Determination of the discharge capacity of buckled PVD’s

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ABSTRACT: Small important details, or lack of details, of the current testing procedures for the testing of the buckled discharge capacity of prefabricated vertical drains can have a large influence on the measured discharge capacities. It is shown that for specific types of prefabricated vertical drains there is large difference between the discharge capacity of a single sharp kink and three sharp kinks. This is partly due to the shape of the core, but mainly addressed to the quality of the filter in relation to the fixation of the filter to the core, leading to a particular collapse and thereby blocking the channels. The practical problem of air blocks is also addressed as currently there is no standardized method of removal. The statements are supported with test results of various drain types.

Keywords: Prefabricated vertical drain, Discharge capacity, Buckled testing, EN-ISO 12958

1 INTRODUCTION

The most important parameter and characteristic of a prefabricated vertical drain (PVD) is the discharge capacity and its ability to maintain these characteristics in time and under deformation. After the installation of a PVD, water is discharging from compressible soil layers. This discharge of water causes a vertical deformation of the soil layers and deforms the PVD, resulting in buckling, kinking or folding of the PVD, see Figure 1. This deformation will reduce the discharge capacity. It is therefore important to know how a PVD behaves in folded, kinked, buckled and other deformed conditions while it could affect the consolidation process when the discharge capacity is highly reduced. The extent of the reduction of the discharge capacity is depending on the quality of the PVD. Small important details, or lack of details, of the current testing procedures can have a large influence on the final results of the test. This article focusses on the effect and influence of the specimen preparation on the discharge capacity for buckled testing. The statements made are supported by laboratory test results. All tests were performed in the laboratories of Geotechnics with over 15 years of experience in the testing of PVD. All results have been shared with the ISO TC221 WG 4 committee that prepares the CD 18325, a new standard for the testing of vertical drains.

2 DEFORMATION OF PREFABRICATED VERTICAL DRAINS DURING LIFETIME

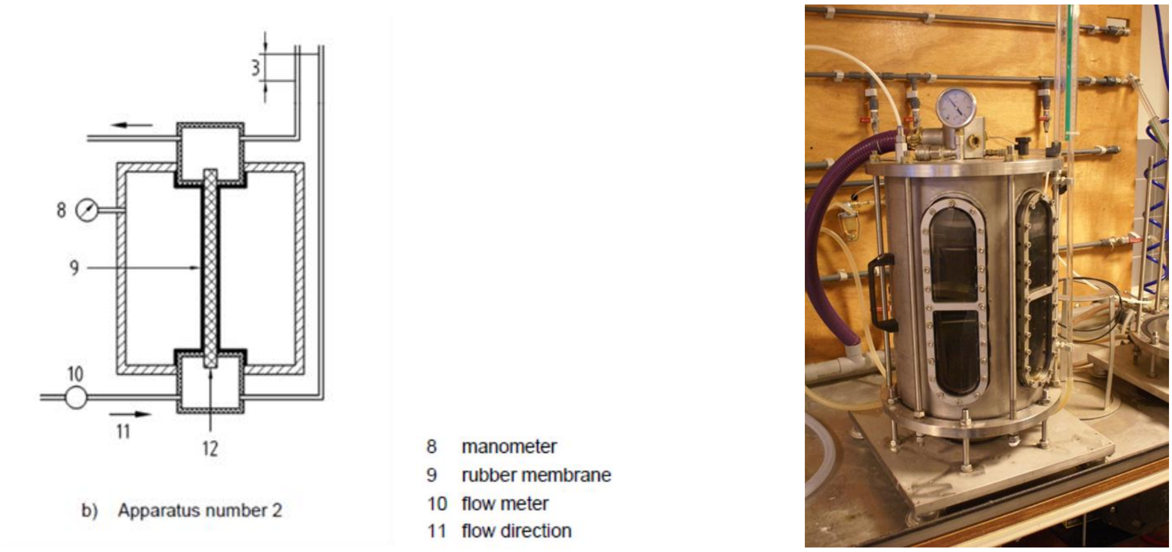
Prefabricated vertical drains (PVD’s) are used to accelerate the consolidation of soft compressible soils. The only period the drains are straight inside the soil is immediately after the installation. The moment the settlement starts to occur, the PVD will deform with the soil and the information of the discharge capacity in buckled, folded or kinked condition will become governing over the straight characteristics, especially in the very soft compressible soils like peat or sludge.

The deformation of the soil and drain is expected to be the largest near the top of the compressible layer as the effective pressure increase is, at this location, the largest. Volume reductions of up 60% are not uncommon. Figure 1 gives an example of a deformed PVD and shows at least three sharp kinks of the drain. When no connection is made with a permeable layer at depth, which is the case in the Netherlands, all the consolidation water is forced through this highly deformed section of the drain towards the draining working platform. It is therefore important to know how much the discharge capacity of the vertical drain is reduced in these highly deformed conditions. This can be determined using standardized methods, like the one described in EN 15237. They have been developed to simulate the deformation at a laboratory scale and measure the "buckled discharge capacity" in time. In the following sections, this method of testing and the specimen preparation to simulate the actual conditions is elaborated.

Figure 1. Drain in buckled conditions after consolidation in peat as shown in the EN 15237

3 TEST EQUIPMENT

In the laboratories in Amsterdam, the "buckled discharge capacity" is determined in a pressure cell with water (apparatus 2 in the EN 15237). The installation in a pressure cell with water has many advantages over the use of foam-foam pressure in the ASTM test (apparatus 1 in the EN15237) as the risk of bridge formation of the foam on the rigid elements of the core is avoided. The used pressure cell is shown in the drawing (a) and picture (b) given in Figure 2. The main principle of the apparatus is the simulation of the soil conditions acting on the PVD by the use of a membrane sealed PVD in a pressurized water cell. The cell is pressurized to a defined pressure and the flow of water through the specimen is measured at a defined head loss (number 3 in Figure 2 (a)). The PVD can be inserted in straight and buckled condition. The measurements are taken during and over a standardized period and are used for the determination of the discharge capacity in time. The results of the test give a good insight into the long-term behavior of a vertical drain.



(a)

(b)

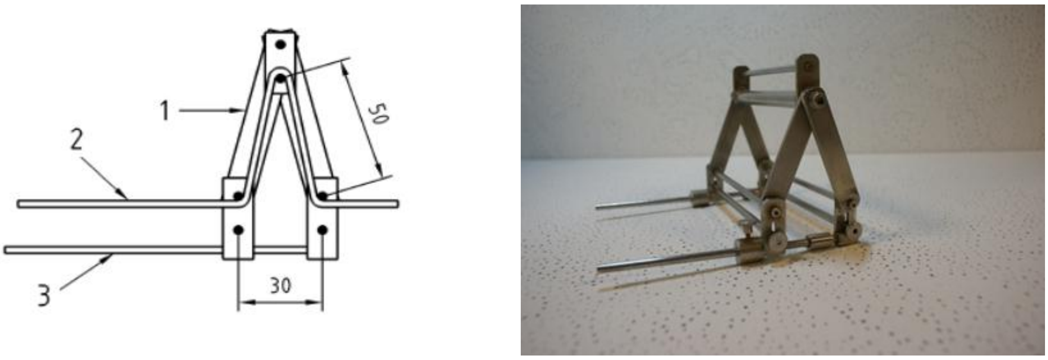
Figure 2. Apparatus a depicted in the EN 15237 (a) and the actual apparatus (b).

4 PREPARATION OF BUCKLED SPECIMENS

4.1 *Preparation procedure*

The EN 15237 is showing, as an example, a device which could be used to fold or kink a PVD specimen for use in the pressure cell. The graphical image of this apparatus is shown in Figure 3 (a). This device is used in the laboratories in Amsterdam as it is, next to the EN 15237, also prescribed in the Dutch guideline BRL 1120 as a device to fold or kink a PVD. The principle of the prescribed device is to fold the PVD, number 2 in Figure 3 (a), around three pins located at specified distances.

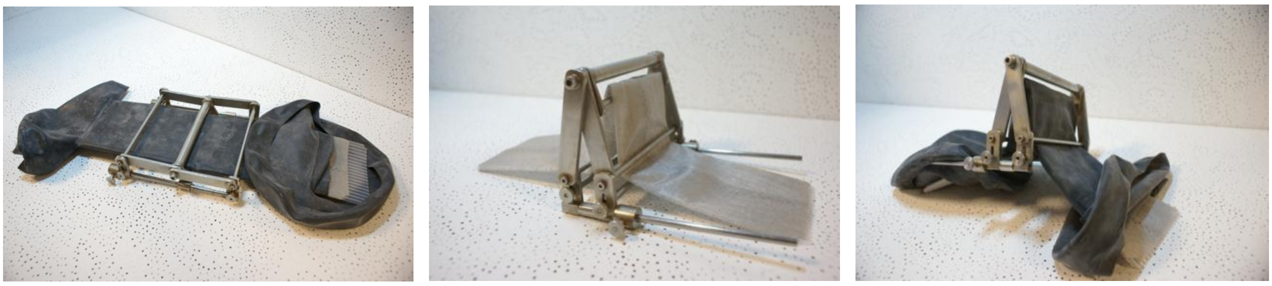
In the EN 13252 and in the Dutch BRL 1120 there is however no written procedure how to use this device in, for example, in terms of speed of kinking or in terms of sharp or soft kinks. From our experience it is known that the apparatus can be used differently and results can vary by the person using the device. Next to this uncertainty it should be noted that the shown device is an example; other devices might be used as well in other laboratories. This adds to the difficulty to compare buckled testing results between batches and laboratories for the same vertical drain type specimens.



(a) (b)

Figure 3. Device for buckling PVD as given in the EN 15237 and BRL 1120 (a) together with a picture of the actual apparatus used (b).

A picture of the device in ‘flat’ condition is shown in the left picture (a) of Figure 4. The middle (b) and right (c) picture shows the same device after the PVD is buckled. The PVD is at the inside of the black latex membrane and is, for reference, shown without the membrane.

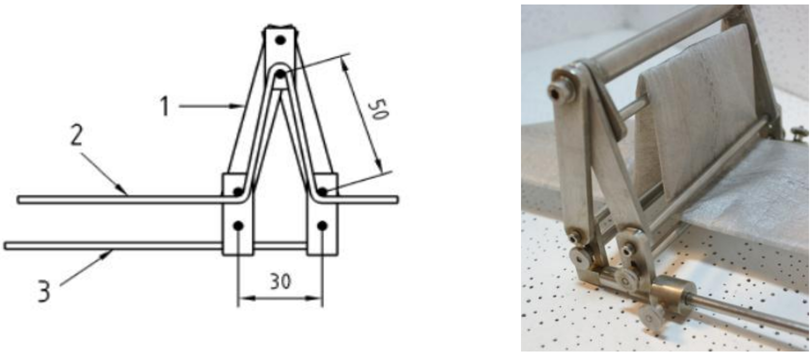


(a) (b) (c)

Figure 4. Picture of the buckled testing apparatus in flat and buckled condition

4.2 *Observations and review of the procedure*

When picture (b) of Figure 4 is compared to the standardized drawing, as shown in Figure 3 (a), it can be noticed that the top section of the kink is similar to the drawing, showing a sharp kink. The fold over the bottom pins in Figure 4 (b) is however not consistent with the drawing. The drain has a slight bend where the drawing seems to indicate a sharp 90 degrees fold over the bottom pins. This situation can most of the time only be met by making a sharp kink over 180 degrees by hand before the insertion of the drain into the apparatus. The result is shown in figure 5 (b). It could be expected that the specimen from Figure 4, with one sharp kink, compared to the specimen in figure 5, with three sharp kinks, will give different results in terms of the discharge capacity.



(a) (b)

Figure 5. Detail of a sharp kink at the top of the kinking device

Another observation is that the standard describes that the drain should be bended over top and bottom pins with a 5mm radius. During the bending of the different types of PVD used in this test series, no folds with a small radius were found. Most PVD types, in normal preparation practice, will form a sharp kink over at least the top pin. The sharp kink is caused by the collapse of the core. When the core collapses the kink will always be sharp and quite irregularly shaped. The angle at which a PVD is collapsing is different for all different types of PVD and depending, amongst others, on the thickness, stiffness and material used. A fishbone core structure is for example collapsing at a sharper angle compared to a channel shaped core. A fixed filter on the other hand gives also a sharper bend compared to a filter jacket. It seems therefore not very realistic to prescribe the bending of a PVD over a pin with a 5mm diameter as is currently done as in most cases the core will collapse anyway.

5 TESTING OF BUCKLED SPECIMENS

In order to investigate the effect of one or three sharp kinks, a test series has been performed on different types of buckled PVD, available in the Netherlands, under equal conditions in terms of pressure, minimal duration and sharp bending conditions. Tests were performed using the apparatus 2 (EN 15237) and the kinking device as described earlier. Specimens were kinked with one (1) sharp kink in the drain and three (3) sharp kinks in the drain.

5.1 *Overview of tested specimens of PVD*

An overview of the specimens which were tested is in this research is given in Table 1.

Table 1. Properties of the used PVD types

Type of PVD		C1	M1	M2	M3	M4
Core properties	Unit					
Shape of core	-	⊓⊓⊓⊓⊓⊓	⊓⊓⊓⊓⊓⊓	⊓⊓⊓⊓⊓⊓	┼┼┼┼┼┼┼┼┼	┼┼┼┼┼┼┼┼┼
Core weight	g	58.0	42.0	42.0	62.0	62.0
Core width	mm	98.0	98.0	98.0	97.0	97.0
Core height	mm	3.0	2.4	2.4	3.1	3.1
Core material	-	PE	PP	PP	PP	PP
Filter properties						
Weight	g/m^2	110.0	95.0	125.0	95.0	125.0
Tensile strength	kN/m^1	6.0	7.6	10.2	7.6	10.2
Material	-	na	PP	PP	PP	PP
Composite properties						
Weight	g	80.0	62.0	68.0	82.0	88.0
Tensile strength	kN	2.5	2.1	2.6	2.6	3.1
Filter bonded to core	-	Yes	No	No	No	No
		Bonded	Jacket	Jacket	Jacket	Jacket

5.2 *Test procedure*

The test procedure followed is consistent with EN 15237. It involves the preparation of the specimens with respectively one sharp kink or three sharp kinks as discussed in previous sections. After the specimens are built into the pressure cell, the cell is filled with water. After filling an air pressure, on top of the water, is used to gradually increase the load on the specimens up to 200 kPa. The pressure on the specimens is increased following a sequence of steps: the pressure is kept for 2 hours at about 20-40 kPa to check the water tightness of the latex membrane and the test cell. This is followed by about 20 hours at 150 kPa pressure to let the filter and core settle properly. Afterwards the pressure is increased up to 200 kPa followed by the first measurement of the initial water flow through the specimen. Each working day the flow is measured at a head loss of 40 mm water column according to the standard. The head loss can be converted to a gradient of 0,1 using the specimen length (core as well as filter) of 400 mm. Before each flow is measured air bubbles are removed from the specimen by flowing water through the specimen at a head loss of about 300 mm (i=0.75) for about 45-60 minutes.

6 TEST RESULTS

The results of the performed tests are plotted per PVD type in Figure 6. For each type of PVD, tests were performed using one sharp fold and three sharp folds. Each test was performed in duplicate to make sure the results are not influenced by air bubbles. For one drain type the procedure of air bubbles removal was deliberately less followed to show the results when air is not removed from the specimens.

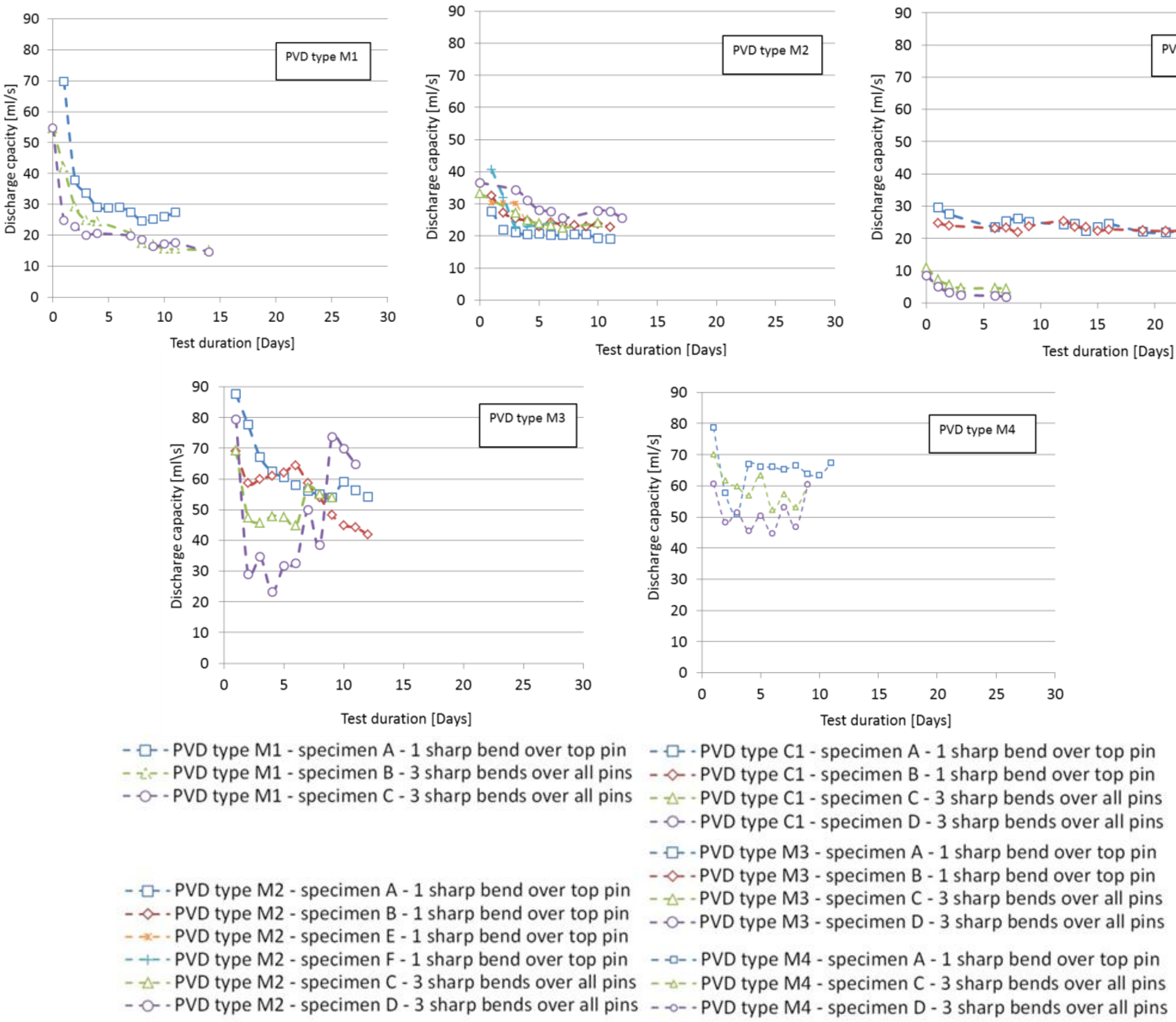


Figure 6. Results of the tested PVD. For drain type M3 the influence of air bubbles in the narrow channels is visible. The increased discharge capacity after 10 days (i.e. the purple line) is caused by flowing water through the specimen and pressing out the air bubbles.

7 DISCUSSION OF THE TEST RESULTS

The results of the test show that the choice of the number of sharp kinks can, depending on the drain type, have a major effect on the measured discharge capacity. Mainly for type C1 the effect of one or three sharp folds is of high importance to the measured discharge capacity. PVD types M1 - M2 and M3 - M4 show more or less similar behaviour when the one kink result is compared to the three kinks result. A summary of the test results is shown in the Table 2.

Table 2. Summary of the test results

Type of PVD			C1	M1	M2	M3	M4
Test	Loading	Gradient	DC in m^3/s	DC in m^3/s	DC in m^3/s	DC in m^3/s	DC in m^3/s
Discharge capacity straight, t=30 days, apparatus 2 *	300 kPa	0.1	57.0 E-6	32.0 E-6	40.0 E-6	35.0 E-6	45.0 E-6
Buckled, 1 sharp fold	200 kPa	0.1	20.6 E-6	27.4 E-6	22.5 E-6	48.0 E-6	63.8 E-6
Deformation resistance **			36%	86%	56%	137%	142%
Buckled, 3 sharp folds	200 kPa	0.1	3.2 E-6	14.9 E-6	24.8 E-6	63.0 E-6	60.5 E-6
Deformation resistance **			6%	47%	62%	180%	134%

DC = discharge capacity

*Values for the discharge capacity straight were taken from specifications or when not given by manufacturer from the internal database.

** Deformation resistance = buckled discharge capacity/initial discharge capacity. Note the difference in confining pressure (taken as per standard.)

7.1 *Core behavior*

From Table 2 it follows that the shape of the core and method of filter connection seems to be of importance to the level of resistance against deformation. The corrugated channel shaped cores are showing a decreasing discharge capacity by deformation with one or three sharp kinks. This behaviour for the types C1 and M1 seem to be logical: the more kinks the lower the discharge capacity. For the PVD type M2 the heavier filter seems to affect the behaviour in a positive manner, the discharge capacity with one kink is equal to the capacity with three kinks. For type C1 however only 5.6% of the straight discharge capacity t=3- days, 300kPa loading is remaining, a reduction of almost 95%, while for type M1 to M2 a reduction of only 38-53% is measured.

For the fishbone cores of the PVD types M3 and M4 only the initial deformation behaviour is seen in the graphs. The deformation between filter and core is taking place within the first few days and afterwards buckling, kinking and folding seems to have hardly any effect on the discharge capacity. Also the level of the discharge capacity is at least over twice as high compared to the channel shaped cores. The slight difference in the measured discharge capacities between M3 an M4 is caused by the filter properties. The filter in the test of specimen M3 is about 40% lighter compared to the filter as used in the test of specimen M4. The increase in discharge capacity of the buckled samples compared to the discharge capacity of the straight samples is mainly caused by the decrease in confining pressure from 300kPa to 200kPa.

A reason for the deviating discharge capacity of PVD type C1 is further investigated. It seems highly likely that the shape of the core is leading in the reduction of the discharge capacity instead of the weight. If for example the ‘one sharp fold’ result of the test of C1 is compared to the result of the M3 and M4 PVD’s, the M3 and the M4 PVD are giving discharge capacities twice as high, although the core weight is about equal (The fishbone shaped cores of M3 and M4 have a weight of about 62 gram/m and the corrugated shaped core of the C1 58 gram/m). When the results of the tests with three sharp folds are compared, the fishbone shaped core is withstanding the huge deformation of kinking far better with a 19 times higher discharge capacity compared to the C1 discharge capacity.

The strong reduction in discharge capacity under buckling of the C1 drain can however not only be accredited to the shape of the core. The core weight of C1 is about 40% heavier compared to the similarly shaped cores the M1 and M2 PVD. These PVD types however show a far lower reduction in the discharge capacity (38% and 53%) under three sharp folds compared to the 94% reduction of the heavier C1 drain type. Therefore what also might affect the found behaviour is that the filter of core C1 is of a different type and attached to the core. The filter of M1 and M2 are jackets around the core. This is further discussed in the following section.

It should be noted that the resistance against deformation (bending) is also strongly depending on the flexural properties of the used plastic material, for the used polypropylene of the PVD's M1-M4 this modules is about 1300 MPa. The modulus of the polyethylene core of C1 is unknown.

7.2 *Filter behavior*

Filters do behave differently depending on the production process used in the manufacturing process of the filters. Spun bonded filters (PVD types M1-M4) are stiff compared to the filter of the PVD type C1. These stiffness and strain characteristics are affecting the intrusion of the filter into the core channels; the higher the stiffness, the less intrusion into the channels will take place. It is also possible that there is no intrusion at all when the width of channel of the drain core is too small to be intruded by the filter (like with the M3 and M4 type PVD). Less intrusion will also take place when the filter is connected to the core (PVD type C1), but in this case the deformation characteristics of the filter itself is becoming governing. In any case the intrusion of the filter into the core channels will lead to a reduction of the discharge capacity. By folding a PVD, the filter could be of help to keep channel in the core open or could give extra load on the core resulting in lower discharge capacities. The results of the tests and comparison with the other drain types seems to indicate that the glued filter of the PVD type C1 could be the reason for a more or less complete block of the samples with three sharp kinks and leads to a particular collapse of the core, thereby blocking the channels.

7.3 *Air block in PVD channels*

Air blockage of the channels in PVD is very tricky; if the procedure of pressing out air bubbles is not correctly followed a measurement will give results as shown in Figure 6, type M3, specimen D. A normally seen test behaviour of a fishbone shaped core in a PVD test is shown in for example the type M3, specimen A in Figure 6. The big changes in the measured values of PVD type M3 are only caused by air blocks of the cores channels. Obviously the fishbone shape core is more sensitive for air bubbles due to the small channels: the channels in straight unfolded condition are rather small. By deformation, the channels get smaller and the possibility of an air block is increasing. The lines in the graph are much more irregular compared to the other PVD types, a behaviour that is regularly seen during the tests in our laboratories.

Although it is thought that most of the air bubbles will be removed by following our previously described procedure of flushing the specimen with a high water flow before testing ($i=0.75$ for 45-60 minutes), it cannot be guaranteed that all the air bubbles are pressed out of the PVD core channels. A simple test that could prove this is to add a surfactant like Marlon. This will show a short improvement of 20% to the discharge capacity immediately and could also affect the results of the test. Therefore there is, next to the buckling procedure, a need for a standardized procedure to be used in all laboratories to get equal procedures and better comparable outcomes.

8 INITIAL DEFORMATION OF FILTER AND CORE

The effect of instant deformation and creep is clearly visible in the test results and shows as a strong reduction in discharge capacity over the first few days. This coincides with the practical situation where the load on a PVD is building up in the first hours after the installation, by the soil closing the installation hole. This is however strongly dependant on soil properties and installation depth. After the initial deformation, the discharge capacity is more or less in a linear stage. In this linear stage the constant loading on the specimen will cause creep behaviour of the core and filter. It is therefore important to investigate the 'long term' behaviour of a PVD as this is giving relevant information for designers. A brief test of a few hours/days gives no information about the long term and actual behaviour in the ground and therefore conform EN-ISO 12958 a creep reduction factor should be applied to the obtained values. The reduction values are given in Table 3. The table reveals that the discharge capacity could be required to be reduced by a factor of 10 when the initial in-plane flow capacity is given and the 30 day behaviour from apparatus 2 is requested. It might therefore perhaps also be better to rename the discharge capacity of a straight PVD to the "Initial discharge capacity" in order to help/guide the end user of the parameter.

Table 3. Reduction factors to include the creep in the measurement results or to compare a specified value with apparatus 2 30 days test results, when a duration of the test is used other than specified in the standard. (A flow capacity foam-foam - 1 day would thus be required to be reduced by a factor 10 to make a comparison with the required 'in plain' discharge capacity BRL - Delftse test duration 30 days (EN 15237))

Test period days	Creep factor Fcr	
	Apparatus 1 (ASTM)	Apparatus 2 (Delft)
2	10	5
7	8	3
30	3	1

9 CONCLUSION AND RECOMMENDATIONS

The correct folding or kinking of a specimen of a PVD for the testing of the buckled discharge capacity is important as it could govern the discharge capacity. Currently no standardized and strict kinking procedure is present, leaving it to the laboratory to use one or three sharp kinks. A uniform standardized method of buckling is therefore required to improve the quality and comparability of test results. Due to the expected high deformations of the PVD, with volume reductions of the surrounding soil of up to 60%, and the requirement that all the consolidation water has to flow through the most deformed section, it is advised to test and present the lower boundary of buckled discharge capacity.

This is supported by the test results. From the presented results it can be observed that specific types of PVD, specimen C1, are highly sensitive to the multiple sharp kinks and show a staggering 94.4% reduction in the discharge capacity when compared to the straight discharge capacity measured under a higher confining pressure. This large reduction is partly accredited to the channel shape of the core, but mainly to the specific filter type used in relation to the fixation of the filter to the core. This can be concluded from a comparison between 5 types of PVD with either similar channel shape, height of the core, similar weight of the core and variable filter properties.

The channel shaped specimens of type M1 and M2 show a reduction of 38 to53% compared to the straight discharge capacity. The fishbone structured M3 an M4 types of PVD show an increase in the discharge capacity due to the lower confining pressure and seem to perform very well under buckled conditions.

The air blocks of drain channels is more a practical problem but must also not be neglected. There is a need for a standardized procedure as the procedure for pressing out air bubbles is currently not part of the standard. It should be such that all the different laboratories will have the possibility to get as close as possible to the (maximum) result for the discharge capacity. For the repeatability of the measurement is absolutely necessary to follow (normalized) equal procedures.

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