Evaluation of friction head loss as a function of media filter performance via different underdrain types and media specifications

Mohamed Gamal Hussien Zaki[1,2*], Mohamed EL-Sayed Abuarab[1], Wael Mahmoud Sultan[2], Mohamed Abd El-Wahab Kassem[1]

(1. Agricultural Engineering Department, Faculty of Agriculture, Cairo University, Egypt. PO box 12650, Giza, Egypt
2. Irrigation and Drainage Department, Agriculture Engineering Research Institute. PO box 12613, Giza, Egypt)

Abstract: The main objective of this study was to assess the combination effect of media types, media bed depths, drain types and number of drains on friction head loss in media filter. An experimental study with scaled media filter prototype was conducted with three different media types (basalt, crushed marble and sand), three media bed depths (30, 50 and 70 cm), and three commercial underdrain types referred as a single (SD1, SD2 and SD3) and double underdrain (DD1, DD2 and DD3) under three superficial velocities (50, 87.5 .5 and 125 m h^{-1}). Under single drains, the best operating combination i.e., minimum friction head loss H_L was achieved using (SD2, 30 cm of basalt and 50 m h^{-1}), which was 63.5 mbar. While the maximum H_L was 991 mbar resulted by the following combination: SD3, 70 cm of sand and 125 m h^{-1}. On the other hand, as expected the H_L values under DD for the three underdrain types were lower than SD. The minimum H_L value was 41 mbar under the following combination DD2, 30 cm basalt and 50 mh^{-1}. While, the maximum H_L was 578.3 mbar for: DD3, 70 cm of sand and 125 m h^{-1}. The results showed that the H_L of basalt produced reliable results ($p < 0.05$; $R^2 = 0.806$) in relation to values derived from the independent variables superficial velocity, underdrain type, number of drains and media bed depth. The results emphasized the role of proper selection of underdrain types and number as an impacting factor for saving power in comparison to the other mentioned variables.

Keywords: media filter, friction head loss, underdrain, superficial velocity, granular bed

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1 Introduction

Currently, the irrigation water, confronting many obstructions in adapting to new models, such as environmental laws stress, the high cost of energy and decreasing in water resources as a comparison with rapid population growth, and reduction in agricultural water availability. according to these reasons the agriculture taking the way to non-conventional water resources, using the waste drainage water treatment, rain harvest and water desalination in irrigated water (Trooien and Hills, 2007).

Irrigated agriculture was represented 20% of the cultivated land worldwide in 2012, but it contributed 40% of the total food production (Valipour, 2015). The micro-irrigation systems increase the water efficiency compared to the other systems of irrigation (Lamm et al., 2007). However, it is only used worldwide in 3% of the irrigated land. The total world micro-irrigated land increased by 31% from 1990 to 2012 on the other hand the total

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[*]**Corresponding author: Mohamed Gamal Hussien Zaki,** Ph.D., Associate Professor of Agricultural Engineering Department, Faculty of Agriculture, Cairo University, Egypt. E-mail: zaki.m.gamal@gmail. Tel: +2-01100476010.

irrigated land only increased by 22% in the same period (Valipour, 2015).

The hydraulics performance of micro-irrigation systems affects the efficiency of the emitters. One of the main constraints to the use of micro-irrigation systems is the emitters clogging and the high cost of construction and operation. This has led farmers to not use this system. In order to avoid these constraints using physical, chemical or both treatments (Mesquita et al., 2012).

The sand media filter is the most used type in micro-irrigation systems, especially when the water contains effluents (Burt and Styles, 2007). That is recommended filter when there are algae in the irrigated water (Naghavi and Malone, 1986) or high percentage of other organic components (Haman et al., 1989). In addition, the sand media filter can guarantee high hydraulic performance for the micro irrigation system especially when using poorly treated wastewater (Abd El-Hameed et al., 2018; Capra and Scicolone, 2007).

In the process of filtration and backwashing, the necessary precautions should be taken when running the filter to avoid the fine particles from causing emitters clogging, Especially, when new media are used, it is recommended to conduct several initial back flushing and to get rid of the initial backwashing water (Elbana et al., 2013).

The underdrain system and the diffuser plate are the main internal auxiliary components, which affect the friction head loss in sand media filters. Therefore, the head loss resulting from the passage of water inside the internal parts of the sand filter and the head loss as a result of passage of water through sand granules is the total friction head loss in the sand filter (Testezlaf, 2008). On the other hand, the other internal auxiliary component which affected in friction head loss is back flushing valve (Burt, 2010). The friction head loss in underdrain system increases with filtration surface velocity (Bové et al., 2015; Burt, 2010; Mesquita et al., 2012).

The head loss in sand media filters can be more important in the underdrain elements than in the filter bed as reported by previous studies. Another research design a new underdrain could reduce the head loss by 50% compared with a scaled commercial filter taken as reference, especially under backwashing conditions (Bové et al., 2017).

Additional filtration processes are recommended to maintain the system at acceptable performance, especially at sedimentation loads of 50 mgL^{-1} and more. Emitter design should be carefully considered before making water treatment recommendations. Head loss development across the filter media is directly proportional to the bed depth, sedimentation loads and accumulated filtration time and inversely with the medium size (Schwankl et al., 2008).

The head loss produced by media filters in clean condition has a practical interest as the designer must select the pump that overcomes the friction of a clean filter, plus an additional loss due to accumulated dirt. When the total loss equals a pre-set value, the filter will automatically back flush (Chang et al., 1999; Clark et al., 2007; Mesquita et al., 2012). However, few studies analyze the effect of the auxiliary components of media filters on head loss, which is related to water and energy consumption as well as filter efficiency.

Pump discharge and pressure requirements in micro-irrigation systems are usually determined by manufacturer's filter specifications, which may be 50% to 100% higher than those of the emitters and drip lines (Burt, 2010).

Pujol et al. (2016) found that the energy required to filtration reduced to 25% at the same open area of the drain nozzle, a proper location of the slots, with some at the top of the cylindrical nozzle. When substituting the classical nozzle with an underdrain using 40% more slots in its cylindrical surface the filter efficiency had increased.

The performance of the media filter operation is affected by the amount of water which passes through the media particles. The amount of this water decreases progressively by the suspended solids trapped in the filtration medium (Lamm et al., 2007). The time and/or head loss across the filter are two common factors which are controlled in automatic backwashing process. The rat holes form is defined as the large and interconnected pores in the sand medium and, this holes decreasing the filter performance especially, when sand media filters are not flushed frequently enough (Lamm et al., 2007). In the case of rat holes, the head loss across the filter is not a good indicator of backwashing process. Therefore, the frequently backwashing is recommended (Pitts et al., 1990). The intervals spaces and durations time reduces of backwashing caused to decreasing the performance in subsurface drip irrigation systems (Enciso-Medina et al., 2011).

The most common indicator for back flushing process is a differential pressure between the inlet and outlet filter. The back flushing process is a verse of the filtration process in flow direction. Which water moving from down to back flushing line and carry out the suspended particles through the media porous to outside the filter.

The daily backwashing is a maintenance practice recommended to increase dissolved oxygen and reduces inefficient backwashing that is usefully when hypoxic water used in irrigation. A 15 min is a recommended period from the experiment for the filter ripening (Elbana et al., 2012).

Bové et al. (2017) designed a new underdrain for a micro-irrigation sand filter that resulted less pressure loss to 25% in lower superficial velocity <0.01 ms^{-1} and 45% in higher superficial velocity > 0.02 ms^{-1} under silica sand grain size between 0.63 and 0.75 mm and a height of 300 mm

Mesquita et al. (2012) studied sand characteristics such as sand particles effective size (0.5, 0.85 and 1.15 mm), and media bed depths (20, 29 and 37.5 cm) on pressure drop through sand filter. The results revealed that head loss of the filters is significantly affected by sand characteristics on pressure drop in sand filter.

The main objectives of this study were to evaluate the effect of media types, media bed depths, drain types and number of drains on friction head loss in media filter and the interaction between these parameters under three superficial velocities.

2 Materials and methods

2.1 Experimental site

Laboratory experiments were carried out at the Egyptian ministry of agriculture and land reclamation, Agricultural Research center (ARC), National Irrigation Laboratory of Agricultural Engineering Research Institute, Giza, Egypt. The research experiments were carried out on a media filter prototype that was scaled to the filtration surface area as a dimension of the commercial filters. The prototype was connected by pressure drop test facilities that are measuring the friction head losses.

2.2 System installation and experimental treatments

In order to study the impact of various drain types on the filter performance, the prototype media filter was scaled to one drain nozzle. The commercial filter dimensions was 609.6 mm internal diameter and 600 mm filter height up to the drain system. It also had 15 underdrain cups thus, the filter dimensions was rescaled to one drain nozzle Therefore, and the same volume flowed through the scaled underdrain nozzle. The prototype inner plate was welded at 140 mm above the bottom of the filter to fit the underdrain element (nozzle) and to support the sand. A centrifugal pump (ALLWEILER FARID NT 40-80) was used for suction of the water from a tank and to provide the pressure to the filter. Flow rate was measured by using a flow meter (ENDRESS+HAUSER, PROMAG F, GERMANY).

The prototype filter dimensions were 160 mm outer diameter with wall thickness 1.8 mm, filter high 900 mm up to the underdrain plate and filter had total filtration surface area 192.11 cm^2.

Figure 1 shows the different drain types while table 1 illustrate the drain specifications. The inlet and outlet diameter were 25 mm. The differential pressure was connected after the inlet valve and before the outlet valve.

The experimental treatments included three types of underdrain cups, which were used as a single underdrain (SD1, SD2 and SD3) and a double underdrain (DD1, DD2 and DD3). Three types of media (basalt, crushed marble and sand) with media depths of 30, 50 and 70 cm and three superficial velocities of 50, 87.5 .5 and 125 m h^{-1} were tested for each underdrain.

Each treatment was replicated three times. In each replication, filter performance was assessed at three different filtration surface velocities 50, 87.5 and 125 m

h^{-1}. Thus, a total of 486 experimental points were obtained.

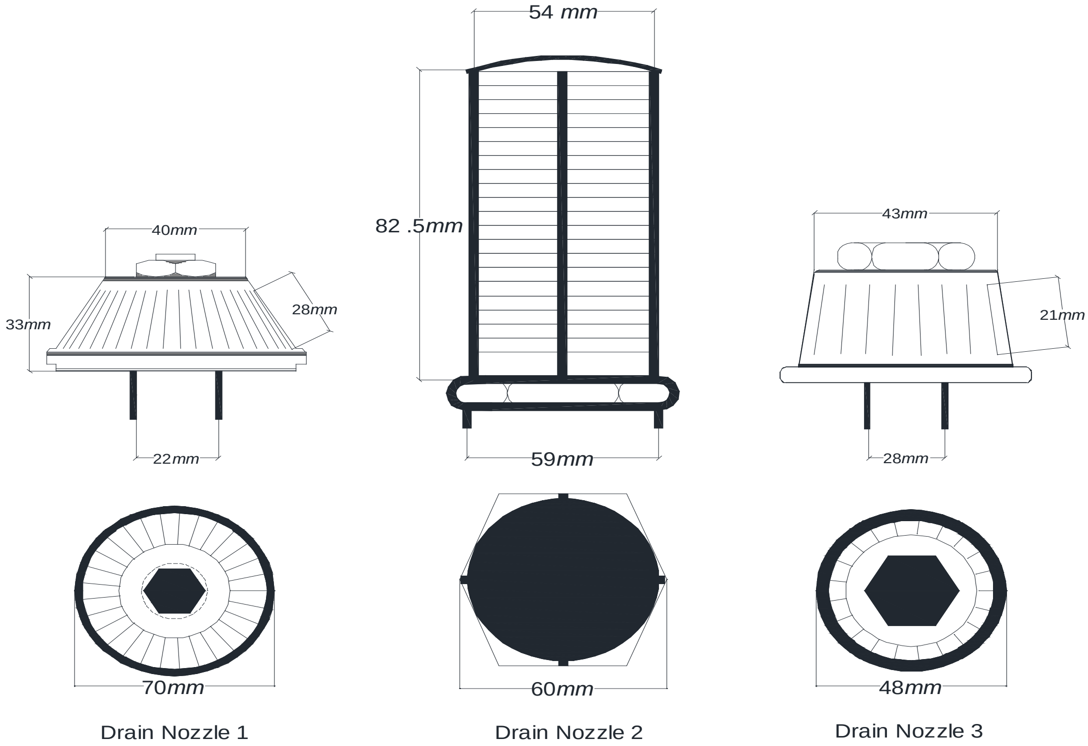


Figure 1 Types of underdrain.

Table 1 The three underdrain cups specifications

Parameter	Drain type		
	Underdrain 1	Underdrain 2	Underdrain 3
Mean slot length (mm)	28	29	21
Mean slot width (mm)	0.5	0.3	0.025
Slot number (mm)	40	84	26
Drain opening area (mm^2)	560	730.8	13.65
Drain effective area (mm^2)	2.914	3.804	0.06
Drain outlet diameter (mm)	22	59	28

2.3 Media properties

Basalt, crushed marble and sand were the three media used in the experiment. These types were selected as the most frequently media used in Egypt. The mechanical analysis and physical properties were done by using 1 kg of homogenous media to determine the particle size distribution curve, Bulk density, Particle density, and Porosity (Table 2). The following physical parameters for each medium were determined: bulk density, particle density, equivalent diameter and porosity.

Table 2 Physical properties of the applied media types

Physical Parameter	**Media types**		
	Basalt	Crushed marble	**Sand**
Uniformity coefficient	1.56	1.28	1.6
Effective size D_{10} (mm)	1.6	2.1	2.5
Bulk density (g cm^{-3})	1.46	1.44	1.47
Particle density (g cm^{-3})	2.01	1.96	1.7
Porosity (%)	27.69	26.68	13.34
Void ratio (%)	38.29	36.73	15.38

The particle size distribution curve for the three types of media is shown in Figure 2. The mainly parameters that are determining the d_{10}, d_{60} to calculate the CU for three media types.

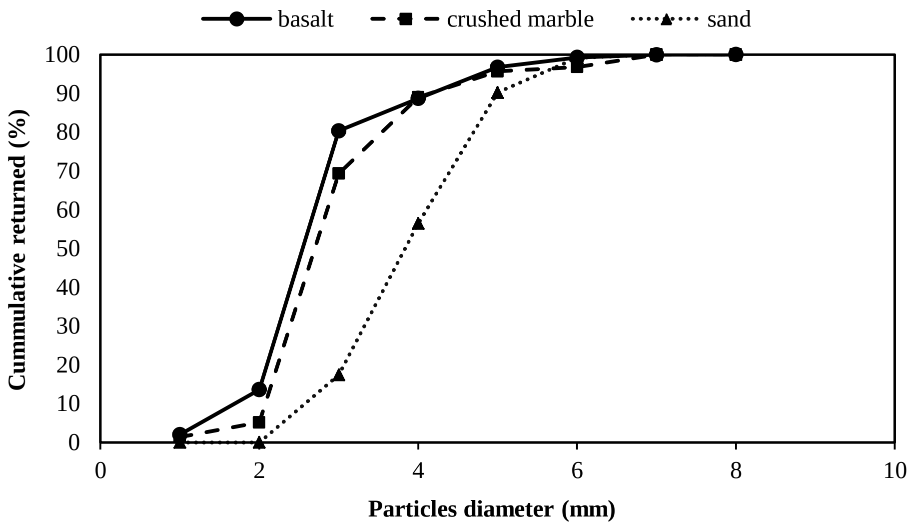


Figure 2 The particle size distribution curves

2.4 Pressure head loss test facilities

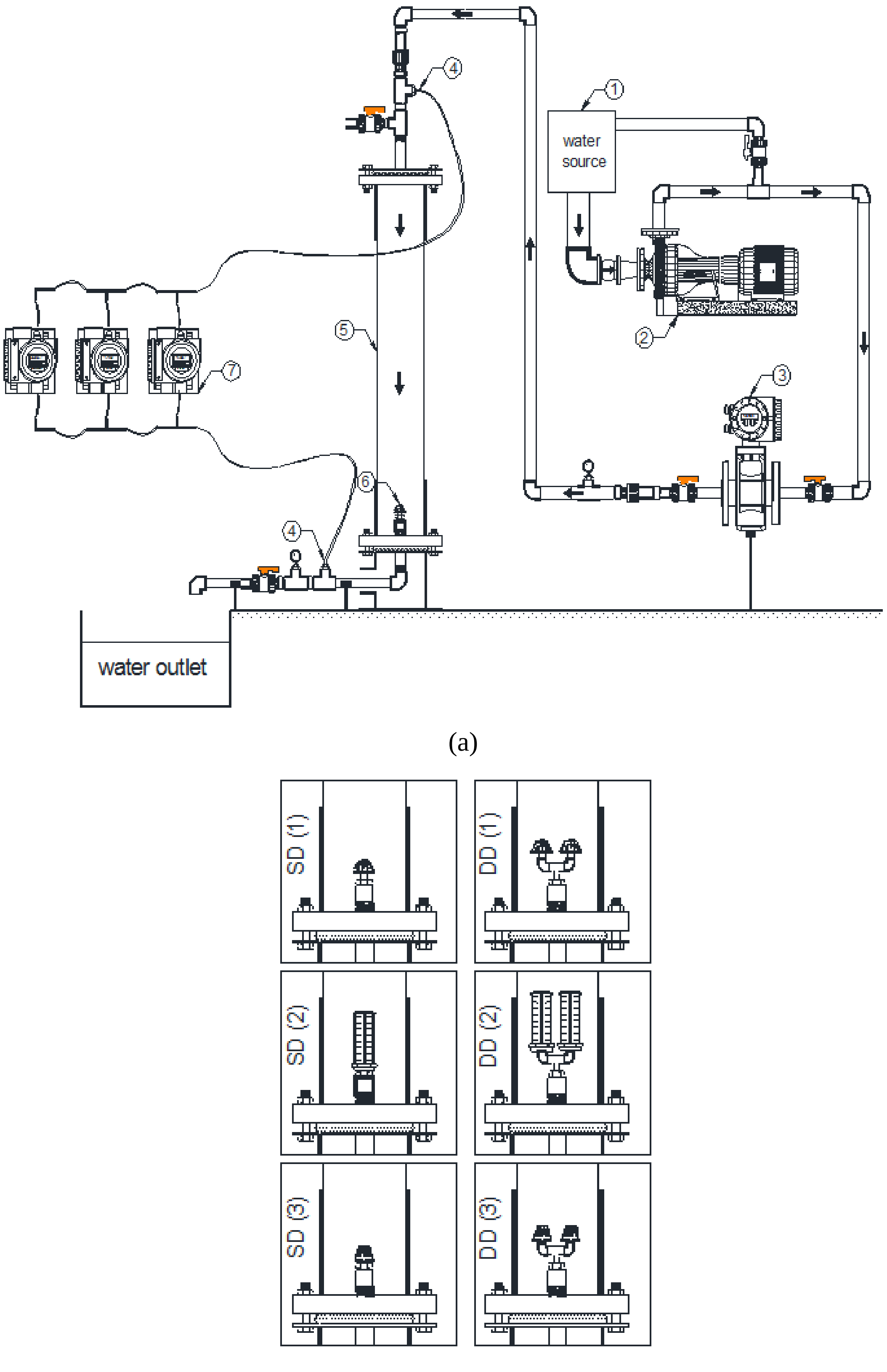
The pressure head loss test facilities have 75 mm main inlet diameter with three sub main lines with diameters 25, 50 and 75 mm respectively. Three digital flow meters jointed to the sub main lines with measure ranged from 0 to 20 $m^3 h^{-1}$, 0 to 60 $m^3 h^{-1}$ and from 0 to 100 $m^3 h^{-1}$ respectively. The differential pressure system contained three gauge with measure ranges 0 to 500 mbar, 0 to 2 bar and 0 to 6 bar connected in bypass (Three gauge recording at the same time). During the trials the pressure was measured at both inlet and outlet of the sand filter by a digital differential pressure (ENDRESS+HAUSER, DELTA BAR, GERMANY) with ± 0.07% accuracy (Figure 3). The total friction head loss was measured as combination of head expansion and throated in the inlet and the outlet of the filter in addition to the friction through media particles and drain nozzle.

The water flow was measured after 15 min from starting operation of the filter. Each friction head loss value was observed three time every 15 min in total 45 mine for one velocity.

2.5 Statistical analysis

The aim of the statistical analysis was to comprehensively evaluate the combination effect of media types, media bed depths, drain types and number of drains on friction head loss in media filter. Regression analysis was performed without applying an intercept to study the slope and fit of the regression equations between friction head loss for the three media types (basalt, crushed marble and sand) as dependent variables and the superficial velocity, media bed depth, and drain type as independent variables.

Relationships among dependent variables and independent variables were studied. Multiple regression analysis was performed as outlined by Draper and Smith (2014) to get the prediction equations to estimate the relative contribution of independent variables (R^2) in the total variation of the dependent variable, and stepwise multiple regression analysis that aims to determine the variables accounting for the majority of the total variability in dependent character. This procedure develops a sequence of multiple regression equation in a stepwise manner. Stepwise regression analysis was performed as described by Draper and Smith (2014). The statistical analysis was carried out using SPSS (ver. 20).



1. Water source, 2. Pumping Unit, 3. Flow meter, 4. Differential pressure lines, 5. Filter Body, 6. Underdrain Cup, 7. Differential pressure system

(a)Schematic sketch of experimental setup. (b). Experimental treatments for drain types and number.

Figure 5 Schema of experimental treatments.

Note: SD: Single Drain; DD: Double Drain

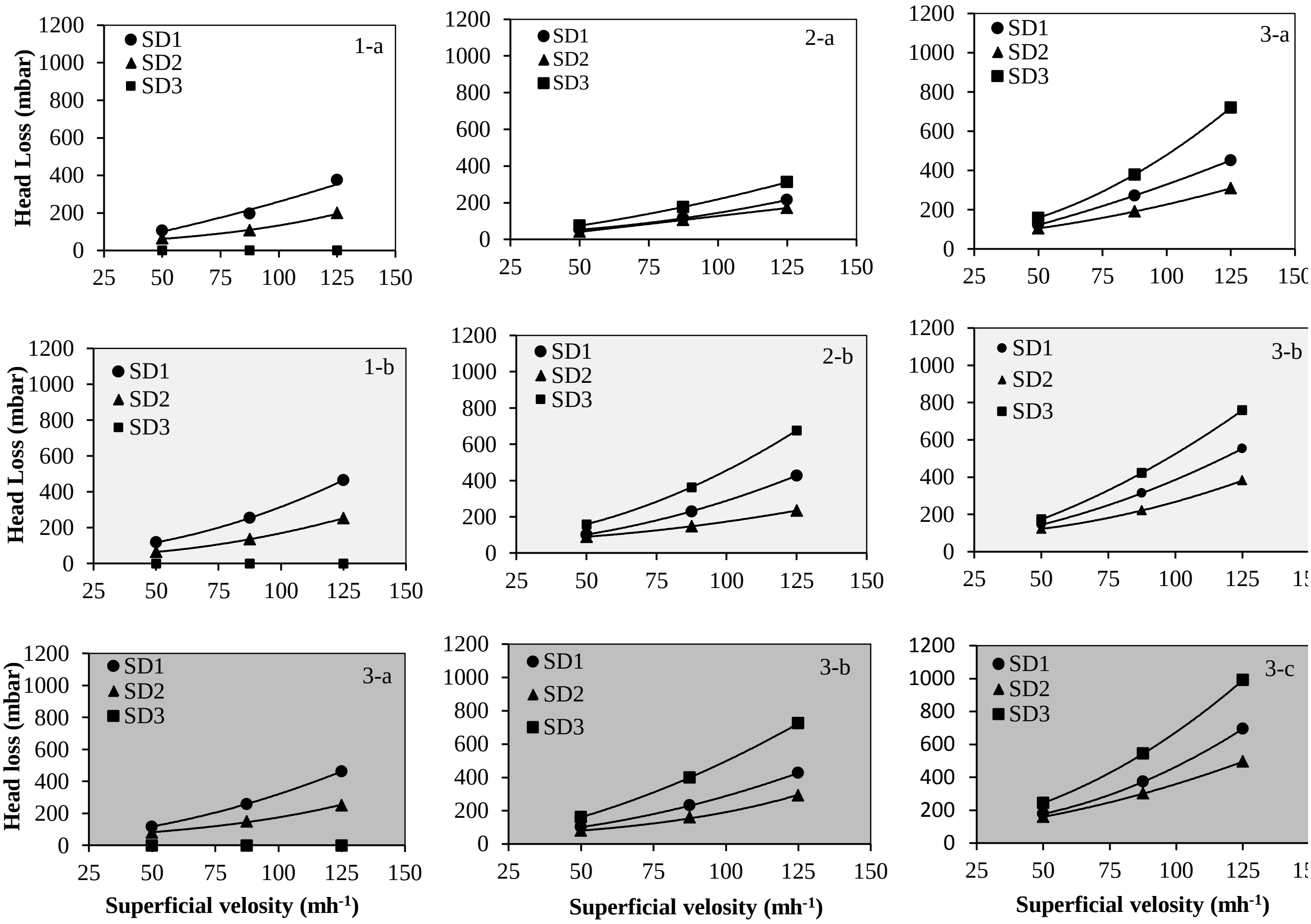
3 Results and discussions

3.1 Friction head loss

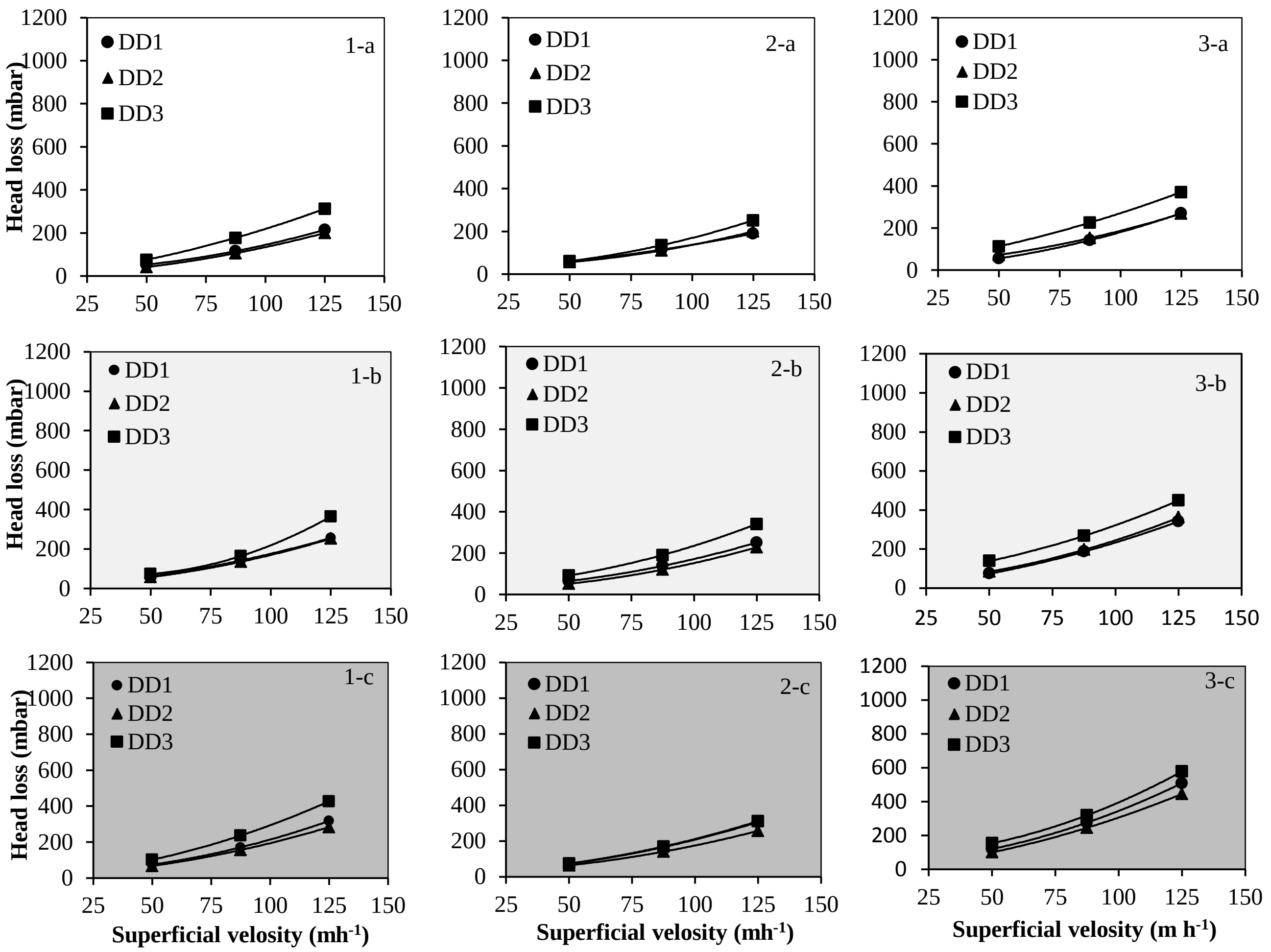
Results shows the main values of friction head loss (H_L) as a function of the superficial velocity ($^\gamma$) in the filtration flow direction. The minimum value of friction head loss was 63.5 mbar generated form SD2 under basalt with media bed depth 30 cm and superficial velocity 50 mh^{-1} (Figure 4-1a), while the maximum H_L was 991 mbar for SD3 in sand with medium bed depth 70 cm and superficial velocity 125 mh^{-1} (Figure 4-3c).

The friction head loss was directly proportional to media bed depth and superficial velocity. Therefore, the minimum values of H_L were 63.5, 68.8 and 105.2 mbar for basalt, crushed marble and sand respectively, they were generated from 30 cm media bed depth and superficial velocity 50 m h^{-1}. On the other hand, the maximum H_L values 465.2, 724.2 and 991 mbar for basalt, crushed marble and sand respectively, they were achieved under 70 cm media bed depth and superficial velocity 125 m h^{-1} (Figure 4).

The filter was blocked in the case of using single underdrain 3 (SD3) with basalt media, due to the impact of small total drain opening area and drain effective area for this underdrain which is not compatible with this medium. This conclusion was confirmed when using double underdrain 3 (DD3) where total drain opening area and drain effective area were multiplied and there is no any block happened. There are no clear differences of H_L values in three types of underdrain at the minimum superficial velocity 50 m h^{-1}, while the H_L differences between three underdrains were increased significantly at the maximum superficial velocity 125 m h^{-1}. The H_L was decreased under the three types of underdrain in case of using double underdrain compared with single underdrain at the same operational conditions (Figure 4 and 5).



1: Basalt, 2: Crushed marble and 3: Sand a: 30 cm bed depth, b: 50 cm bed depth and c: 70 cm bed depth
Figure 4 The relationship between the friction head loss sand superficial velocity for three media types under different media bed depths using three types of underdrain cups as a single drain



1: Basalt, 2: Crushed marble and 3: Sand a: 30 cm bed depth, b: 50 cm bed depth and c: 70 cm bed depth

Figure 4 The relationship between the superficial velocity and friction head loss for three media types under different media bed depths using three types of underdrain cups as a double drain

The minimum value of friction head loss H_L was 41 mbar measured for (DD2) under basalt with media bed depth 30 cm and superficial velocity 50 mh^{-1} (Figure 5-1a), while the maximum HL was 578.3 mbar for DD3 in sand with media bed depth 70 cm and superficial velocity 125 mh^{-1} (Figure 5-3c).

The friction head loss under double underdrain was also directly proportional with media bed depth and superficial velocity. Therefore, the minimum values of H_L were 41, 51.9 and 72.6 mbar for basalt, crushed marble and sand respectively, they were measured under 30 cm media bed depth and superficial velocity 50 m h^{-1}. On the other hand, the maximum H_L values, 341.3, 426.5 and 578.3 and 991 mbar for crushed marble, basalt and sand respectively, they were achieved under 70 cm media bed depth and superficial velocity 125 m h^{-1} (Figure 5).

The curve fitting for the pressure head loss for underdrain 2 tend to be linear for all superficial velocities in case of single and double underdrain. DD1 similar to DD2 in curves linearity (Figure 4 and 5).

The data obtained agree with the data obtained by Mesquita et al. (2012) and Chang et al. (1999). Chang et al. (1999) identified two distinct flow behaviors in the head loss of the porous filter beds, defined as both linear and nonlinear (exponential) behaviors.

The minimum percentage of head loss reduction as a result of using double drain in basalt, crushed marble and sand were 2.81% (DD2), 2.51% (DD3) and 5.27% (DD3) respectively, while the maximum percentage of head loss reduction were 79.48% (DD3), 59% (DD1) and 54% (DD2) respectively.

3.2 Data analysis

Multiple linear regression methods were used to determine the role of head loss (HL) components in sand media filters and their impact on filter performance through some parameters that can be taken as an effective indicator to meet evaluation objectives.

In the present experiment, the multiple linear regression analysis of head loss (HL) and other characteristics (flow velocity, media bed depth, underdrain types and number) were proceeded for the three media types (basalt, crushed marble and sand). The results showed that the multiple linear regression could be used, since there was significant relation between head loss and other parameters (Table 3).

Table 3 Model summary and analysis of variance for the relationship between response variable and explanatory

Media Type	Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
Basalt	(Constant)	-215.583	68.806		-3.133	0.003
	Media depth	1.230	0.775	0.163	1.587	0.119
	Drain opening Area	0.083	0.041	0.205	2.002	0.051
	Underdrain No.	31.659	25.310	0.128	1.251	0.217
	Superficial velocity	2.557	0.413	0.633	6.186	0.000
Crushed marble	(Constant)	110.103	57.721		1.907	0.062
	Media depth	1.007	0.650	0.106	1.549	0.128
	Drain opening Area	-0.206	0.035	-0.408	-5.949	0.000
	Underdrain No.	-108.893	21.232	-0.351	-5.129	0.000
	Superficial velocity	3.467	0.347	0.685	9.999	0.000
Sand	(Constant)	-17.122	55.926		-0.306	0.761
	Media depth	3.259	0.630	0.271	5.174	0.000
	Drain opening Area	-0.212	0.034	-0.330	-6.291	0.000
	Underdrain No.	-120.985	20.572	-0.308	-5.881	0.000
	Superficial velocity	4.910	0.336	0.767	14.615	0.000

Since the significance in the ANOVA table is less than 0.05 level of probability, there is a statistically significant relationship between the variables at 95% confidence level. The R^2 statistic indicates that the model for different media types were 80.6%, 67.1% and 48.5%for basalt, crushed marble and sand, respectively. The adjusted R^2 statistic, which is more suitable for comparing models with different number of independent variables, were 79.0%, 64.4% and 44.3% for basalt, crushed marble and sand, respectively, indicating that the fitting degree is relatively high in basalt and dependent variable is significant. However, it was low in crushed marble and sand (Table 4).

Table 4 Model summary and analysis of variance for the relationship between variables

Media Type	Model	df	Sum of Squares	Mean Square	F	Sig.
Basalt	Regression	4	400884.834	100221.208	11.589	.000[a]
	Residual	49	423743.448	8647.825		
	Total	53	824628.281			
Crushed marble	Regression	4	998571.278	249642.820	41.021	.000[a]
	Residual	49	298203.997	6085.796		
	Total	53	1296775.275			
Sand	Regression	4	1796919.504	449229.87	78.632	.000[a]
	Residual	49	279941.486	5713.092		
	Total	53	2076860.990			

In this analysis, all variables were added in the prediction equation. It is well known that as more variables were added, the interpretation of association become more complex. On the other hand, some variables may contribute a little to the accuracy of the prediction equation. In addition, given that the number of observations was much greater than the number of potential independent variables (x) under consideration, the addition of a new variable will always increase R^2 but it wills not necessary increase the precision of the estimate of the response. At this point, the stepwise multiple linear regression analysis was carried out to determine the best variables accounted for the most of variance in head loss.

The multiple linear regression analysis between the friction head loss (HL) for the different media types (Basalt, crushed and sand) as dependent variables, with superficial velocity, media bed depth, and drain type as independent variables, showed that the best R2 value was 0.865 between $H_{L\,Sand}$ and all independent variables, and the lowest R2 value was 0.486 between $H_{L\,Basalt}$ and all independent variables:

$$H_{L\,Sand} = -215.583 + 1.230(\mathrm{MD}) + 0.083(D_{OA}) - 31.659(DN) + 2.577(^{\gamma}) \quad (1)$$

$$R^2 = 0.865 \quad Standard\ Error = 75.5850$$

$$H_{L\,Crushed} = 10.103 + 1.007(\mathrm{MD}) - 0.206(D_{OA}) - 108.893(DN) + 3.467(^{\gamma}) \quad (2)$$

$$R^2 = 0.770 \quad Standard\ Error = 78.0115$$

$$H_{L\,Basalt} = -17.122 + 3.259(\mathrm{MD}) - 0{,}212(D_{OA}) - 120.985(DN) + 4.91(^{\gamma}) \quad (3)$$

$$R^2 = 0.486 \quad Standard\ Error = 92.9937$$

where H_L is the friction head loss *mbar*, whether single or double, γ is the superficial velocity mh^{-1}, D_{OA} is the drain opening Area mm^2, DN is the number of drains (single and double) and MD is the media bed depth *cm*. Comparing the resulting equations, Equation 1 shows that the $H_{L\,Sand}$ has the highest R^2 value of 0.865 ($p < 0.05$) in relation to the independent variables, which are superficial velocity, underdrain type, number of drains and media bed depth. Therefore, the Equation 1 for sand is more accurate.

4 Conclusion

The friction head loss was affected by the internal components of the media filter. Additionally, the performance of media filter was affected by the media types, media bed depth, drain type, number of drains and flow rate.

1. The friction head loss was significantly high impacted by the media types, underdrains type, number of drains and flow rate as a single and double effect.

2. DD2 resulted the minimum friction head loss while SD3 resulted the maximum friction head loss.

3. The friction head loss (H_L) was decreased under the three types of underdrain in case of using double underdrain (DD) compared with single underdrain (SD) at the same operational conditions.

4. The regression equation which represent the friction head loss under basalt as dependent variable and superficial velocity, underdrain type, number of drains and media bed depth as independent variables is the best one with R^2 equal to 0.865.

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