz grains in the lower 60 cm. Figure 2(b) shows the opposite situation in which there is no grain-size difference over depth, indicating complete mixing of the dual media from top to bottom. Note that the bimodal curve clearly indicates the presence of two grain sizes (presumably a larger anthracite and a smaller quartz) in all depths. All but two of the eight dual media filters more closely resembled Figure 2(b). The authors' experiences indicate that the sand grain size and backwash flow rates used at these waterworks are typical for Danish waterworks using dual media, suggesting that dual media mixing is common in Danish full-scale filters.

To verify this surprising result, the filter media type in each depth sample was determined visually after removing the coating from the grains with acid. This was necessary since the grain size distribution alone cannot confirm whether the large grains are anthracite or quartz with a thick coating. Figure 2(c) shows qualitatively that most of

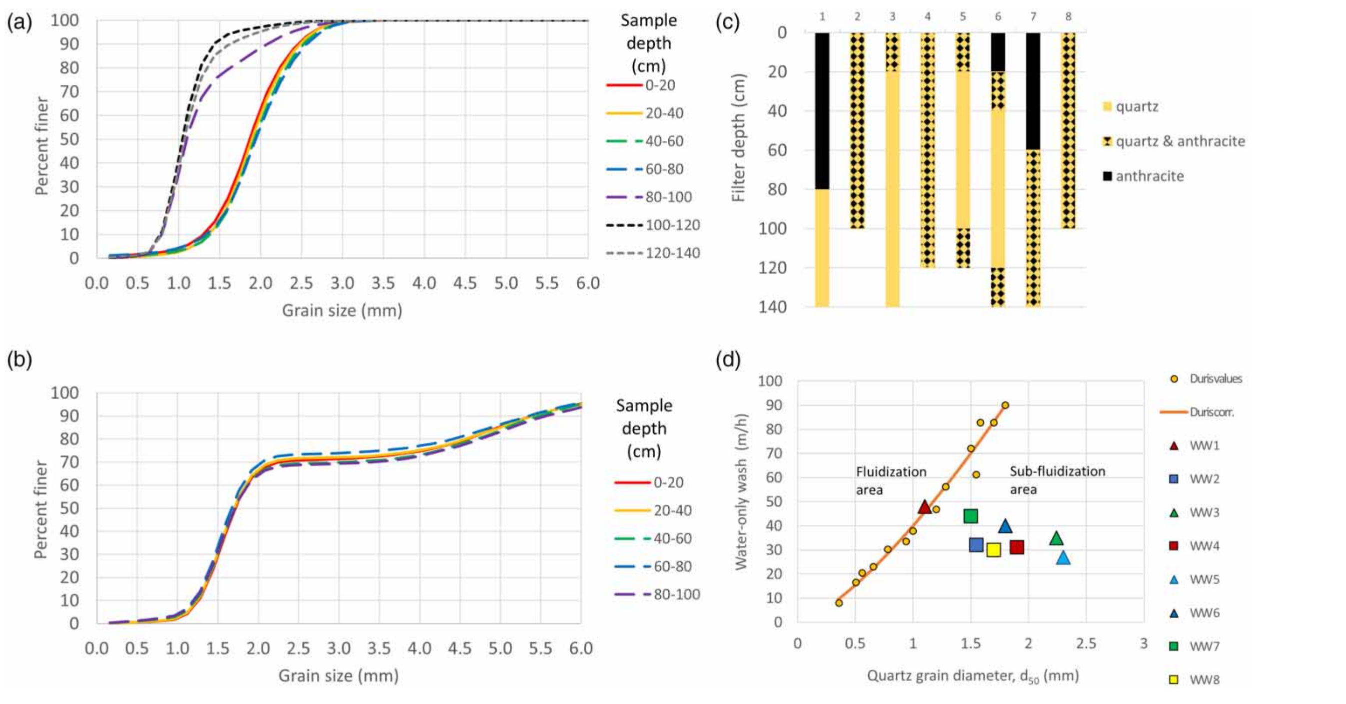


Figure 2 | Full-scale filter media samples. (a) and (b) Examples of grain-size distributions (Waterworks 1 and 2). (c) Type of filter media, determined visually. (d) Fluidization status during final backwash step (includes data from Duris *et al.* 2016).

the waterworks filters did indeed exhibit significant mixing of the anthracite and quartz dual media, in general supporting the conclusion of the grain size distributions.

Figure 2(d) shows the relationship between the flow used for the final backwash step and the media grain size (for bimodal grain-size distributions, the d_{50} for the quartz grain section of the curve was used). With the exception of Waterworks 1, Figure 2(d) clearly indicates that the minimum fluidization velocity was generally not reached in the final backwash step. Sub-fluidization flows are not expected to allow for the density segregation of the dual media to be restored, should mixing have occurred during a previous backwash step. This result would be consistent with media mixing taking place during the air-and-water wash followed by sub-fluidization water-only wash that does not restore segregation.

It should be noted that the filter media coatings exhibited large variations (not shown) between bed depths and between waterworks (the coatings comprised from 1 to 45 percent of the total weight of the grains). As the weight of the coating increases over time, the difference in density between anthracite and quartz decreases, which may exacerbate the mixing of dual media.

These full-scale results unveil a problem, since mixing of dual media counteracts the very idea of using dual media, (i.e. delaying filter clogging by segregating the anthracite at the top of the filter bed where clogging challenges are greatest when treating iron-laden groundwater).

Movement phenomena

Visual movement of filter media during backwash has been previously studied (Baylis 1959a; Ives 1989; Fitzpatrick 1993). In this study, seven distinct movement phenomena were observed through the Plexiglas window of the pilot filter and are described below in order of increasing displacement.

1. Megapore rotation (Figure 3(a)): voids of 0.5–1 cm (similar to lenticular voids described by Ives 1989) were formed during the first 0.5 minute of the air scour step. The megapores were partially interconnected (similar to wormholes described by Ives 1989) allowing for the upward passage of air. Grains were observed to rotate within the megapores, causing slight displacement.
2. Wobbling: The top layer (20 cm) of the pilot filter was observed to wobble slightly from side to side as a unit especially during the air-and-water step. This phenomenon results in only small net displacement.
3. Sand boiling (Figure 3(b)): This phenomenon is easily observed at the media surface in open gravity filters during an air scour step. Media grains erupt from the surface into the standing water above the media. In this study, observations through the Plexiglass window of the pilot-scale filter established that grain displacement is confined to the top few centimetres.
4. Crack crawling (Figure 3(c)): Horizontal cracks partially filled with air appeared during the water-only wash when air trapped in the filter from the previous backwash step collected in distinct entities. The cracks were observed to slowly crawl upward as grains on the roof of the crack collapsed to the crack floor. This appeared to be an important mechanism for removing trapped air prior to the subsequent filter run.
5. Subsidence (Figure 3(d)): This very slow downward bulk movement replaces medium that has been displaced upward from lower levels as a result of jetting and other movement phenomena.
6. Jetting (Figure 3(e)): Flows far greater than the average cross-sectional flow were occasionally observed in narrow columns (5–10 cm) within the filter bed during the final water-only wash, causing significant upward displacement of grains in limited areas.
7. Bulk circulation (large scale mixing): Filter media spanning the entire pilot filter observation window was seen to move upward as a unit during water-only wash. Although it was not observed due to the absence of an observation window in the core of the filter, the grains must have returned to the bottom of the window in a different portion of the filter. This phenomenon is likely due to heterogeneous flow of water leaving the support layer but may also in part be an artefact of the pilot filter dimensions.

It should be noted that no collapse pulsing movement phenomena as described by Amirtharajah (1993) were observed despite the use of a wide variety of concurrent air and water flows.

The plethora of movement phenomena indicates that grain displacement is more complex than simple macro-

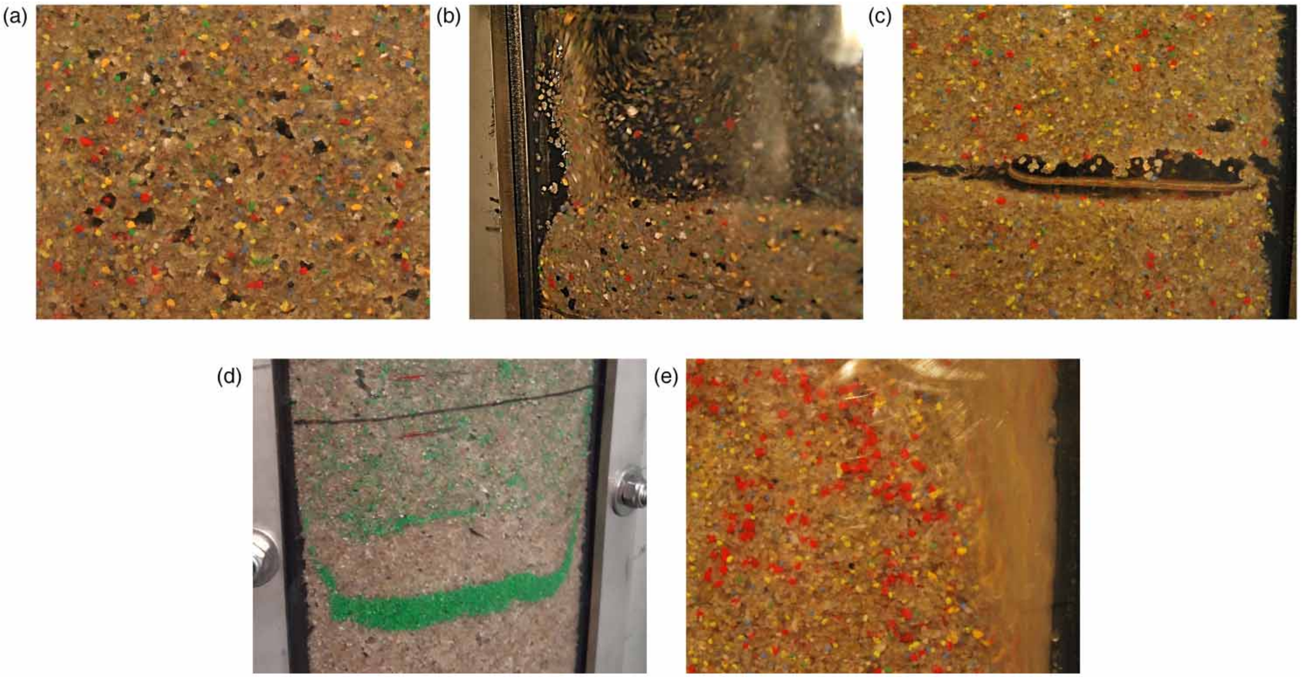


Figure 3 | Filter media movement phenomena observed during backwash. (a) Megapores, (b) sand boil (side view of top of sand with sand boil on left side of photo), (c) crawling crack, (d) subsidence (colored sand originally placed at the black line), (e) jetting (blur on right side of photo – shutter speed 1s).

parameters such flow and bed expansion can reveal. There is a risk that this inhomogeneity of movement may be overlooked in small laboratory-scale set-ups. In modelling, the three phases (solid, water and air) and the inhomogeneities impose nearly insurmountable challenges in determining accurate predictions of grain movement. The approach used here is therefore to refrain from modelling the movement of individual grains. Instead, the final displacement of a specific layer of tracer grains in a pilot-scale filter is described by simply calculating the statistical moments of the resulting distribution of tracer grains.

Grain displacement

Filter media samples were collected from each depth interval of the filter following 10 backwashes. The number of tracer grains in each sample were counted and plotted to visualize the resulting distribution of the tracer grains. Graphs (not shown) were prepared for all 39 displacement tests. An example is seen in Figure 4, in which the tracer grains were near the same size and density as the fill media.

It is clear from Figure 4 that the 10 backwashes spread these tracer grains to some degree all the way to the top of the filter, while the tracer grains were spread only slightly below their original position. Since the physical characteristics of the tracer grains and the fill were nearly identical, the results indicate that mixing of filter media during backwash in general is greater in the top part of the filter (when using sub-fluidization as the final backwash step). This important result must be kept in mind during the interpretation of subsequent displacement tests and has implications for the function of biofiltration in full scale.

Figure 5 shows results of selected displacement tests. Each of the five pairs of graphs highlight certain tracer characteristics (a: same as fill characteristics, b: placement depth, c: size, d: density, e: shape). Each set consists of two graphs, left and right. The average displacement of the tracer grains (first moment) is shown in the left graphs, which are valuable for determining if tracer grains rise or sink in the filter bed. The standard deviation of the tracer grain distribution (second moment) is shown in the right graphs, which are valuable for determining if the emplaced layer of tracer grains spreads out in the filter by mixing with

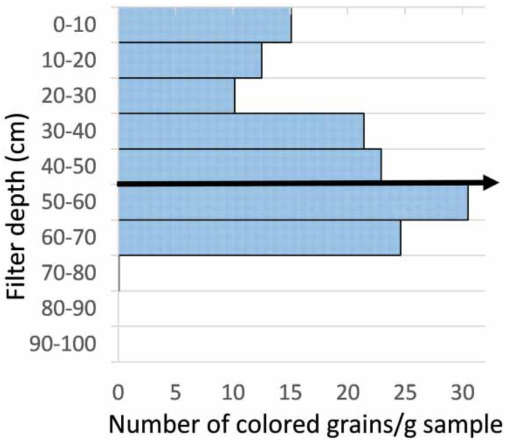


Figure 4 | Depth distribution of tracer grains after 10 backwashes. Test conditions were (1) fill: fine sand, (2) tracer grains: colored fine sand with near-identical grain size and density, (3) placement: 2 cm thick layer in the middle of the pilot filter (heavy black arrow) and (4) final water-alone backwash step: sub-fluidization.

the fill media, thereby becoming 'diluted' or whether the layer remains 'concentrated' in a narrow band.

Figure 5(a1) shows that colored grains in fill with the same size, density and shape show a slightly upward net shift following 10 sub-fluidization backwashes when originally placed in the middle of the filter. This indicates that more mixing within one-media fill occurs in the top half of the filter following backwash with a sub-fluidizing final step (asymmetrical displacement). When backwashed with a fluidizing final step, however, no net shift direction is apparent due to symmetrical displacement. Figure 5(a2) shows that the standard deviation of the colored grains following sub-fluidization backwashes is only in the medium 15–20 cm range, since little spreading to the bottom half of the filter column takes place. Following fluidization, the standard deviation is very great (28.6 cm), indicating full mixing in the entire filter column (a perfectly mixed column would give a standard deviation of 28.7 cm).

Figure 5(b1) shows that the depth at which the tracer grain layer is placed prior to backwashing makes a difference in the direction of the net shift. Due to the boundaries of the filter, tracer grains originally placed in the top of the filter show a downward net shift while the opposite is true for tracer grains placed in the bottom (with the exception of coarse tracer grains, which showed no change in average placement). As previously shown in Figure 5(a1), grains placed in the middle of the filter show a slightly upward net shift, due to greater movement in the top part of the filter. Figure 5(b2) shows that the spreading of tracer grains placed in the top and bottom of the filter is limited (standard deviation about 10 cm) compared to tracer grains placed in the middle of the filter (standard deviation about 18 cm), where displacement in both directions is possible. In general, colored fine tracer grains spread more in fine fill than colored coarse tracer grains spread in coarse fill.

Figure 5(c1) shows the effect of a difference in average grain displacement when the quartz tracer grains have a different size than the fill. Fine tracer grains in coarse fill show a great net tendency to shift upwards on average during backwashing at sub-fluidization flows. This shift is much more pronounced than the shift of fine tracer grains in fine fill (Figure 5(a1)) and is therefore due to the size difference. The shift of coarse tracer grains in fine fill is small, likely because the generally enhanced mixing in the top of the filter balances the tendency of the large tracer grains to sink in the fine fill. Coarse tracer grains in fine fill show a somewhat downward net shift during backwashing at fluidization flows. Figure 5(c2) shows that medium to high spreading takes place when tracer grain size is different to the fill, with the smallest spreading occurring with fine tracer grains in coarse fill (since these grains are unable to spread downward in the filter). Coarse tracer grains in fine fill show significant spreading even though Figure 5(c1) showed no net displacement.

Figure 5(d1) shows the effect on average grain displacement when using tracer grains with varying densities (anthracite and garnet). When using backwash with a final sub-fluidization step, the upward shift of anthracite is no different than colored sand (compare with Figure 5(a1)). At fluidization, however, an upward net shift is seen. Garnet shows a tendency to migrate downward in coarse fill when using backwash with a final sub-fluidization step. Here, it should be remembered that garnet has a smaller grain size as well as a greater density than the fill. At fluidization, a clear downward net shift is seen for garnet. Figure 5(d2) shows the most significant spreading occurs during fluidization.

Figure 5(e1) shows the effect on average grain displacement when using tracer grains (large and small glass beads) with a grain shape that differs from the fill media. Using backwash with a final sub-fluidization step, the net tendency of glass beads to migrate upwards during backwashing is no different

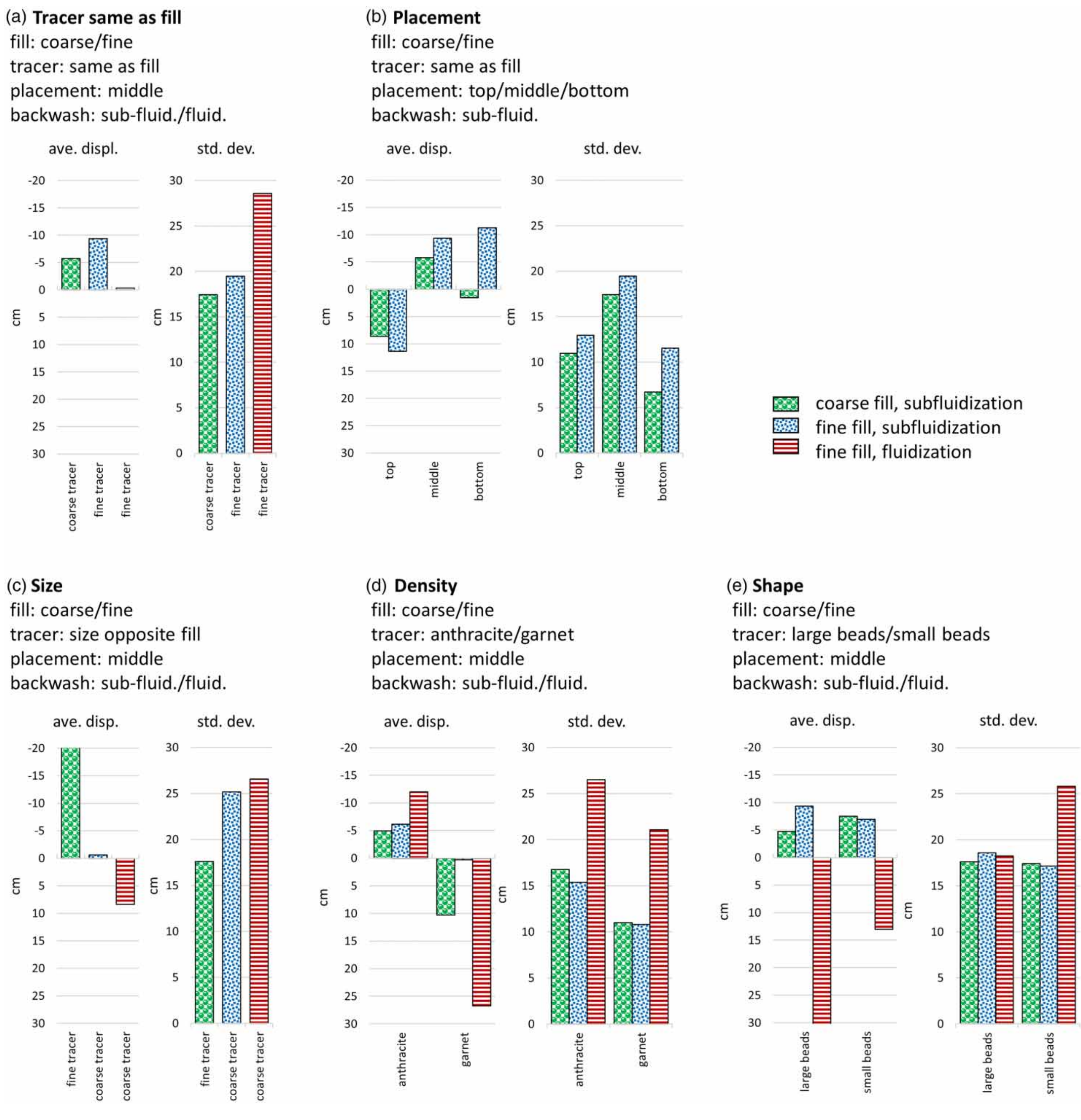


Figure 5 | (1) Average grain displacement (left graphs) and (2) standard deviation (right graphs) of tracer grain distribution after 10 backwashes. Each pair of graphs highlight certain characteristics as follows: (a) tracer same as fill, (b) placement depth, (c) size, (d) density, (e) shape. Conditions of the displacement tests are shown above the individual graphs.

than colored sand (compare with Figure 5(a1)). At fluidization, however, both sizes of glass beads show a downward net shift, with the large beads migrating the most. This is presumably because the highly spherical shape and smooth surface of the beads provides less uplift during backwashing than the less spherical shape and rougher surface of the quartz fill. Figure 5(e2) shows medium spreading of glass beads throughout the filter when using backwash with a final subfluidization step. When using backwash with a final fluidization step, full mixing for small glass beads in fine fill was seen.

CONCLUSIONS

Movement phenomena

Seven different grain movement phenomena were visually observed in the pilot-scale filter during the three-step backwash procedure. It is presumed that these phenomena are also present in varying degrees during full-scale backwash. Collectively, these movement phenomena indicate that grain movement during backwash is highly complex and inhomogeneous in four dimensions, i.e. the horizontal location of the grains with respect to the location of nozzles/slits in the underdrain, the depth of the grains in the filter bed and the elapsed time of the individual backwash step.

This inhomogeneous movement undermines the value of parameters that use average conditions such as backwash flow rate and bed expansion. Therefore, these parameters are inadequate metrics for describing movement phenomena or grain displacement during full-scale backwash. Inhomogeneous movement also has ramifications for the small diameter filters used in many laboratory experiments. Although small diameter filters may provide more homogenous flows, results from such experiments are not likely to represent full-scale conditions.

Sub-fluidization displacement

When using a backwash procedure concluding with a sub-fluidization water-only wash, grain displacement was still apparent. In general, the top half of a granular filter was mixed more than the bottom half.

With the exception of fine quartz in coarse fill, grain displacement was largely independent of size, density and shape differences in grain characteristics. This supports the full-scale finding at six of eight waterworks in which dual media filters (coarse anthracite and fine quartz) were found to be mixed at all depths. This mixing of media types in dual media filters is normally considered counterproductive. Further investigation is recommended to quantify the extent to which this mixing may aggravate premature clogging during a filter run.

Air bubbles have the potential to create problems during a filter run by blocking pore spaces and creating headloss during normal filter operation. Observations of the grain movement phenomenon 'crack crawling' showed that a significant amount of trapped air was removed from the filter media in the pilot filter during water-only wash at sub-fluidization flows. However, removal of trapped air may be incomplete when sub-fluidization flows are used.

Fluidization displacement

When using a backwash procedure concluding with a fluidization water-only wash, spreading of the tracer grain layer was generally much greater than backwashing with a sub-fluidization flow. Partial segregation (downward net shift) was seen for garnet and large glass beads. For the other tracer grains, fluidization caused a high degree of mixing, defined as standard deviation >25 cm.

Practical implications

The results obtained in this study have direct practical implications, since it appears impossible to achieve aggressive cleaning of a clogged filter while avoiding grain displacement.

Firstly, evidence for potential optimization of the backwash process has been obtained. For example, the air scour step showed grain movement only at the surface of the media (sand boiling) or during the first 0.5 minutes of the backwash with very little subsequent movement (megapore rotation). This suggests that extended air scours are without significant cleaning value. Instead, short combinations of air scour followed by concurrent air-and-water wash that are repeated may be much more efficient.

Secondly, if grain displacement must be avoided, then solutions involving multi-stage filtration design are needed to physically divide the filter media in separate filters. Avoiding grain displacement may be especially relevant for biofilters treating groundwater sources. Here, grain displacement may impair the biologically mediated removal of biodegradable organic matter (BOM), ammonium and manganese, since formation of filter media stratification may be counteracted by diluting filter media that is well-suited for substance removal with filter media from a less suitable layer. In colder climes, slow-growing bacteria such as nitrifiers may benefit from avoiding displacement from their proper stratum. Conversely, grain displacement may improve the robustness of the biofilter by ensuring that at least some removal capacity for all substances is relocated to all depths.

Finally, using the backwash procedure that was observed in Denmark for dual media filters and which consists of a concurrent air-and-water wash (that mixes the media) and a subsequent sub-fluidization water-only wash (that fails to re-stratify the media) should perhaps be abandoned. On the positive side, it should be noted that this practice has allowed for the use of larger grain sizes (extends filter runs) as well as larger underdrain strainer openings (reduces the risk of clogging and lowers headloss). It has also allowed for lower backwash water flows (reduces water loss and requires smaller backwash pumps). Despite these advantages, this backwash procedure results in unwanted mixing of the media types. To achieve better backwash performance, solutions may include the use of larger backwash flows, smaller grain sizes or lighter media types to ensure fluidization re-segregates the two media or a return to designs using single media filters.

ACKNOWLEDGEMENTS

This project was financed in part by The Environmental Technology Development Program (MUDP) in connection with the project 'Smart Re-design of Drinking Water Production'. The authors acknowledge the project collaborators: Aarhus Water, VandCenter Syd, Dansk Kvarts Industri, Vand & Teknik, NIRAS, Amphi-Bac and VIA University College.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 27 June 2020; accepted in revised form 23 October 2020. Available online 6 November 2020