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Performance evaluation of the Hydroluis drainpipe-envelope system in a saline-sodic soil

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ABSTRACT

Subsurface drains, when installed in non-cohesive soil, are typically covered with an envelope to tackle problems of clogging and siltation. Selecting a suitable envelope material, however, is complicated and depends primarily on soil characteristics in the area where the drains are to be installed. A new promising drainpipe-envelope concept, Hydroluis, has been developed which the designers claim works in a wide range of soils. The Hydroluis drainpipe consists of a corrugated inner pipe with three rows of perforations at the top and an unperforated outer pipe that covers the top two thirds of the inner pipe. We analysed the hydraulic and filter functions of this new drainpipe in a soil tank laboratory model with a saline-sodic problem soil from south-western Iran and compared Hydroluis performance with that of a locally-manufactured synthetic envelope material (PP450). The silty clay soil used in this study was 40 % clay, with a plasticity index (I_P) of 16.9 and an exchangeable sodium percentage (ESP) of 60.4 %. The Hydroluis drainpipe clogged during the first two weeks of the test due to invasion of the test soil into the space between the inner and outer pipes. Of the substantial volume of sediment that entered the Hydroluis inner pipe, 38 % removed from the pipe in the first day. In contrast, the PP450 drainpipe showed good hydraulic and filter functions, entering very little sediment to drainpipe during the entire test period and stabilizing at drainage rate of 28 mm/day and entrance resistance of 55 days/m, at around day 50. Our analyses suggest that the clogging and poor drainage function of the Hydroluis drainpipe was caused by the higher flow velocity (21.5 times higher) at the soil-envelope interface of the drainpipe, in addition to the lower Hydroluis drainpipe's soil retention capacity (18 times lower) compared to the PP450 drainpipe. Assuming Stokes' Law governs filter function, the results of Hydroluis design evaluation also suggest that in stable soils, very fine sand or coarser soil particles ($D > 0.05$ mm) place no serious limitations for Hydroluis drainpipe application, whereas the current design is unsuitable for filtering fine silt particles ($0.002 < D < 0.02$ mm). In conclusion, we suppose the Hydroluis drainpipe does not perform well in silty saline-sodic soils, such as those found in south-western Khuzestan Province, Iran.

1. Introduction

Subsurface drains in arid and semi-arid areas are primarily installed to reclaim waterlogged or salt-affected lands and prevent soil waterlogging and salinization. Typically, subsurface drains are covered with an envelope to restrict soil particles from entering the drainpipe (filter function) and to create a more permeable area around the pipe (hydraulic function) (Ritzema et al., 2006). A wide variety of materials are used as envelopes for drainpipes, ranging from organic and mineral materials, to mineral fibres and synthetic material (Cavelaars et al., 2006). Granular mineral materials have been used for decades and are still commonly used in arid and semi-arid countries, yet they are expensive due to high transport cost (Stuyt and Dierickx, 2006). Nowadays, pre-wrapped envelopes of synthetic material are used almost everywhere in the world because they are cheap, light weight and simple to install even with trenchless drainage machinery.

In cohesionless soils, the main causes of failure of subsurface drains are clogging and siltation of drainpipes or envelope with soil particles, linked to improper selection of the envelope material. Clogging is defined as a decrease in the permeability of the soil-drainpipe-envelope system after installation, due to particles of the base soil being carried towards the subsurface drainpipes by drag forces of the moving water

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(Stuyt and Dierickx, 2006).

Most soils in south-western Khuzestan Province, in arid Iran, are problem soils for which subsurface drainpipes need an effective envelope. Khuzestan's soils consist in large part of silt and clay, and are saline and saline-sodic and without structure in subsurface horizons (Pazira and Homaee, 2010). Clogging of subsurface drains in Khuzestan Province is usually a result of the instability of local soils, shallow saline groundwater and high soil salinity.

Ghane (2007) compared the performance of two synthetic envelopes (PP450 and PP700) with a gravel envelope in a sand tank model using a problem soil from Abadan, Khuzestan Province. They reported that the gravel envelope performed better than the synthetic envelopes, despite the acceptable performance of the synthetic envelopes.

Formulation of criteria for envelope design is complicated and depends on soil characteristics and installation conditions (Stuyt and Dierickx, 2006; Stuyt and Willardson, 1999). Many physical criteria have been published during the past 50 years to suggest whether a soil is unstable and needs an envelope. However, the structural stability of a soil, especially in arid regions, is affected not only by a soil's physical properties but also by its salt and sodium content. A high exchangeable sodium percentage (ESP) usually indicates poor physical soil conditions and a likelihood of displacement of colloidal soil particles. In general, in arid climates, drainpipe clogging problems are not experienced in non-sodic soils with ESP values below 15 % (Stuyt et al., 2000). Yet, so far no sufficient criteria are available to classify envelope need for soils with ESP values higher than 15 % (especially saline-sodic soils) according to their chemical composition. It is therefore recommended that the effectiveness of an envelope be proven in field trials at the locations where the subsurface drains are to be installed (Vlotman et al., 2001; Stuyt et al., 2000).

To tackle the complication of envelope design, a new pipe-envelope concept was recently developed in Turkey that does not use any envelope material. The new concept, called Hydroluis, consists of a corrugated inner pipe with three rows of perforations at the top and an unperforated outer pipe that covers about the top two thirds of the inner pipe. The 8 mm distance between the inner and outer pipes determines the flow velocity and thus the filter function of the pipe (Bahçeci et al., 2018). Bahçeci et al. (2018) tested the Hydroluis system in a field with a stable, non-saline soil (clay > 56 %, ECe < 1 ds/m) in Turkey during 2015 and 2016. They concluded that the Hydroluis envelope was a good alternative for a gravel or synthetic envelope for irrigated lands with a wide range of soil textures. The Hydroluis pipe was not, however, tested with a saline-sodic problem soil.

Investigating a new drainpipe in an area is usually conducted in two consecutive steps to prevent waste of time and money. Examining the drainpipe in the laboratory with the soil of experimental field in a short term and consequently if the laboratory results prove promising, investigating the long term effects of the drainpipe installation in the field. Accordingly, the objective of the laboratory experiments is to quantify the flow entrance resistance (hydraulic function), investigate clogging of pipe or envelope and explore substantial passage of mineral particles (filter function), for short time after drainpipe installation (Stuyt et al., 2000). Analogue models that have been extensively used in the laboratory for these purposes are soil tank and flow permeameter models.

Examining a drainpipe in the laboratory has some important limitations compared to field that should be under considerations when interpreting the results. First, the drainpipe-envelope combination is tested in a rather short time, while in the field increase in entrance resistance or clogging may occur in long time (Wesseling and Homma, 1967). Second, the soil used in the test is disturbed, although it should have similar soil texture and chemical composition to the field. Thus the test soil has different bulk density and hydraulic conductivity compared to the field. Soil tanks, in particular, have some additional limitations in comparison with flow permeameters. Rather large amount of homogeneous soil is needed to fill the soil tank models, which is quite labour-intensive and limits the repeatability of the test. Moreover, applying varied hydraulic gradient cannot be easily maintained in the soil tank models.

In this study we have analysed the hydraulic and filter functions of the Hydroluis pipe-envelope system in a soil tank model with a saline-sodic problem soil from south-western Iran, and compared performance with a locally-manufactured synthetic envelope drainpipe (PP450). We have explained the possible causes of failure or success of each drainpipe. In addition, we have evaluate the filter function of the current Hydroluis design and have given recommendations for future application or design of the next generations of the Hydroluis drainpipe.

2. Material and methods

2.1. Soil tank

Laboratory tests using soil/sand tank models and flow permeameters have been extensively done worldwide with different envelope materials to formulate criteria for selecting the right envelope material (Wesseling and Homma, 1967; Willardson et al., 1968; Qureshi et al., 1990; Fischer et al., 1994; Shi et al., 1994; Bonnell et al., 1986). In our experiment we used a laboratory soil tank to investigate the drainage function of the Hydroluis drainpipe-envelope system under a possible maximum drainage rate of drainage practice in Khuzestan Province. We chose the soil tank model for experiment among analogue models because the special design of Hydroluis drainpipe (with no envelope material) can only be studied under this kind of laboratory experiments.

The soil tank in this experiment was constructed according to the method introduced by Eichenauer et al. (1994). The soil tank consisted of a steel frame measuring 150 cm in length, 80 cm in width and 200 cm in height, with four glass outer walls and two perforated steel inner walls (Fig. 1). The perforated walls formed an inner tank measuring 60 cm in width, leaving a 10 cm gap to the outer wall on two sides. The perforations on the walls were 0.8 cm in diameter and 10 cm apart. The drainpipe was installed horizontally in the middle of the inner tank, with the centre of the pipe 50 cm above the tank floor. The characteristics of the drainpipes used in this experiment are presented in Table 1.

Ten piezometers were installed above, below and to the sides of the drainpipe. One piezometer, P10, was installed between the inner and outer pipes. The piezometers were connected to transparent pipes to enable measurement of their piezometric heads.

The soil tank model in this study attempts to simulate field conditions of a newly installed and backfilled drainpipe in a trench with 1.2 m depth in a saline sodic soil, undergoing leaching practice for few months. A constant water level of 110 cm above the drainpipe was maintained. This level is representative of the leaching practices in Khuzestan Province, where leaching after drainpipe installation is used to reclaim saline and/or sodic soils before cultivation. Leaching here is usually done by making a continuous water pond on a field for a few months.

A representative saline-sodic soil was collected from the top 50 cm depth of an uncultivated plot in the Salman Farsi sugarcane agro-industrial area (Farm R8−18; 48°27′ N, 30°56′ E) in the south-western Khuzestan Province, with no subsurface drains or history of leaching or cultivation practices. The soil texture was identical from soil surface to 1.5 m depth. The soil was collected from the more saline topsoil with the assumption that during leaching practice the salts from the topsoil layers would leach to drain level subsoil, which then may affect soil particle bonds and movements near drainpipes. The soil had a clay content of 40 %, plasticity index of 16.9, saturated electrical conductivity (EC_e) of 188 ds/m, a sodium adsorption ratio (SAR) of 104.2 and an exchangeable sodium percentage (ESP) of 60.4 % (Table 2). Based on the Larry Cihacek (2012) classification, this soil with EC > 4, ESP > 15, SAR > 13 and pH < 8.5 is a saline-sodic soil with a limited drainage ability.

We analysed particle size distribution of soil samples using a Malvern Mastersizer, which employs laser diffraction to measure the size of soil

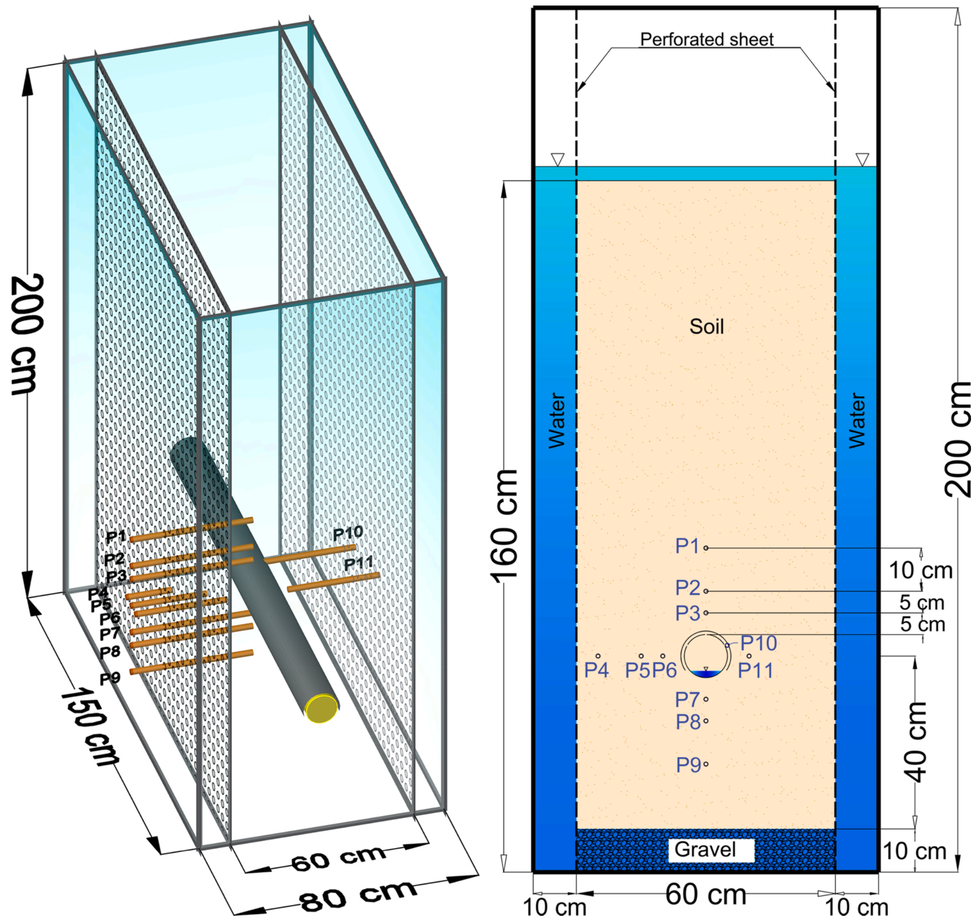

Fig. 1. Schematic of the soil tank in 3-D view (left) and cross-section view (right) for testing the Hydroluis drainpipe.

Table 1
Characteristics of the Hydroluis and PP450 drainpipes used in this experiment.

	Pipe				Envelope/ Outer pipe			
Drainpipe	Diameter (mm)	Length (m)	Number of perforations per unit length	Size of perforations (mm × mm)	Thickness/ Opening (mm)	Mass per unit area (g/m^2)	O90 (μm)	Production standard
Hydroluis	100	1.25	192	2 × 4	8	400	–	TSE K 522*
PP450	100	1.25	384	1.3 × 5	4.87	484	450	DIN 1187 NEN 7090

* Turkish Standards Institute, 2016.

Table 2
Physical and chemical properties of the test soil and water.

Physical	Sand (%)	Silt (%)	Clay (%)	Soil texture	d_{60}* (μm)	d_{10} (μm)	Coefficient of uniformity (C_U)	Plasticity index (I_P)
Soil	5.3	54.7	40.0	Silty clay	5.36	0.31	17.29	16.9

Chemical	Anions (meq l^{-1})				Cation (meq $^{-1}$)			EC$_e$ (ds/m)	SAR (-)	ESP (%)	pH (-)
	Cl^-	$SO4^{2-}$	$HCO3^-$	$CO3^{2-}$	Sum	Na^+	$Ca^{2+}{}_+ Mg^{2+}$	Sum				
Soil	2660	502.6	2.3	0.0	3165	2270	949	3219	188	104.2	60.4	7.56
Water	16.4	11.0	4.2	0.0	31.6	17.5	14.3	31.8	2.8	6.5	7.7	7.6

* Particle diameter for which 60 % of the soil particles, by dry weight, had a smaller diameter.

particles, ranging from 0.1–1000 μm (Malvern Instruments, 2004). The Mastersizer provides fast, simple and precise particle size distribution results, allowing differentiation of a wide range of soils. In comparison, the traditionally used hydrometer method is more time consuming and error prone, as it requires multiple steps over several days.

For our tests, we used water from Karoon River, which is the irrigation source for the Salman Farsi sugarcane agro-industry area.

In the laboratory, the test soil was first air dried for nearly 10 days, and then crushed and passed through sieve number 4 (4.75 mm) to remove trash. The bottom 10 cm of the tank was filled with gravel, and then further filled with 150 cm of the prepared soil in 5 cm increments. After each increment, the soil was slightly compacted manually. Once the soil level reached the drain level (45 cm from the bottom), a Hydroluis drainpipe 125 cm in length was installed and fixed to the inner tank at a slight slope of 1% to the outlet. The drainpipe and envelope were completely sealed at the head end of the pipe, which was in contact with soil. The outlet end was connected to a PVC outlet pipe to allow measurement of drain discharge. The filling of soil above the drainpipe then continued in a similar fashion to the previous stages until the soil level reached 160 cm above the soil tank floor. Discounting the 10 cm gravel layer at the bottom of the inner tank, the depth of the test soil was 150 cm.

Prior to commencing the test, the soil was saturated. The drainage outlet was blocked and water was allowed to enter the outer tank gradually over a period of about 5 days. After each 5 cm increase in the water level of the outer tank, the inflow was stopped and the water was allowed to infiltrate into the soil for at least one hour to ensure that no air bubbles remained in the soil. The water level was thus increased until it reached 160 cm above the tank floor. Because some soil subsidence occurred during the saturation phase, an additional amount of soil was added to the inner tank to restore the soil depth to 160 cm.

The test started on 1 August 2018 by opening the drain outlet. During the test period, piezometer water levels were measured daily, and daily drain discharge was measured using a stopwatch and graduated cylinder. The electrical conductivity and temperature of both internal water and drained water were measured on a daily basis using an EC meter and thermometer. Moreover, the sediment load of the drained water was measured by putting a 10 L container under the outlet PVC pipe and measuring the dry weight of the gathered sediment on a weekly basis. The laboratory test continued until an equilibrium was reached.

The entrance resistance of the soil-envelope-pipe combination to water movement was then calculated using the following equation (Dieleman and Trafford, 1976):

$$W_e = h/q \tag{1}$$

where, W_e is the entrance resistance (day/m); h is the head loss, or the difference between the piezometer water level and the water level in the drainpipe (m); and q is the drain discharge per unit drain length (m^3/day/m).

At the end of the experiment, clogging and sedimentation of the envelope and pipe were analysed by excavating the pipe, weighing the sediment in the inner pipe and the soil trapped between the inner and outer pipes and determining the soil texture of these sediments.

The same procedures were used to test the locally-manufactured synthetic envelope PP450 drainpipe with the same soil and under the same laboratory conditions.

3. Results and discussion

3.1. Need for an envelope

Based on the currently used criteria for soil texture and stability, our soil did not need an envelope (Table 3). Similarly, the particle size distribution of our soil was not within the range of particle size distributions likely to clog, so here too, no envelope was indicated as required (Fig. 2). However, experience in Khuzestan Province strongly suggests the use of an envelope around subsurface drains, as soils here are inclined to dispersion due to the shallow, saline water table and soil sodicity (Hasan Oghli, 2008; Kooti, 1994). These local experiences point to the limitations of using the criteria in the literature to determine need for an envelope in saline-sodic soils in Khuzestan Province.

3.2. Hydraulic function

The 11 piezometers in the Hydroluis test showed slightly higher water levels than those in the PP450 test, 4.65 % higher on average, under free drainage conditions for both drainpipes (Fig. 3). All the piezometers above and to the sides of the Hydroluis drainpipe (P_1, P_2, P_3, P_4, P_5, P_6, P_{11}) had water levels nearly equivalent to the tank water level (163 cm), indicating virtually no flow of water above and sideways of the drainpipe. Only the piezometers below the drainpipe (P7, P8 and P9) and the piezometer between the inner and outer pipes (P10) showed a lower water level during the test period. This is logical, as the outer pipe of the Hydroluis system is unperforated, so water can only enter the drainpipe from below. The high water level in piezometer P10 for the Hydroluis system indicated clogging of the perforations and/or the space between the inner and outer pipes.

While an average head loss of around 3.2 cm in the direction of flow was observed below the PP450 drainpipe from piezometer P9 to P7, no logical trend in head loss was observed for the same piezometers below the Hydroluis drainpipe.

Changes in drainage rate and entrance resistance of the Hydroluis drainpipe occurred in three phases (Fig. 4). In phase 1 (days 1–7), the Hydroluis drainage rate dropped sharply from a high of around 250 mm/day to just below 50 mm/day. In this phase, the entrance resistance of the Hydroluis drainpipe increased gradually from around 7 days/m to around 50 days/m. In phase 2 (days 7–15), the drainage rate of the pipe continued to decrease, but more gradually, to reach just under 4 mm/day at the end of day 15. The entrance resistance of the Hydroluis drainpipe suddenly jumped to around 800 days/m at the end of this phase. At the start of phase 3 (days 15–71), the drainage rate of the Hydroluis pipe stabilized at around 2 mm/day, remaining at this level for the rest of the test period. The entrance resistance of the Hydroluis drainpipe, however, continued to increase gradually in this phase, reaching 1100 days/m at the end of the experiment.

Drainage rate and entrance resistance for the PP450 drainpipe started off similar to the Hydroluis drainpipe. But for the PP450, the drainage rate and entrance resistance changed more gradually and stabilized at around 28 mm/day and 55 days/m, respectively, at about day 50. These values are in the range of those reported by Ghane (2007), who found a drainage rate of 140 mm/day and an entrance resistance of 5 days/m when testing a PP450 drainpipe in a silty clay loam soil in Khuzestan Province (unknown chemical properties) under the same laboratory conditions of this experiment.

Head loss was high near both drainpipes and more or less the same for both systems, increasing gradually from 104 mm/day to almost

Table 3
Available physical criteria to determine need for an envelope for the test soil.

Decision parameter	Criteria	Classification	Reference	Properties of the test soil	Need for an envelope
Clay content	Clay > 30 %	No need for envelope	Abdel-Dayem, 1987; Rajad Project Staff, 1995	Clay fraction = 40 %	No
Mechanical stability*	50 µm < d_{50} < 150µm	Unstable soils which requires an envelope	Dierickx and Leyman, 1991	d_{50} = 3.33 µm	No
Erosion likelihood	C_u > 15	Uniform soil and no danger of erosion	Olbertz and Press (1965)	C_u = 17.29	No
Clay/silt ratio	Clay/silt > 0.5	No risk of mineral clogging	Dieleman and Trafford (1976)	Clay/silt = 0.73	No
Structural stability*	I_p > 12	No tendency to siltation	Dieleman and Trafford (1976)	I_p = 16.9	No

* Mechanical stability is an intrinsic property of a soil and depends only on soil texture, while structural stability depends on various conditions, such as chemical properties and water content. d_{50} = the particle diameter for which 50 % of soil particles, by dry weight, have a smaller diameter; C_u = uniformity coefficient; I_p = plasticity index.

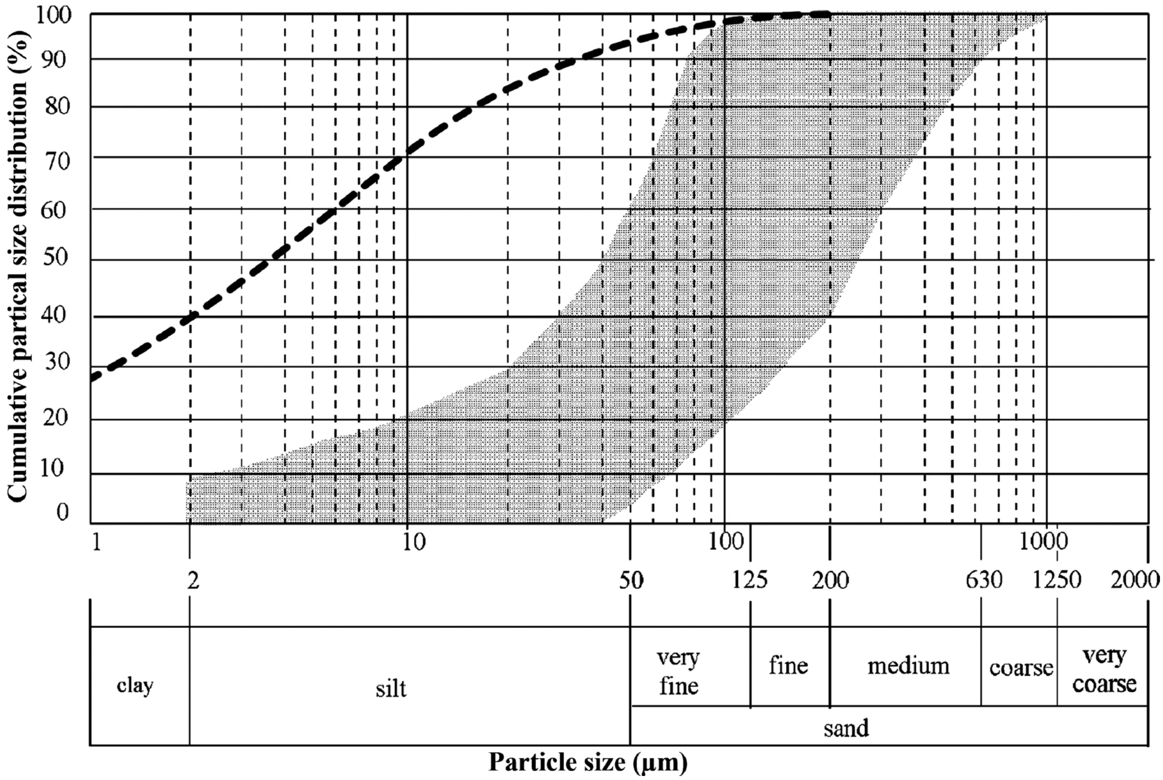

Fig. 2. Particle size distribution of the test soil (dashed line) and the range of problem soils with likelihood of mineral clogging (Cavelaars et al., 2006).

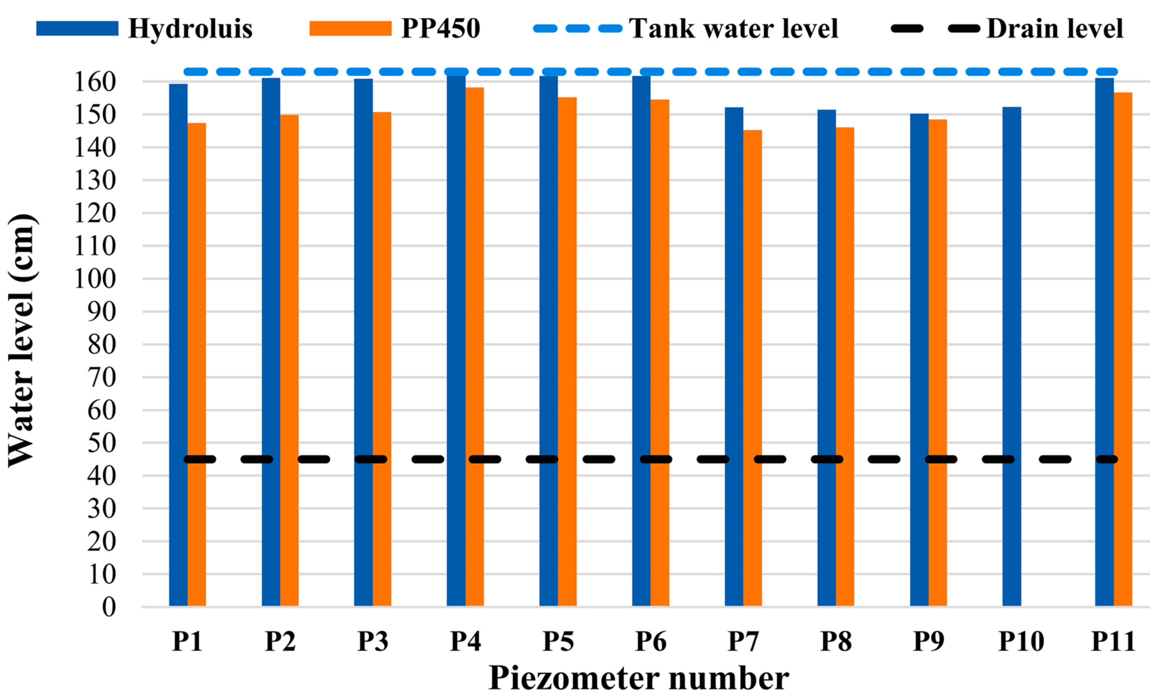

Fig. 3. Average water levels in piezometers (from the soil tank floor) for Hydroluis and PP450 drainpipe.

111 mm/day during the test period. Head loss here is defined as the difference between the average water level for the piezometers 5 cm from the drainpipe and the water level in the drainpipe (around 45 cm from the tank floor).

These results indicate good hydraulic function of the PP450 drainpipe and poor hydraulic function of the Hydroluis drainpipe. At the end of the experiment, the entrance resistance of the Hydroluis drainpipe was 20 times greater than that of the PP450, while the Hydroluis drainage rate was 20 times lower than that of the PP450 drainpipe. The poor hydraulic function of the Hydroluis system can probably be explained by a sudden rush of unstable soil particles toward the pipe perforations and into the space between the inner and outer pipes in phase 1, alongside the almost complete clogging by the end of phase 2 and compaction of the soil between the inner and outer pipes in phase 3.

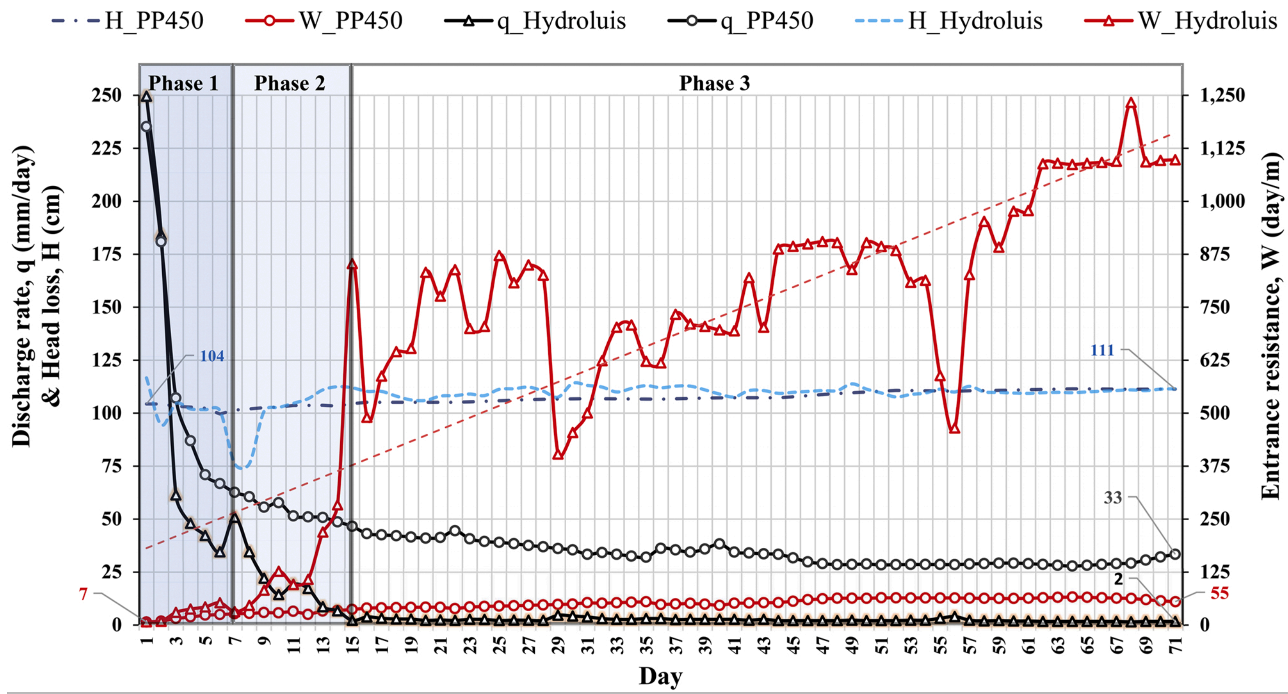

Fig. 4. Discharge rate, head loss and entrance resistance of PP450 and Hydroluis drainpipes.

3.3. Filter function

To understand the hydraulic behaviour of the drainpipes, we must look at their filter function. For the Hydroluis system, it is the space between the inner and outer pipes (8 mm) that determines the filter function of the drainpipe. Bahçeci et al. (2018) assumed this space would be filled with water or air during operation. However, upon excavation of the Hydroluis pipe used in our test, we found the space between the inner and outer pipes was almost completely filled with soil. Furthermore, a thick sediment layer was collected on the inner pipe surface, blocking the perforations (Fig. 5). In contrast, upon excavation of the PP450 drainpipe, the perforations were found to be unclogged despite the considerable amount of soil retained in the envelope material. Surprisingly, an insignificant amount of sediments observed inside

Fig. 5. Excavated drainpipes at the end of the experiment, Hydroluis (a, b) and PP450 (c, d).

the PP450 drainpipe during excavation.

In addition to visual inspection of the excavated drainpipes, we analysed the filter function of both drainpipes by measuring soil particle sedimentation during the test (Fig. 6). In the Hydroluis system, 916 g of sediment was removed with drain outflow on the first day of the experiment, compared to almost no sediment in the PP450 drainpipe test. Similarly, after excavation, 1.35 kg of sediment was removed from the Hydroluis inner pipe, compared to an insignificant amount of sediment from the PP450 drainpipe. Examining the total amount of sediment that entered the Hydroluis system (7070 g), 4684 g (66 %) was retained in the space between the inner and outer pipes, 1396 g remained in the inner pipe (19 %) and 1040 g (15 %) was removed with drain outflow. Of all the sediment that passed through the Hydroluis inner pipe during the test, around 38 % passed on the first day. Examining the total amount of sediment that entered the PP450 drainpipe (1111 g), 1090 g (98 %) was retained by the envelope material, and the 2% that did enter the pipe was removed with the drain outflow. If all the sediment entering the drainpipes during the tests had remained in and been uniformly deposited in the drainpipes, it would have occupied around 17 % (1678 cm^3) of the inner space of the Hydroluis pipe and only 0.2 % (15 cm^3) of the PP450 drainpipe (Fig. 7).

We thus conclude that the main cause of failure of the Hydroluis system was the clogging of the space between the inner and outer pipes, and that the clogging effect of the sediment accumulated in the inner pipe was insignificant. The question then arises what soil particle sizes were responsible for the clogging.

Silt and fine sand are considered as problem soil particles that can silt up into drainpipe and cause clogging. This is why envelopes are used for filtering. To better analyse the filter function of the Hydroluis drainpipe and detect the soil particle sizes responsible for clogging, we compared the original test soil with several sediment samples gathered during our test: sediment removed with drain outflow on the first day, sediment remained in the inner pipe and sediment retained between the inner and outer pipes. The percentage of soil particles, the coefficient of uniformity, the coefficient of curvature and the particle size distribution of these sediments were found to be almost identical to the original soil (Table 4 and Fig. 8).

Therefore, we can conclude that the space between the inner and outer pipes of the Hydroluis system, which was supposed to serve the filter function, did not in fact filter the problem soil particle sizes. In the drainage conditions of our test, the test soil entered into both the inner pipe and the space between the inner and outer pipes. No analysis of sediment particle size could be done for the PP450 drainpipe, as the amount of sediment collected during the test was insufficient for testing, both for the sediment collected each week and for the sediment left inside the drainpipe upon excavation.

3.4. *Causes of failure in Hydroluis performance*

From the above discussion, we can conclude that in an unstable fine-textured soil, the Hydroluis drainpipe may fail, as soil may clog the space between the inner and outer pipes. The pre-wrapped PP450 envelope, in contrast, maintained acceptable drainage performance. This raises the question of what could cause soil mass movement between the inner and outer pipes of the Hydroluis system and why the PP450 envelope retains its filter function even in such an unstable fine-textured soil. First we look at the drag forces.

3.4.1. *Drag forces at the soil-envelope interface*

The performance of a drain envelope material depends mainly on the relative stability of soil particles at the soil-envelope interface. Water passing through a saturated soil exerts a frictional drag force on soil particles. As the soil water velocity increases approaching the drain envelop, the forces exerted by the water on soil particles may reach a limit at which the soil particles can no longer resist the drag forces of the water. At that point the soil particles begin to separate. Water velocity reaches its maximum at the soil-envelope interface, where flow lines have maximum convergence. Flow enters the PP450 drainpipe from a circular perimeter around the synthetic envelope, while the design of the Hydroluis drainpipe compels the flow to enter the drainpipe only from two narrow spaces below the drainpipe (Fig. 9). This latter flow pattern results in greater convergence of flow lines at the Hydroluis soil-envelope interface, increasing flow velocity and drag forces below the drainpipe.

The wetted area of the envelope in contact with the soil conveying the water determines the flow velocity at the soil-envelope interface and thus the risk of soil erosion. We compared the flow velocity ($v = q/A$) of the Hydroluis and PP450 drainpipes at their soil-envelope interface with a saturated soil profile using the following assumptions:

- The Hydroluis and PP450 drainpipes have the same drainage rate (q).
- Envelopes are much more permeable than the soil nearby.
- No clogging exists of the envelope, perforations or in the soil.

We see that, for the same drainage rate, the flow velocity at the soil-envelope interface is 21.5 times greater for the Hydroluis drainpipe than the PP450 drainpipe (Eq. 2). In other words, soil erosion at the soil-envelope interface is far more likely to occur with the Hydroluis drainpipe than the PP450 drainpipe. Therefore, with the Hydroluis system, soil particle movement takes place at lower hydraulic gradients and lower drainage rates compared to the PP450 drainpipe.

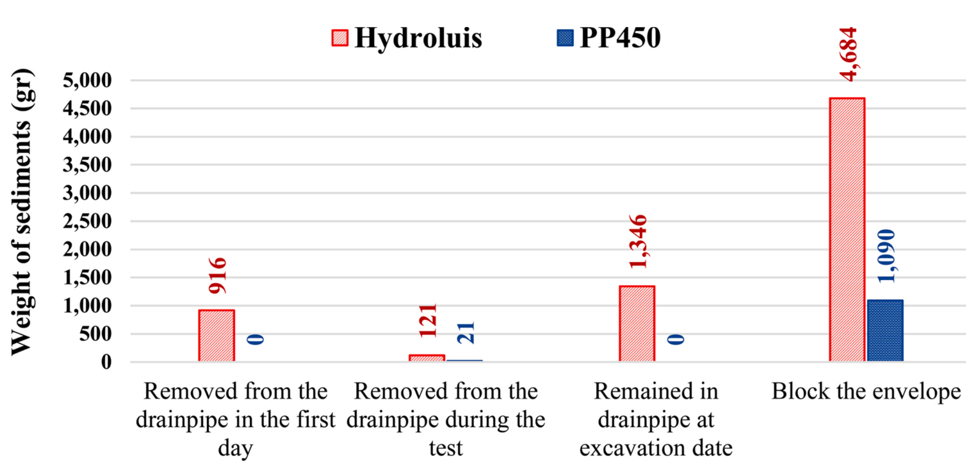

Fig. 6. Final destination of sediment that entered the Hydroluis and PP450 drainpipe-envelope systems.

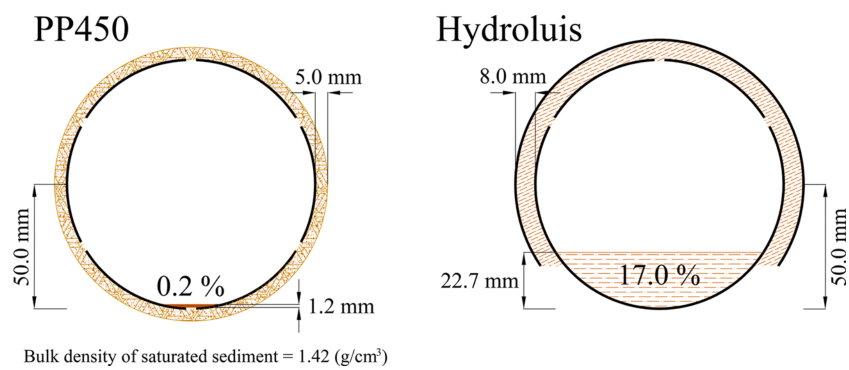

Fig. 7. Volumetric percentage and depth of the sediment that entered the drainpipes during the test.

Table 4
Physical characteristics of three sediment samples from the Hydroluis drainpipe-envelope system and the original test soil.

No	Soil samples	Mastersizer analysis (USDA classification)				Coefficient of uniformity (C_U)	Coefficient of curvature (C_c)
		Sand (%)	Silt (%)	Clay (%)	Soil texture	d_{60}/d_{10}	$d_{30}^2/(d_{10}*d_{60})$
1	Original soil	5.3	54.7	40.0	Silty clay (-loam)	17.29	0.73
2	Sediment removed on first day with drainage outflow	9.6	52.1	38.3	Silty clay loam	18.47	0.79
3	Sediment remained in inner pipe	7.6	55.0	37.4	Silty clay loam	19.76	0.85
4	Sediment retained between inner and outer pipes	4.7	58.4	36.9	Silty clay loam	22.47	0.79

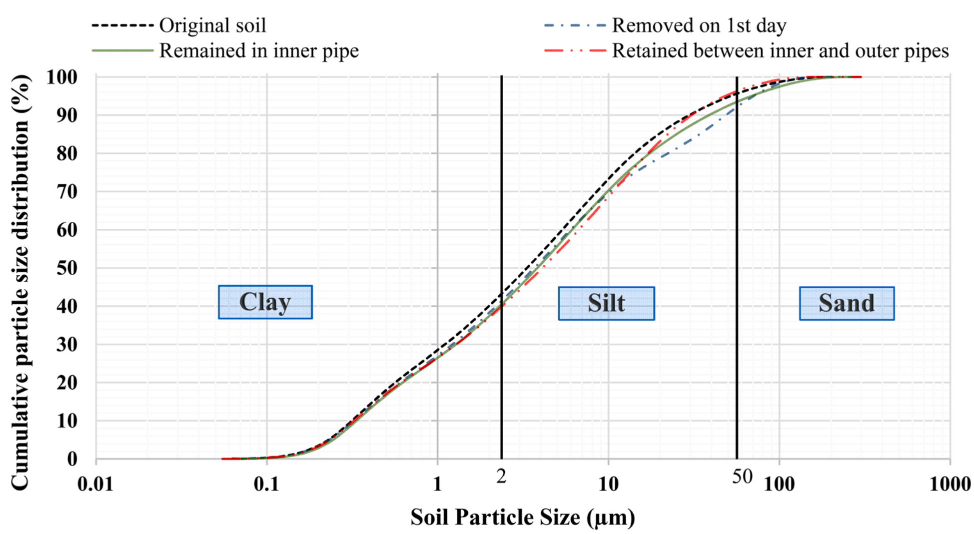

Fig. 8. Soil particle size distribution curves for original test soil and Hydroluis sediment samples.

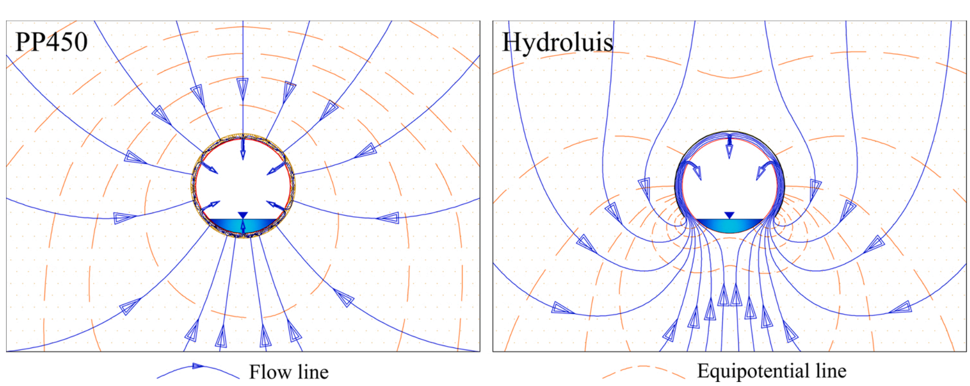

Fig. 9. Pattern of flow and equipotential lines near the PP450 drainpipe and the Hydroluis drainpipe.

$$\frac{v_{Hyd}}{v_{PP450}} = \frac{A_{PP450}}{A_{Hyd}} = \frac{\pi \times (D + 2t)}{2 \times d} = \frac{\pi \times (10 + 2 \times 0.487)}{2 \times 0.8} = 21.5 \quad (2)$$

where, v is the flow velocity at the soil-envelope interface (cm/hr), A is the effective area of flow at the soil-envelope interface per unit length of the drainpipe (cm^2), D is the diameter of the drainpipe (cm), t is the thickness of the synthetic envelope for the PP450 drainpipe (cm) and d is the distance between the inner and outer pipes for the Hydroluis drainpipe (cm).

3.4.2. Ability of drainpipes to retain soil particles

At very low moisture contents, soils behave more like solids, though when moisture content is high, the soil and water mix can behave more like a liquid. In 1911, Swedish scientist Albert Atterberg developed a method to describe the consistency of fine-grained soils at varying moisture contents. He defined the plastic limit (PL) and liquid limit (LL) as soil water contents at which the mechanical properties of soil change (Atterberg, 1911). According to Atterberg, when soil water content exceeds the liquid limit, the soil mass may flow like a liquid. However, the liquid behaviour of a soil seems to be related not only to soil water content but also to hydraulic gradient.

The plasticity limit and liquid limit of our test soil were 18.5 % and 34.8 %, respectively, resulting in a plasticity index (PI) of 16.3 %. According to Sowers (1979), this classifies the test soil as medium plasticity ($7 < PI < 17$). Therefore, mass movement of the test soil is likely in saturated conditions with a high hydraulic gradient, which is the case for most subsurface drainpipes after a heavy rainfall or irrigation. This suggests that an envelope material is needed around the drainpipe to inhibit soil mass movement in such conditions.

A frequently used retention criterion for synthetic envelopes is O_{90}/d_{90} ratio. Here, O_{90} is the pore size for which 90 % of envelope pores are smaller, and d_{90} is the particle diameter of the soil in contact with the envelope for which 90 % of the particles, by weight, is smaller. Stuyt (1992) found in three experimental plots in the Netherlands that envelopes with large O_{90} values had poorer soil retention properties. Dierickx and Van der Sluys (1990) recommended the following simple retention criterion for synthetic geotextiles and prewrapped loose materials (PLMs) to minimize the risk of mineral clogging of subsurface drainage installations: $1 \leq O_{90}/d_{90} \leq 4$ for envelope thickness between 3 and 5 mm with $O_{90} \geq 200$ µm.

For PP450, O_{90}/d_{90} is 3.75 times greater than the upper limit recommended by Dierickx and Van der Sluys (Table 5). However, the retention function of the PP450 envelope proved acceptable in our test soil. On the other hand, though the O_{90}/d_{90} criterion was not developed for envelope designs such as the Hydroluis envelopes, the 18 times higher value of this retention criteria for the Hydroluis drainpipe than PP450 drainpipe may explain the poor retention function and the mass movement of the base soil into the space between the inner and outer pipes of the Hydroluis drainpipe.

3.5. Evaluation of the current Hydroluis desing and recommendations for future application or design

In this section the pattern of filter behaviour of the Hydroluis drainpipe is described, assuming the Stokes' Law is the governing rule of the filter function. Then, based on the Stokes' Law, the current design of Hydroluis drainpipe is evaluated. Also, suggestions are provided for application of the current design of Hydroluis drainpipe or for designing new generations of Hydroluis drainpipes.

In well-structured soils with low hydraulic gradients, the soil mass may stay stable and not enter the space between the inner and outer pipes of the Hydroluis system, even under saturated conditions. Yet, individual soil particles will never stop moving and may clog the drainpipe gradually.

Table 5
Retention criteria of the Hydroluis and PP450 drainpipes in the test soil.

Drainpipes	Envelope thickness/ Opening (mm)	O_{90}_ envelope (µm)	d_{90}_test soil (µm)	O_{90}/d_{90}
PP450	4.87	450	29.67	15
Hydroluis	8	8000	29.67	270

3.5.1. Stokes' Law governing filter function

A soil particle may be filtered by the Hydroluis drainpipe if the downward falling velocity of that particle in the water suspension between the inner and outer pipes is greater than the upward velocity of flow. According to Stokes' Law (Stokes, 1851), the falling velocity of a soil particle is related to the diameter squared of that soil particle as follows:

$$v = \frac{g(d_s - d_w)D^2}{18\eta} = \frac{980(2.65 - 0.997)D^2}{18 \times 0.0089} = 10112\ D^2 \quad (3)$$

where, v is the velocity of the falling particle (cm/s), g is acceleration due to gravity (980 cm/s^2), d_s is the density of the particle (g/cm^3, 2.65 for most mineral soils), d_w is the density of the medium (g/cm^3, 0.997 for water at 25 °C), D is the diameter of the particle (cm) and η is the absolute viscosity of the medium (dyn-s/cm^2, 0.0089 for water at 25 °C).

Stokes' Law is based on assumptions which somewhat limit its application in real conditions. These assumptions include (i) the falling soil particles are smooth spheres, (ii) terminal velocity is reached instantaneously, (iii) resistance when settling is due to fluid viscosity and is not influenced by the wall of the pipes, (iv) soil particles move individually and there is no interaction between them and (v) no variation occurs in the temperature of the fluid.

3.5.2. Maximum allowable drainage rates and spacing

Accepting Stokes' assumptions, we calculated the velocity of falling particles between the inner and outer pipes of the Hydroluis system using Eq. (3) for the problem soil particle sizes (silt and fine sand) as classified by the USDA (Soil Science Division Staff, 2017). Based on the lower limit diameter in each textural class, we calculated the maximum allowable velocity between the inner and outer pipes and the corresponding maximum allowable drain discharge per unit length of the Hydroluis drainpipe (Table 6). For instance, to avoid entry of fine silt particles into the drainpipe, the velocity of falling particles between the inner and outer pipes of Hydroluis must remain less than 1.46 cm/hr, corresponding to a drain discharge of 0.23 L/hr/m. Clay particles ($D <$ 0.002 mm) in subsurface drainage, however, are not considered problematic, since these very fine particles can safely remain in suspension and be removed with drain outflow.

The drainage rate of the Hydroluis drainpipe on the first day of the experiment, when the most soil invasion into the pipe occurred, was 6.24 L/hr/m (≈249.6 mm/day). This is 27 times greater than the lower limit calculated for the drain discharge for fine silt particles (0.23 L/hr/

Table 6
Maximum allowable velocity between inner and outer pipes and drain discharge for Hydroluis drainpipe in stable soils for problem soil particles.

Textural name	Textural subclass	Particle diameter, D (mm)		Maximum allowable inter-pipe velocity (cm/ hr)	Maximum allowable drain discharge per unit length (l/ hr/m)
		Lower limit	Upper limit		
Sand	Fine sand	0.1	0.25	3640	582
	Very fine sand	0.05	0.1	910	146
Silt	Coarse silt	0.02	0.05	145.6	23.3
	Fine silt	0.002	0.02	1.46	0.23

m, ≈9.3 mm/day). Thus, if the test soil in our laboratory experiment had remained stable, only fine silt particles would be expected to enter drainpipe.

To make the results of Table 6 more practical, we converted the maximum allowable drain discharge per unit length of Hydroluis drainpipe to equivalent maximum drainage rates and drain spacing for problem soil particles (Fig. 10). Fine silt and coarse silt are the soil particles that, if abundant in the soil profile, can seriously limit the Hydroluis drainpipe application. In particular, in soils with a large proportion of fine silt particles, Hydroluis drainpipe can only be used in unreasonable low spacing and drainage rates (L_m =5.6 m for q_m =1 mm/day). Coarser soil particles ($D > 0.05$ mm), on the other hand, are not an impediment to Hydroluis drainpipe application in usual drainage practices.

3.5.3. Estimating maximum project drainage rate

The maximum drainage rate of a project is an important factor for predicting the filter performance and possible clogging of the Hydroluis drainpipe. The maximum probable drainage rate needs to be carefully estimated in a particular drainage project to ensure that no problem soil particles enter the drainpipe. The maximum drainage rate is dependent on project drainage properties, such as the saturated hydraulic conductivity of the soil profile, drainage depth, drain spacing, drain radius and depth to the impermeable layer. Skaggs (2017) proposed the maximum subsurface drainage rate equivalent to a saturated profile with a ponded surface. Providing that the hydraulic capacity of the drainage network is greater than the maximum drainage rate, he suggested equations developed by Kirkham (1957) for calculating this drainage rate. Therefore, to use Hydroluis drainpipe in a subsurface drainage project, it is recommended that the maximum probable drainage rate of the project be compared to the maximum allowable drainage rate proposed in Table 6 and Fig. 10. If necessary, drain spacing can be adapted to account for the finest problem soil particles found in the soil profile.

3.5.4. The role of inter-pipes distance in filter function

The distance between the inner and outer pipes (d) determines the inter-pipe upward flow velocity and filter function of the Hydroluis drainpipe. Future studies thus may focus on different d spacing to improve filter function of the Hydroluis drainpipe in different soils. Increasing the d spacing is one feasible way to decrease inter-pipes flow velocity and possibly improve the filter function in stable silty soils. Based on the Stokes' Law, coarse silt particles, for example, at a drain spacing of 100 m can only be filtered at a maximum drainage rate of 5.6 mm/day with the current design of the Hydroluis pipe (Fig. 11). For coarse silt particles, the design of the Hydroluis drainpipe at this spacing can be improved by increasing the d spacing, from 0.8 cm to 1.1 and 1.4 cm, to safely withstand maximum drainage rates of 7.5 and 10 mm/day, respectively. Nevertheless, the current Hydroluis drainpipe design remains unsuitable for filtering fine silt particles even at low maximum drainage rates, nor can it be logically improved by increasing d. For instance, a subsurface drainage project with a drain spacing of 30 m and a maximum drainage rate of just 2 mm/day would need a Hydroluis drainpipe with an unreasonable d spacing of 8.6 cm.

It should be noted that although increasing the distance between the inner and outer pipes may improve the filter function of the Hydroluis drainpipe, such an increase conflicts with the retention function of the drainpipe. This is because the larger the distance between the inner and outer pipes (larger O_{90}) the poorer will be the retention function of the Hydroluis drainpipe and easier will be mass movement of the base soil.

3.6. Justify good field performance of the Hydroluis in Turkey

The above mentioned discussions may explain why the Hydroluis drainpipe did not clog in the field test conducted by Bahçeci et al. (2018) in Turkey. As they reported, the field in which the Hydroluis drainpipe was installed had an average clay content of 59 %, a saturated electrical conductivity of 0.91 dS/m and 34 % of lime. They, however, did not report detailed chemical compositions of their soil, including ESP percentage. Non-saline soils (ECe < 4 ds/m) with clay content more than 30 % are generally stable enough and there is no need for an envelope. In addition, considerable amounts of lime, a traditional soil amendment, will increase the soil stability and stabilize soil particles to withstand higher drag forces at the soil-envelope interface. Therefore, considering the facts that clay soils generally have a low hydraulic conductivity, we suppose that in absence of the problem soil particles in the soil profile, the flow velocity at the soil-envelope interface of Hydroluis drainpipe under the maximum drainage rate of the field experiment in Turkey would have remained below the limit at which soil erosion and mass movement of the base soil could occur.

4. Conclusion

This study compared the hydraulic and filter functions of the Hydroluis drainpipe-envelope system to a locally manufactured synthetic envelope drainpipe (PP450) in a soil tank laboratory model with a saline-sodic problem soil from south-western Iran. The test showed that existing criteria for determining the need for an envelope are

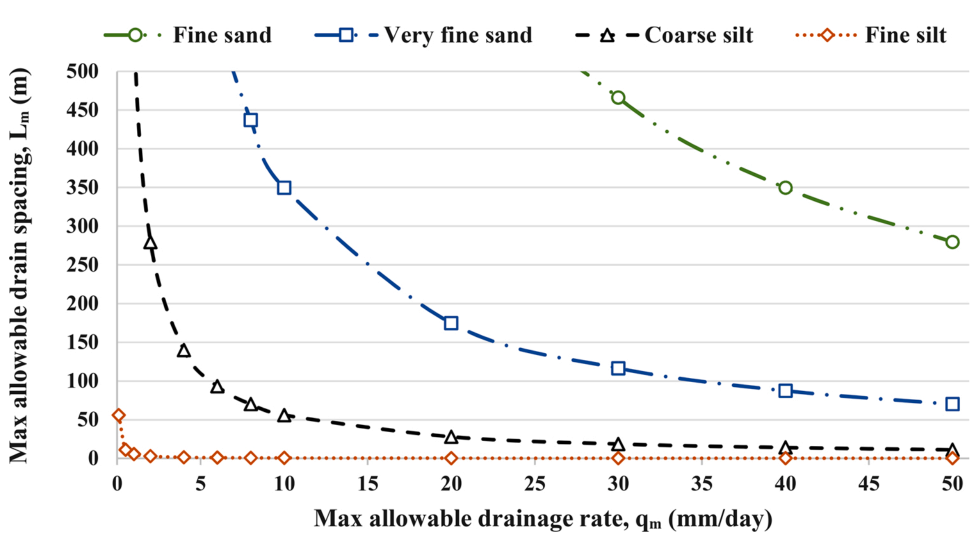

Fig. 10. Maximum allowable Hydroluis drainpipe spacing and drainage rates for problem soil particles.

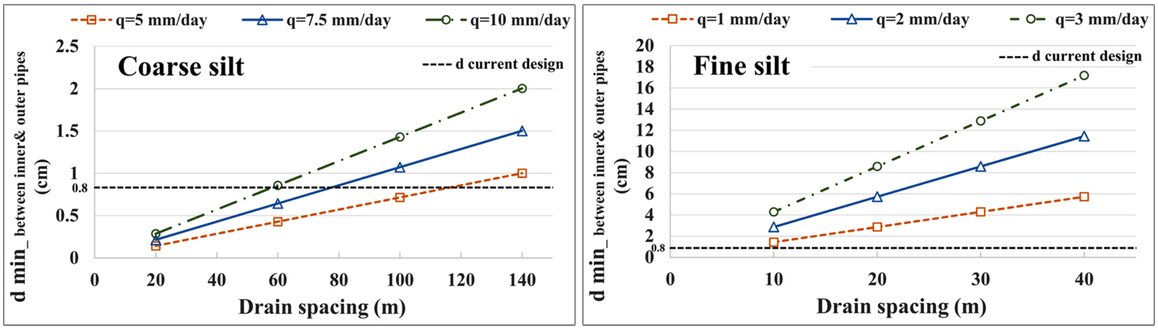

Fig. 11. Minimum distances between the inner and outer pipes of the Hydroluis drainpipe for fine and coarse silt particles.

inconsistent with local experiences with the saline-sodic soils (ESP > 15 %) in Khuzestan Province, Iran. In the laboratory tests, the hydraulic and filter functions of the Hydroluis drainpipe were poor because soil around the drainpipe lost its stability and completely clogged the space between the inner and outer pipes. In contrast, the PP450 envelope had satisfactory drainage function, stabilizing at a drainage rate of 28 mm/day and an entrance resistance of 55 days/m, at around day 50. The results of PP450 drainpipe confirm previous findings in soil tank models performed with soils from Khuzestan Province.

This study showed that, contrary to the assumption of the Hydroluis designers, soil particles of an unstable soil may clog the space between inner and outer pipes of Hydroluis drainpipe and significantly reduce the pipe retention and hydraulic functions.

Possible explanations for the poor drainage function and clogging of the Hydroluis drainpipe are the 21.5 times higher flow velocity at the soil-envelope interface, in addition to the 18 times lower soil retention capacity of the Hydroluis drainpipe compared to PP450 drainpipe. Therefore, soil erosion at the soil-envelope interface is far more likely to occur with the Hydroluis drainpipe than the PP450 drainpipe. Installing Hydroluis drainpipe in unstable soils or with high hydraulic gradients and drainage rates warrants careful consideration.

Stokes' Law indicates that very fine sand or coarser soil particles ($D > 0.05$ mm) place no important limitations on use of the Hydroluis drainpipe in stable soils. Our results, however, indicate that silt particles can seriously limit the applicability of this drainpipe. Our results suggest that Hydroluis, as currently designed, is unsuitable for filtering fine silt particles ($0.002 < D < 0.02$ mm), even at low rates of drainage and close spacing. Therefore, use of the Hydroluis drainpipe in stable soils with a high percentage of fine silt is not recommended. Additionally, to avoid entry of coarse silt ($0.02 < D < 0.05$ mm) into the drainpipe, it is suggested that the drain discharge per unit length of the Hydroluis drainpipe remains lower than 23.3 L/hr/m.

For use of the Hydroluis drainpipe in unstable soils or fine silty soils we recommend a voluminous (or even thin) layer of envelope beneath the Hydroluis drainpipe. This layer can significantly improve the hydraulic and filter functions of the drainpipe not only by diminishing the convergence of flow lines and flow velocity at the Hydroluis soil-envelope interface but also by reducing the retention ratio of O_{90}/d_{90}.

It is doubtful that increasing the distance between the inner and outer pipes would improve the filter function of the Hydroluis drainpipe because larger inter-pipe distance would reduce the retention function of the drainpipe, resulting in easier soil instability and mass movement of soil into the drainpipe.

Thus, we conclude that the Hydroluis drainpipe does not perform well in saline-sodic soils, such as those found in south-western Khuzestan Province, Iran. This experiment, however, was carried out in the laboratory with a disturbed sample of a very unstable soil type. Results may differ under field conditions. Further laboratory and field studies are recommended to test the Hydroluis drainpipe with different hydraulic gradients and drainage rates in different soil types to determine the stability limit of soil around the drainpipe and better understand the clogging process and likelihood.

CRediT authorship contribution statement

Seyed Abdollah Alavi: Formal analysis, Conceptualization, Visualization, Writing - original draft, Writing - review & editing, Data curation. **Abd Ali Naseri:** Supervision, Conceptualization, Methodology. **Azam Bazaz:** Investigation, Methodology. **Henk Ritzema:** Supervision, Writing - review & editing. **Petra Hellegers:** Project administration.

Declaration of Competing Interest

The authors report no declarations of interest.

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