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Interface stability of granular filter structures under currents

Henk VERHEIJ[1], Gijs HOFFMANS[2], Kees DORST[3], Stefan VANDESANDE[4]

[1] Delft University of Technology and Deltares
Rotterdamseweg 185, 2600 MH Delft, The Netherlands. Email: h.j.verheij@tudelft.nl

[2]Deltares
Rotterdamseweg 185, 2600 MH Delft, The Netherlands. Email: gijs.hoffmans@deltares.nl

[3]Rijkswaterstaat
Griffioenlaan 2, 3526LA Utrecht, The Netherlands. Email: kees.dorst@rws.nl

[4]Delft University of Technology
Stevinweg 1, 2628 CN Delft, The Netherlands. Email: stefan_van_de_sande@hotmail.com

Granular filters are used for protection of structures against scour and erosion. For a proper functioning it is necessary that the interfaces between the filter structure, the subsoil and the water flowing above the filter structure are stable. Stability means that there is no transport of subsoil material through the filter to the water above the filter, and there is no filter material removed by the currents above the filter. In principal, two types of granular filters can be distinguished, based on the two criteria enabling erosion: (1) base material can pass the pores in the filter material, and (2) hydraulic load is larger than threshold value: - geometrically sand-tight filters: no transport of base material is possible due to pores in the filter too small to allow base material to pass,- hydrodynamically sand tight filters: the hydraulic load at the interface is less than the threshold value of the base material.

In the past various design methods have been published, amongst others by Wörman (1989) for a stable riprap protection at bridge piers without filters, and Bakker et al (1994) with respect to more general riprap protections without filters. All formulas are based on a limited number of tests. Recently, a desk study has been carried out focusing on two particular aspects: 1. interface stability as function of the thickness of the filter layer consisting of standard armour stone gradings, and 2. interface stability of gravel mixtures with a wide gradation.

Based on a theoretical approach the study resulted in a new design formula for geometrically-open but hydrodynamically sand tight granular filter structures under currents. The new formula relates the required filter layer thickness to a characteristic diameter of the filter material taking into account the influence of the grading of filter and base material, the influence of turbulence and the damping of the hydraulic load in the filter. Laboratory experiments were carried out to validate the new formula. The paper presents the new design formula including the derivation. Furthermore, experimental set-up, test program and measurements of the laboratory experiments are presented.

Key words

Filter, granular filter, interface stability, bed protection, riprap.

I INTRODUCTION

Granular filters protect the underlying soil, i.e. the base layer, from erosion by flow induced loads (static and fluctuating components from turbulence). The approach flow velocity or water level difference produces the static load over hydraulic structures, whereas the fluctuating load reflects the turbulence caused by the geometry of the structures or by the roughness of the top layer. The erosion resistance (or strength) of granular filters is mainly characterized by the geometrical properties of the materials used.

The following types of filters can be distinguished with respect to the retention criterion, based on the two criteria enabling erosion: (1) Base material can pass the pores in the filter material, and (2) Hydraulic load is larger than threshold value:

- *Geometrically closed (sand-tight)* filters: no transport of base material is possible
- Stable *Geometrically-open (sand-tight)* filters, also called hydrodynamically sand tight filters: the hydraulic load is less than the threshold value for incipient motion

- Instable Geometrically-open or *transport filters*: the hydraulic load is occasionally larger than the threshold value

For the geometrically closed filters well-known criteria have been determined, for example the Terzaghi and Peck (1948) criterion $d_{f15}/\ d_{b85} < 4$ where d_{f15} is the particle (or grain) diameter in the filter layer for which 15% of the mass of the particles is smaller than d_{f15} [m], d_{b85} is the particle (or sand) diameter in the base layer for which 85% of the mass of the particles is smaller than d_{b85} [m].

For the geometrically-open filters no generally accepted design equation is available. For this condition the results derived by Klein Breteler (1989) can be applied. The main input variable for this equation is the hydraulic gradient parallel to the filter. Wörman (1989) investigated granular filters at bridge piers. In the vicinity of these hydraulic structures the flow is more turbulent than the flow in uniform flow. Based on accepted theories he arrived at the relation for the minimum thickness D_F of a filter layer. Bakker et al. (1994) discussed a filter model that includes near-bed pressure fluctuations and also presented a design equation for the filter thickness. Recently, Hoffmans (2012) presented a new design formula based on a theoretical approach. This equation will be discussed in Section II, and in the next sections validation tests at Delft University of Technology are described.

Finally, a design method for the last filter type, e.g. transport filters, differs from that for the other two. Relevant is the total amount of eroded material as function of the hydraulic load (duration and magnitude) during the life time of the filter structure. These filters are not treated in this paper.

II NEW GRANULAR FILTER DESIGN FORMULA

Granular filters may fail by two mechanisms (Figure 1):

- shear failure, which refers to failure due to entrainment of stones on top of the filter by the local flow field;
- winnowing failure, which is related to erosion of the finer underlying base material through the voids of the coarser filter material.

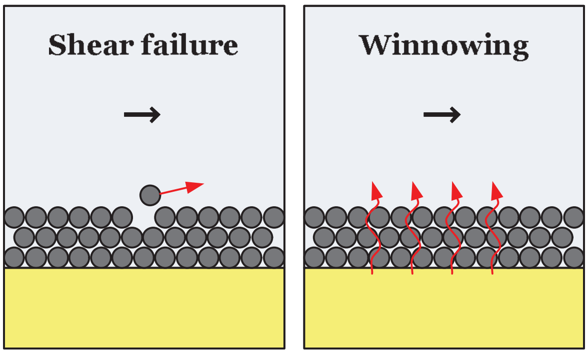

Figure 1: Failure mechanisms

The first failure mechanism have been thoroughly investigated in the past and is subject of various design guidelines. Stability equations are based for example on the Shields (1936) or Izbash (1970) equations. Filter criteria such as the Terzaghi and Peck (1948) criterion address the second failure mechanism. However, an optimal design is based on instantaneous instability of the filter material at the water-filter interface and the base material at the filter-base interface.

Starting point for the derivation of the new formula was the filter model as presented by Bakker et al. (1994) and a paper by Hoffmans et al (2000) in which the shear stress concept in a granular filter is discussed in a horizontal one-layer filter with a thickness (D_F) above the base material in open channel flow (Figure 2). The figure shows on the left side the structure considered and on the right side the flow velocity distribution and the shear stress distribution over the vertical. At the transition of flow and filter layer the flow velocity is lower than the average flow velocity in the flow, whereas the shear stress goes to a maximum value. Inside the filter the flow velocity has a constant value which is lower than in the flow; the shear stress decreases to a minimum value and even zero if there is no flow velocity gradient. At the transition between filter and base material the flow velocity decreases again and the shear stress increases.

The derivation of the new formula resulted in the following equation (Hoffmans, 2012):

$$\frac{D_F}{d_{f15}} = \alpha_d \ln\left(\frac{d_{f50}}{d_{b50}}\frac{\Delta_f}{\Delta_b}\frac{\Psi_{c,f}}{\Psi_{c,b}}\frac{1-\gamma V_f}{1-\gamma V_b}\right) \tag{1}$$

Where d_f is the diameter of the filter material, d_b is the diameter of the base material, V_i is the variation coefficient that represents the influence of the non-uniformity, γ is determined by an allowable transport of the bed material, Δ is the relative density, Ψ_c is the critical Shields parameter. An earlier result was published in CUR (2010).

Assuming that $d_{f50}/d_{f15} \approx 1.25$, $\Delta_f = \Delta_b$, $\Psi_{c,f} = \Psi_{c,b}$, $\gamma V_f = \gamma V_b$, and $\alpha_d = 1.5$, Eq. 1 becomes:

$$\frac{D_F}{d_{f50}} = \frac{d_{f15}}{d_{f50}}\alpha_d \ln\left(\frac{d_{f50}}{d_{b50}}\right) = 1.2\ln\left(\frac{d_{f50}}{d_{b50}}\right) \tag{2}$$

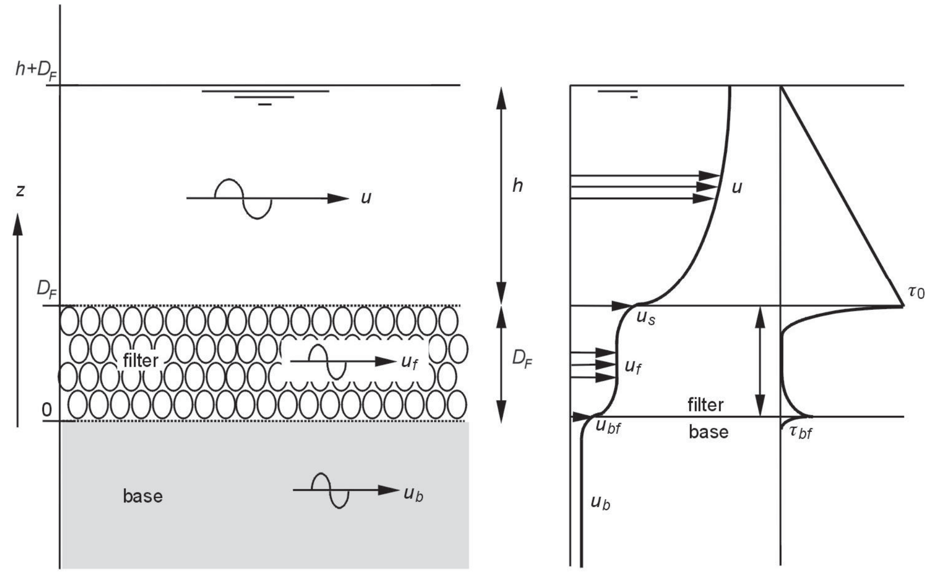

Figure 2: Distribution of the flow velocity and the shear shear
(D_F = filter thickness, h = water depth, u = flow velocity, τ = shear stress)

Wörman (1989) investigated granular filters at bridge piers. In the vicinity of these hydraulic structures the flow is more turbulent (the depth-averaged turbulence intensity varies from 0.15 to 0.25) than the flow in uniform flow. His research resulted in:

$$\frac{D_F}{d_{f15}} = 0.16\frac{n_f}{1-n_f}\frac{d_{f85}}{d_{b85}}\frac{\Delta_f}{\Delta_b} \tag{3}$$

where n is the porosity of the filter material.

If $d_{b85}/d_{b50} = d_{f50}/d_{f15} \approx 1.25$, $n_f = 0.4$, and $\Delta_b = \Delta_f$, then Eq. 3 reads

$$\frac{D_F}{d_{f50}} = 0.085\frac{d_{f50}}{d_{b50}} \tag{4}$$

Implicitly, it is assumed in the above equations that the penetration in the filter layer of the hydraulic load decreases with increasing depth in the filter:

$$\eta = \frac{k_f(z)}{k_b} \approx \exp\left(\frac{z}{L_d}\right) \tag{5}$$

With : $$k_f(z) = k_b \exp\left(\frac{z}{L_d}\right) \text{ and } k_b = \tfrac{1}{2}\left[u_{\mathrm{RMS}}^2 + v_{\mathrm{RMS}}^2 + w_{\mathrm{RMS}}^2\right] \tag{6}$$

where $k_f(z)$ represents the turbulent energy in the filter, k_b is the bed turbulent energy, L_d is a damping length related to the load penetration in granular filters, and u_{RMS}, v_{RMS} and w_{RMS} are the root mean square values of the local fluctuating velocities in the x, y and z directions. Klar (2005) carried out measurements of the turbulent energy in the filter layer and his results proved the decreasing load penetration. The results of these measurements were used in this study to derive the new filter criterion.

Since turbulence is related to the particle size, it is assumed that the damping length is a function of the particle size:

$$L_d = \alpha_d d_{f15} \tag{7}$$

Bakker et al. (1994) made a similar assumption by relating the load penetration or relative load (η) at the transition of the filter-base layer to a turbulence parameter (C_0) and the relative roughness d_{f15}/R_h:

$$\eta \equiv \frac{C_0 d_{f15}}{R_h} \tag{8}$$

where R_h is the hydraulic radius of the flow. The ratio d_{f15}/R_h was chosen to compare the size of the filter material with the size of the large eddies in the flow that were considered to be responsible for the turbulence. However, Eq. 8 lacks information about the damping of the load penetration in the filter layer.

Bezuijen and Köhler (1996) investigated the load penetration of wind and ship waves in flexible revetment structures such as rip-rap and placed block revetments. Based on the storage equation they found for the damping length

$$L_d = \sqrt{\frac{T_p c_v}{\pi}} \tag{9}$$

where T_p is the pressure period and c_v is the consolidation coefficient. Although Eq. 9 is deduced for wave periods larger than T_p = 1 s, the damping length can also be predicted for T_p < 1 s, for example, for uniform and non-uniform flow.

Figure 3 shows Eq.2, and Wörman's equation Eq. 4. Moreover, experimental data are plotted for both uniform flow (Van Huijstee and Verheij 1991, Dixen et al. 2008) and non-uniform flow (Wörman 1989). The envelop curve should be considered as a first conservative approximation with α_d = 1.5. Obviously, the flow velocity at the top of the filter or at the top of the base material is higher than the threshold velocity for base or filter material and depends on the characteristics of the materials.

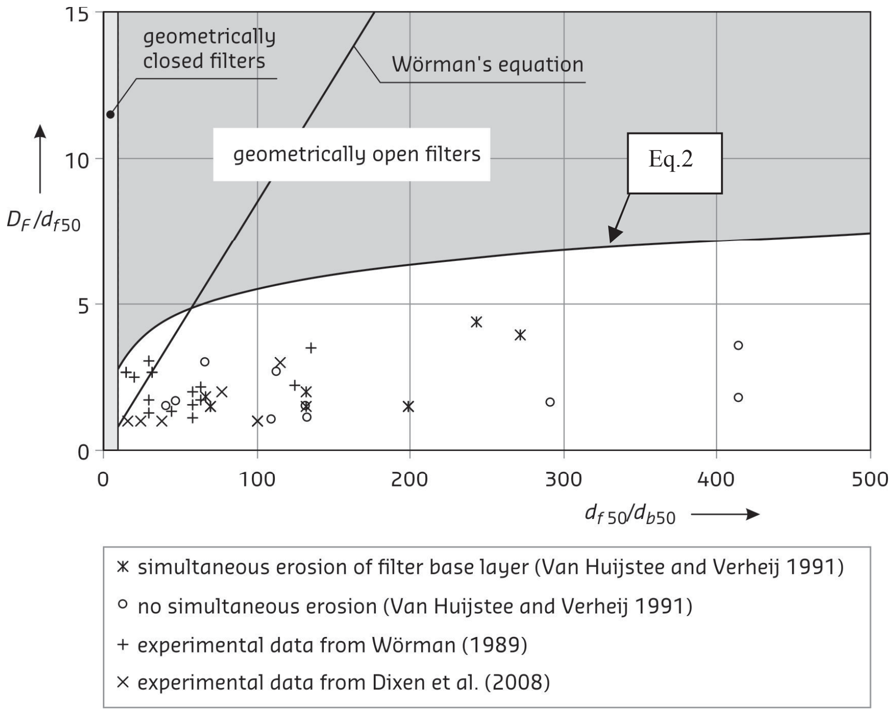

Figure 3: D_F/d_{f50} versus the critical d_{f50}/d_{b50}; Design equations 2 and 4

(note: regarding the experimental data of Wörman (1989) and Dixon et al. (2008) it is unknown whether or not there was simultaneous or no simultaneous erosion of filter and base material)

Although characteristic values for both loading and strength are included, the resulting relative strength and the resulting relative load are independent of the fluctuations in the loading. There are two reasons for this rather unexpected result; first it is assumed that both filter and base material will display initial movement under the same loading conditions. Second, fluctuations in the load exert a load on the filter material similar to that on the base material.

Finally, it is noted that the interesting region for designing and assessing geometrically open filters in non-uniform flow is the stable part that lies above Eq. 2 and adjacent to the zone representing geometrically closed filters.

III SETUP OF LABORATORY EXPERIMENTS

The validation tests have been performed in a flume in the Fluid Mechanic Laboratory of Delft University of Technology. The flume has dimensions of 12m x 0.4m; see Figure 4. The maximum water depth is 0.4m. The maximum discharge is 0.1 m^3/s. No waves were applied.

In the flume two test sections were constructed with a filter layer on top of base material. The median grain size d_{50} of the filter material was 7.1 mm, 15.1 mm and 21.3 mm. Two base materials were used with d_{50} is 309 μm respectively 633 μm.

Figure 4: Flume with test set-up in the laboratory at Delft University of Technology

The flow velocity in the flume was increased step by step with steps of about 0.1 m/s in the first steps and decreasing to 0.05 m/s near the threshold values. Flow velocities were measured with an ADV (Acoustic Doppler Velocity meter) device.

The transport of base and filter material was measured after each step. Transport of filter material has been counted visually. Therefore, in a section of the model coloured stones were placed. The transported base material was gathered in a sand trap at the end of the flume and measured after each step. The sand trap consisted of a stack of sieves (box with a geotextile with an opening size 0.106 mm) with one sieve for each flow step. This enabled to determine the transport of base material for each step. The duration of each step was one hour.

The damping of the turbulent fluctuation in the filter layer was done with four pressure meters. They were placed in two pairs at the transition between the base and filter layer and at the top of the filter layer. Thus, at two locations they measured the pressure differences over the filter. Unfortunately, the measurements could not be used because the presence of the pressure gauges in the filter disturbed the measurements resulting in large scatter and conflicting results.

Validation of the design formula required variation of at least the relevant parameters, viz.:

- ratio between the filter material and the base material d_{f50}/d_{b50}
- layer thickness D_F

Originally, tests were scheduled with wide graded base and filter material. However, due to a lack of time these tests were skipped. This resulted in the test program as shown in Table 1. All tests were carried out with normal turbulence in the flow, except the tests T-06b and T-06c. In test T-06b the turbulence level was increased using a sill upstream of the test section with a height of 65mm. In test T-06c various tests with piers were carried out: a circular pier with diameter 110mm, and square piers with a width normal to the flow of 40mm and length of 65mm and 90mm. These tests have been done to get an idea of the effect of turbulence on Eq.2. However, transport of material during both tests was not measured.

Test	d_{b50} base [μm]	d_{f50} filter [mm]	d_{f50} / d_{b50} [-]	D_F / d_{f15} [-]	Thickness D_F [mm]	remark
T-01	309	7.1	23.0	3.29	20	
T-02	309	21.3	68.9	1.44	27	
T-03	309	21.3	68.9	3.29	61.5	
T-04	633	21.3	33.6	1.44	27	
T-05	309	15.1	49.0	0.57	8	
T-06a	309	15.1	49.0	3.01	40	
T-06b	309	15.1	49.0	3.01	40	High turbulence due to sill
T-06c	309	15.1	49.0	3.01	40	High turbulence due to piers
T-07	309	15.1	49.0	4.13	57	

Table 1: Tested situations

IV TEST RESULTS

Figure 5 shows some results of the tests carried out. On the left side transport of filter material is shown; on the right side the measured transport of base material as function of the flow velocity. Since the derivation of Eq.2 is based on the assumption of simultaneous transport of base and filter material, the test results will be split up in three categories (see Figure 6):

- Base material moves at a lower critical velocity then the filter material (below Eq.2);
- Base and filter material starts to move at about the same critical velocity (zone around Eq.2);
- Filter material moves at a lower critical velocity then the base material (above Eq.2).

This procedure enables to validate the design formula, and if necessary to make changes to the design formula or values of parameters within the design formula.

Figure 5a Transported filter material (black arrow indicates flow direction)

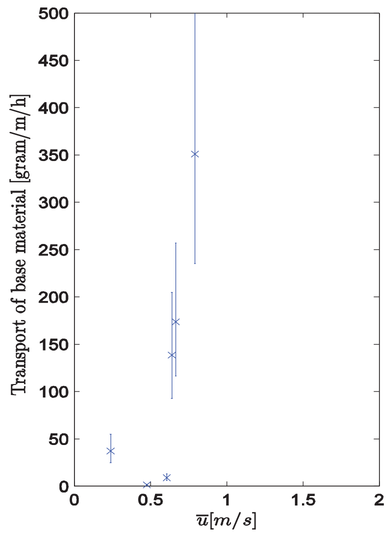

Figure 5b Transported base material, T02

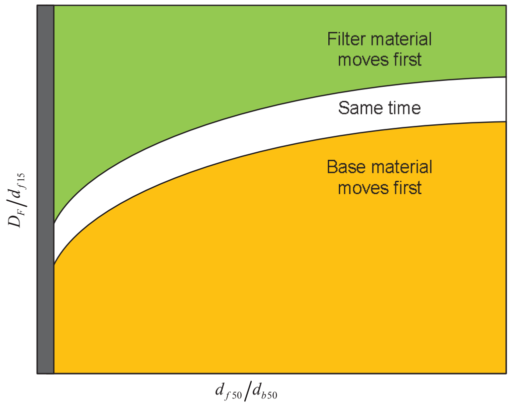

Figure 6 Principle behind Eq.2 regarding transport of filter material and base material

The test results are summarized in Table 2 showing the critical flow velocities for base and filter material as observed and the observed type of transport as explained above.

Test	$U_{c,b}$ [m/s]	$U_{c,f}$ [m/s]	Observed type of transport
T-01	> 0.65	0.65	filter material moves first
T-02	0.65	> 0.65	base material moves first
T-03	0.85	0.85	base and filter material move at the same moment
T-04	0.90	0.90	base and filter material move at the same moment
T-05	-	-	base material moves first
T-06a	0.90	0.90	base and filter material move at the same moment
T-06b	-	-	base material moves first
T-06c	-	-	base material moves first
T-07	>0.80	0.80	filter material moves first

Table 2: Test results

The above mentioned procedure enables to validate the design formula, and if necessary to make changes to the design formula or values of parameters within the design formula. Figure 7 shows the result of this validation. As can be seen, the value of the coefficient α_d is closer to 0.9 instead of the assumed value of 1.5. The figure also contains results of tests by Wörman (1989) and Dixen et al (2008) and ''other'' tests among which the ones of Van Huijstee & Verheij (1991).

Regarding the tests with the higher turbulence it can be concluded that the base material started to move at much lower flow velocities, which is quite obvious. This means that the penetration depth into the filter of the combined effect of a lower flow velocity and a higher turbulence level is larger than for conditions with a "normal" turbulence. It means that a thicker filter layer is required for a stable open granular filter.

V CONCLUSIONS

Laboratory experiments were conducted to validate a new design equation for stable open granular filters under currents. Therefore, test sections were installed in a flume at Delft University of Technology. In total nine tests were performed with different flow velocities, different thicknesses of the filter layer, and different ratios of characteristic filter diameter and characteristic base material diameter. The transport of filter and base material was measured.

The test results confirm the new design equation, Eq.(2). Moreover, earlier test results of Van Huijstee and Verheij (1991) and Wörman (1989) are confirmed.

However, only a limited number tests has been carried out for conditions with a high turbulence level such as downstream of backward facing steps and at piers. Furthermore, the effect of wide graded materials has not been investigated. Also wave conditions have not been investigated, while in principle, the new formula can count for the influence of the wave period via the damping length of the pressure penetration in the filter. Therefore, additional validation is recommended for situations with wide graded materials, high turbulence and with waves. Detailed measurements of the decrease of the turbulence in the filter will increase the insight in the governing processes.

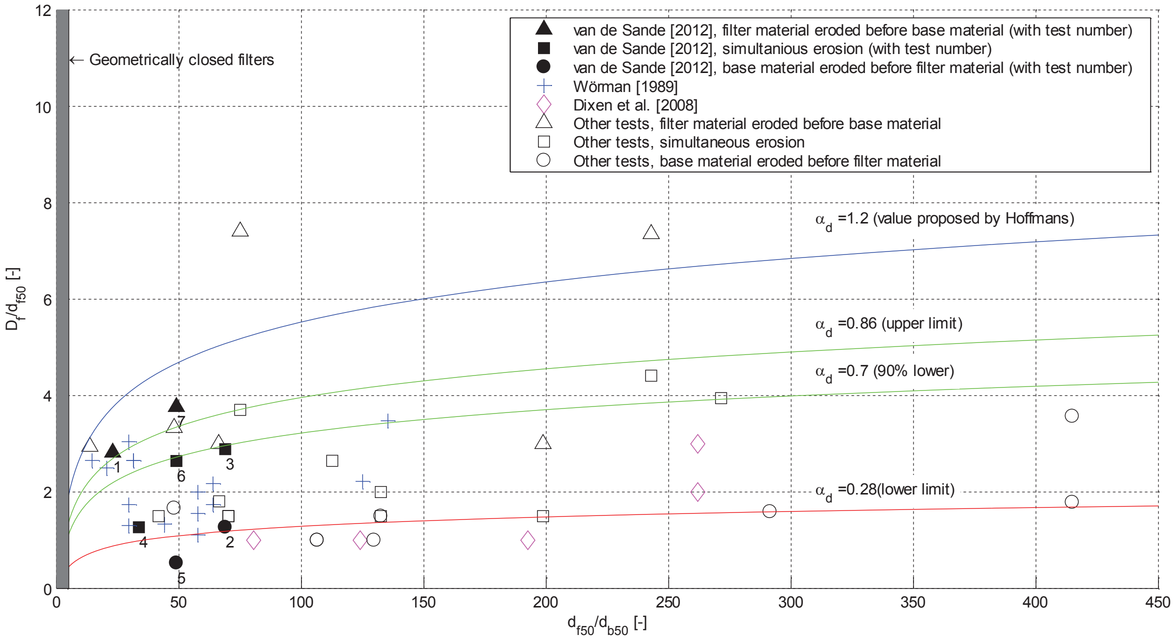

Figure 7: Movement of filter material and base material

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