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Investigating the influence of surrounding soil properties on leakage discharge from cracks in polyethylene pipes

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ABSTRACT

Numerous factors affect the amount of leakage from pipes, e.g. inside pressure, type of pipe failure, soil around the pipe, etc. Few researches have been done on the effect of environment around the pipe on the leakage discharge. In the present study, the leakage from pipes in presence of different soils is experimentally investigated. Leakage from a cracked polyethylene pipe was simulated in the presence of various soils with different properties in a laboratory setup. Leakage-pressure relationships were obtained according to fixed and variable area discharge theory. By quantifying the soil characteristics, the relationship between leakage- pressure coefficients (m and C_d) and soil parameters was obtained. It was concluded that the soil environment affects the amount of leakage discharge. Results show that the particle diameter at 50% passing (D_{50}), dry unit weight (γ_d) and hydraulic permeability coefficient (k) are more appropriate to represent the characteristics of soils. It was also concluded that there are no strong correlation between leakage and some soil parameters. The obtained relationships between different soil parameters and leakage discharge coefficients are also presented.

1. Introduction

Nowadays, the presence of leaks is inevitable in water distribution networks (WDNs). This phenomenon leads to the waste of a considerable part of our valuable water and has many economic and environmental consequences. It is precisely for this reason that leakage reduction through pressure management as well as leak detection are of significant importance in WDNs. Finding leakages in WDNs and implementing repairs is also a very costly process which requires technical and economical assessment. Therefore, studies that can result in a better understanding of the leakage phenomenon in pipes and its affecting factors are considerably valuable.

Variables that affect the amount of leakage discharge are: 1) the fluid pressure within the pipes; 2) the dimensions and shape of the leak; 3) the material and diameter of the pipes; 4) fluid characteristics (e.g. density, viscosity, etc. which are all functions of temperature); and 5) the environment around the pipe. International Water Association (IWA) has proposed the pressure- leakage relationship as bellows [18]:

$$Q = CP^{n_1} \tag{1}$$

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where Q is the output leakage discharge; P is the water pressure within the pipe; C is the equation coefficient; and n_1 is the exponent. C is a function of the cross-sectional area of the leakage, discharge coefficient and other factors. n_1 has been estimated between less than 0.5 (Bernoulli equation) to more than 2.5 [13,8,19].

May [15], found that the exponent of the pressure (n_1) depends on the pipe material and the leakage area shape, because, in deformable pipes the increase in pipe pressure can lead to an increase in the cross-sectional area of the leak:

$$A = A_0 + mh \tag{2}$$

where A is cross sectional leak area during leakage; A_0 is the initial leakage area; h is the pressure head; and m is the pressure- area equation slope. This matter became the basis of the fixed and variable area discharge (FAVAD) theory. Linking the FAVAD theory with the exponential form of the pressure- leakage discharge equation ($n_1 = 0.5$), Cassa et al. [6] presented the leakage equation in the form of equation (3):

$$Q = C_d\sqrt{2g}\left(A_0h^{0.5} + mh^{1.5}\right) \tag{3}$$

where C_d is the discharge coefficient. Ferrante [9] proposed a formula with a variable exponent for h instead of 1.5. van Zyl and Cassa [20] studied the leakage from a 60 mm long crack on a 110 mm uPVC pipe and, using a finite element model, proposed equations to predict the pressure- area slope (m) as a function of the pipe properties (e.g. material, diameter, thickness, etc.) as well as the crack size and type (longitudinal, circumferential and spiral). Di Marchis and Milici [7] compared the various relationships using experimental data for circular and rectangular leaks.

Germanopoulos and Jowitt [11] stated that the leak is affected by the movement and properties of the soil in which the pipe is laid. Coetzer et al. [5] investigated the rate of leakage from 1 mm and 2 mm holes in 3-mm thick uPVC pipes and 7-mm thick HDPE pipes, both with 110 mm diameter. Observations indicated that the leakage behavior are quite similar when submerged in water and buried in glass beads, but very different from that of free leakage to air. In discharge to water and the glass beads, the pressure exponent (n_1) is significantly less than the 0.5 theoretical value (about 0.4 for the submerged in water and 0.42 for the pipe buried in the glass beads).

Noak and Ulanicki [16] numerically studied the effect of soil around the pipe in order to estimate the exponent of pressure in leakage from an orifice. Their main focus was on the soil permeability, and 100 different types of soils with hydraulic permeability varying between 10^{-11} and 10^{-2} metre per second were modeled. It was observed that the n_1 exponent varies between 0.5, for high permeability soils, and 1, for low permeability soils.

In a laboratory study, Fox et al. [10] studied the leakage behavior of viscoelastic pipes in the presence of water, porous media and geotextile fabrics. In addition to the pressure head and leakage discharge, they also measured the leakage area and axial strain. The effect of surrounding environment and its permeability on the amount of leakage was investigated by both laboratory and numerical modeling methods. They concluded that the existence of a porous environment around the pipe increases the axial strain and decreases the leakage discharge.

Latifi et al. [14] experimentally simulated the leakage and investigated the effects of the pipe surrounding soil properties on leakage from an orifice as well as a leaky coupling. Considering the parameters D_{10}, D_{50}, the plasticity index and soil hydraulic conductivity, they obtained relations between leakage discharge and each of the soil parameters. It was observed that by changing these soil parameters, the amount of leakage discharge also changes. The amount of leakage discharge in coarser soils was higher than that of finer soils. The results also show that increasing the clay to silt ratio in fine soils and increasing the plastic properties of soil can lead to a reduction in leakage discharge. Finally, it was concluded that the D_{50}, hydraulic conductivity coefficient and plastic limit were more suitable for describing soil properties.

Pike et al. [17] assessed the effects of various factors on scouring in the pipes resulting from the fluidization of materials around the leakage area. They found that leak jet orientation parameter had the most significant impact on pipe scouring, followed by leakage discharge, sand particles size, pipe material and soil cover depth. They presented figures to show the fluidized and mobile bed zones in different soil particle sizes, which prove that coarser soils result in smaller mobile bed zone and larger scouring rates.

Latifi et al. [21] experimentally studied the factors affecting the fluidized and mobile bed zone geometric properties. They found that water pressure and soil characteristics, particularly the median size of the soil particles, have the greatest impact on height, width and cross section area of the mentioned zones.

Reviewing the carried out research on the effect of pipe surrounding environments on the leakage discharge, it is concluded that the leakage from the pipes with different leak types as well as the presence of different soil types requires further study. In this study, the effects of the surrounding soil properties on the leakage from longitudinal and circumferential cracks have been investigated.

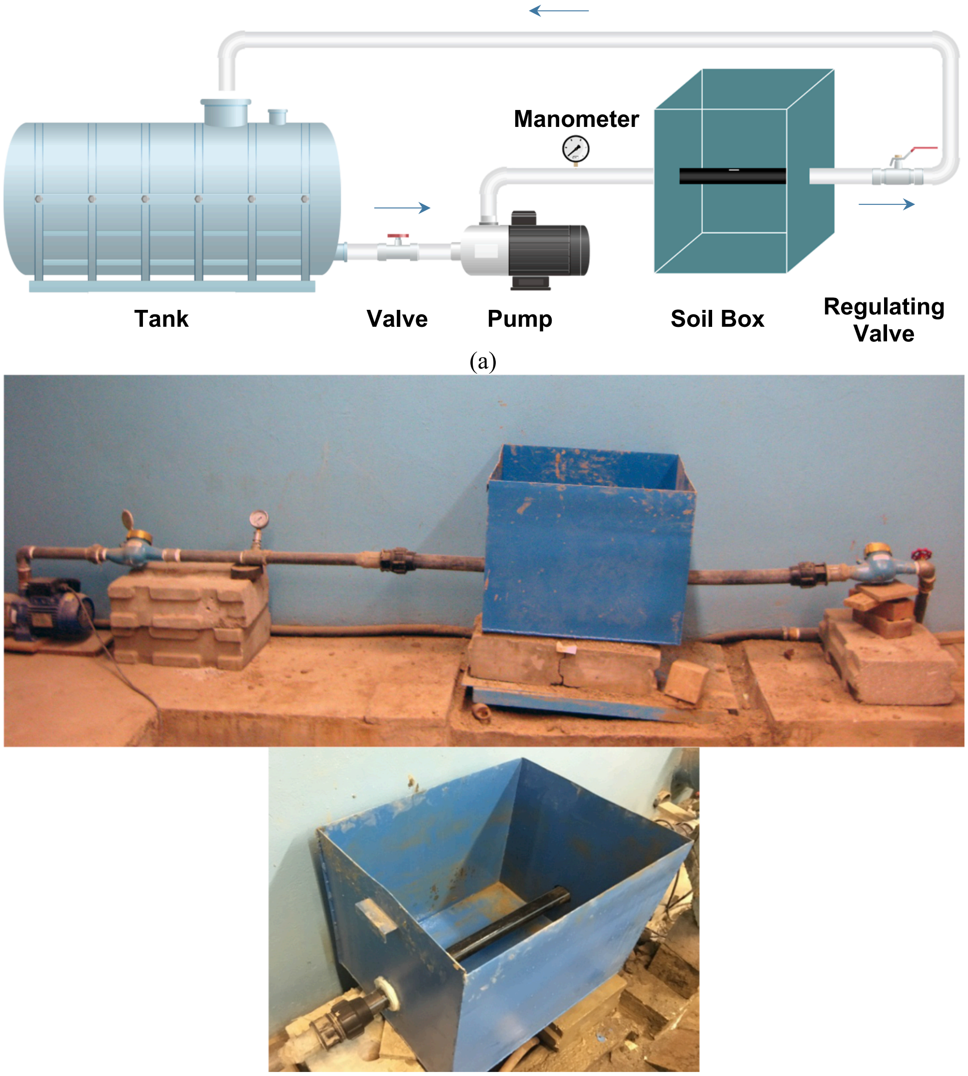
2. Methodology

As indicated in the previous section, numerous researches have been carried out on the leakage phenomenon from pipes. These studies have been conducted in different experimental, numerical modeling, field study and sometimes analytical methods. Most of the studies have focused on the relationship between leakage and pressure, particularly, determination of the pressure exponent and the discharge coefficient, as well as the investigation of the factors that affect them. However, a few studies have been performed in presence of soil around the pipes to determine its effect on the amount of leakage. The present study focuses on the effects of soil type and its properties on the leakage discharge; comparing the effects of soil properties and finding the most effective parameters on leakage. For this purpose, and through carrying out certain experiments, relationships between soil parameters and leakage discharge are achieved and presented.

The laboratory set that has been used to simulate the soil environment in this study is a looped network, consists of; a pump with a nominal power of 1.5 kW, an input power of 2.3 kW and a maximum generated output pressure of 62 m; a 200-liter water tank; a globe valve; a regulating valve; a pressure gauge with a measuring range of 0 to 60 m and 32-mm steel pipes. To simulate a leakage, two longitudinal and circumferential cracks were created on top of a PN10 polyethylene (PE) pipe with a 40 mm diameter and 3 mm wall thickness. A steel soil box with the dimensions of 0.7 m × 0.5 m × 0.5 m was constructed and located in the set-up. A hole is embedded in the bottom of the soil box to allow the leaked water to drain. By placing a multi-layer filter at the holes beneath the box, the escape of fine soil particles are controlled. The main PE pipe with cracks was placed in the box and the soil is surrounded the pipe. The overview of the laboratory set-up is shown in Fig. 1.

To identify the properties of the studied soils and assess their effects on leakage, their geotechnical characteristics are tested. The parameters of hydraulic permeability, porosity, dry unit weight, Atterberg limits, uniformity coefficient, coefficient of curvature and the particles diameter at 10, 30, 50 and 60 percent passing were assessed and investigated. The soils are classified according to Unified Soil Classification System (USCS) (ASTM D2487-11[3]). Plastic limits and Liquid Limits are measured according to ASTM D4318-10e1 [2]. The values of hydraulic permeability are measured according to ASTM D2434-68[1]. The values of porosity were also calculated using the relationships of soil mechanics theory. Experiments performed on the soil samples. Table 1 shows the particle diameter at 10 % passing (D_{10}), particle diameter at 30 % passing (D_{30}), particle diameter at 50 % passing (D_{50}), coefficient of uniformity (C_u), coefficient of curvature (C_c), dry unit weight (γ_d), Plastic Limit (*PL*), Liquid Limit (*LL*), Plasticity Index (*PI*), hydraulic permeability (*k*) and porosity (*n*).

In this study, soils are selected in a way that they include common ranges of soil grading, Atterberg limits and permeability. The



(a)

(b)

Fig. 1. (a) Schematic; and (b) physical view of laboratory set-up.

Table 1
Properties of soils used in the present study.

Soil number		D_{10} (mm)	D_{30} (mm)	D_{50} (mm)	C_u	C_c	γ_d(kN/m^3)	PL (%)	LL (%)	PI (%)	k (cm/s)	n	Soil type
Leakage from longitudinal crack	Soil #1	0.09	0.18	0.23	3.00	1.33	18.88	(N/A)	(N/A)	(N/A)	0.87	0.26	SP-SC
	Soil #2	0.24	0.68	0.85	5.18	2.07	18.72	(N/A)	(N/A)	(N/A)	3.28	0.25	SP
	Soil #3	0.26	0.80	1.20	6.15	1.54	18.19	(N/A)	(N/A)	(N/A)	9.60	0.27	SW
	Soil #4	0.18	0.26	0.46	2.94	0.71	19.63	(N/A)	(N/A)	(N/A)	0.14	0.21	SP
	Soil #5	0.12	0.30	0.80	11.67	0.54	18.5	(N/A)	(N/A)	(N/A)	0.80	0.21	SP-SC
Leakage from circumferential crack	Soil #6	0.17	0.28	0.55	3.88	0.69	13.17	10.8	21.5	10.7	1.94	0.23	SP
	Soil #7	0.075	0.16	0.21	4.00	1.14	15.1	17.6	20.5	4.9	0.05	0.21	SP-SM
	Soil #8	0.20	0.50	0.88	3.00	0.85	13.01	16.1	18.6	2.5	3.00	0.23	SP
	Soil #9	0.19	0.60	1.03	5.63	1.77	11.92	10.9	12.7	1.9	4.03	0.27	SW
	Soil #10	0.12	0.36	0.42	8.50	1.06	14.43	20.7	23.0	2.3	0.63	0.22	SW-SM

C_u: Coefficient of uniformity; C_c: Coefficient of curvature.
PL: Plastic limit; *LL*: Liquid limit; *PI*: Plasticity index.
SW: Well-graded sand; SP: Poorly graded sand; SC: Clayey sand; SM: Silty sand.
N/A: Not available.

gradation diagrams of the soils are presented in Figs. 2 and 3. Two series of experiments were conducted in order to investigate the effects of the existing soil around pipes on the leakage amount. The first series of experiments was carried out on a polyethylene pipe with a 5 mm longitudinal crack, while, the second series of experiments were done on the same type of pipe, but with a 5 mm circumferential crack.

To obtain maximum soil density, enough water was added to soils to achieve the optimum moisture content, and all soils were compacted by the same number of compaction hammer blows (ASTM D698-12e2[4]). A wooden plate was used to evenly distribute the hammer blows tension over the soil layers. Blows are applied to the mentioned plate and tension is also applied to the entire soil under the plate. Therefore, the soil under and around the pipe was compacted properly.

Preparing the set-up and the soil around the polyethylene pipe, the leakage discharge was measured after inducing different pressures. The generated pressures were in the range of 15–55 m with steps of 5 m, which is comparable to the common pressures utilized in urban water distribution networks. The amount of pressure in the laboratory set-up is adjusted manually by means of the regulating valve.

In this study, the leakage discharge was measured manually. Turning on the pump and establishing the flow through the set-up, the

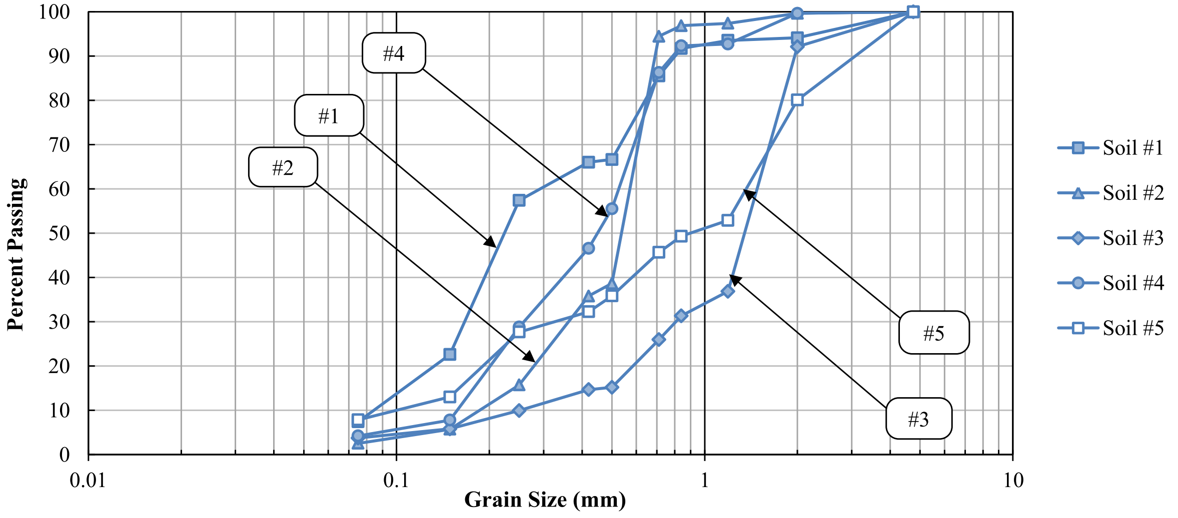


Fig. 2. Gradation diagram of the soils used in the tests of leakage from longitudinal crack.

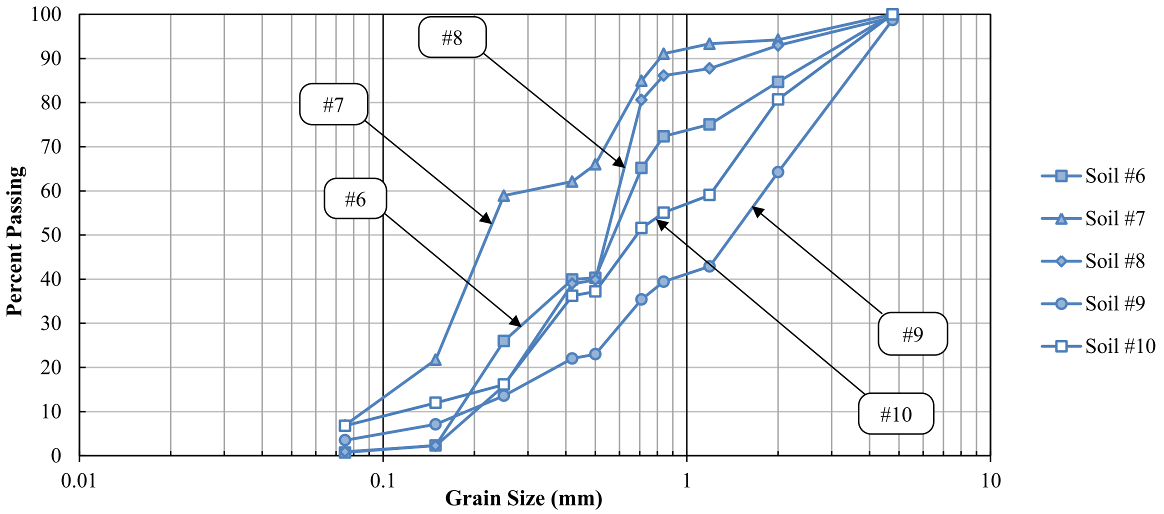


Fig. 3. Gradation diagram of the soils used in the tests of leakage from circumferential crack.

soil around the pipe is completely saturated and water begins to exit through the hole embedded at the bottom of the soil box. After the outflow water discharge reaches a steady state, the outflow rate of the box can be assumed equal to the leakage rate of the pipe. To measure the leakage discharge, water exiting the box was collected during a specific period of time and weighed using a scale. By dividing the volume of water exiting the box (V) by the outflow time (t), the leakage discharge (Q = V / t) was calculated. In this method, considering the high accuracy of the weighing scale and the chronometer, it is possible to reduce many of the possible machine errors and this can be assumed to be one of the most accurate methods. It should be stated that in none of the experiments the leaked water overflowed to the top surface of the soil box.

3. Results

In this section, the results achieved from the experiments will be investigated. The leakage tests were carried out in two states of: 1) discharge directly into air; and 2) pipe buried in soil. Then, the discharge- pressure relationships were extracted. Figs. 4 and 5 represent the leakage discharge- pressure diagram in presence of longitudinal and circumferential cracks.

3.1. Discharge- pressure relationship

According to Figs. 4 and 5, by increasing the pressure in the pipe, the leakage discharge increases, proportionally. In case of leakage into air, leakage discharge is remarkably greater than leakage into soil. The results show that at a given pressure, if there are finer soils

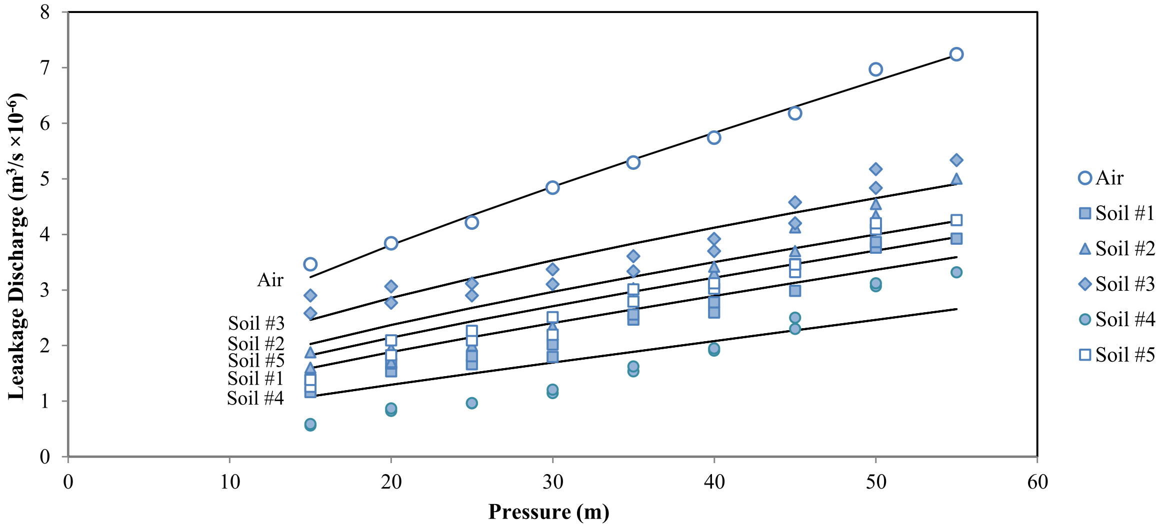


Fig. 4. Leakage discharge from the longitudinal crack in different pressures.

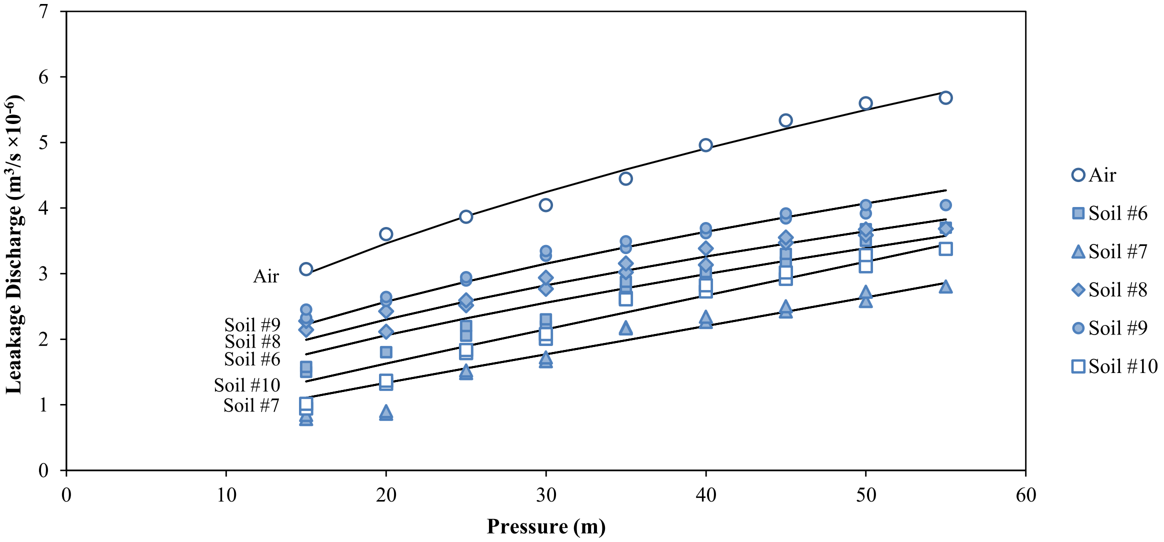


Fig. 5. Leakage discharge from the circumferential crack in different pressures.

around the pipe, less leakage discharge from the pipe will occur. This result proves the hypothesis of leakage discharge dependency on the surrounding soil properties which was previously expressed by Latifi et al. [14]. Moreover, it is observed that in spite of equal dimensions of longitudinal and circumferential cracks, the leakage discharge in longitudinal crack is more than circumferential crack. This is due to the fact that circumferential stresses and strains, which cause the longitudinal cracks, are higher than longitudinal ones. Therefore, in the presence of longitudinal cracks, distribution of circumferential stress and strain in the pipe wall, near the crack, lead to increase in the crack area and thereby increase in the amount of leakage discharge from longitudinal cracks. This has already been mentioned by Greyvenstein and van Zyl [12].

Based on the theory of FAVAD, presented by Cassa et al. [6], in case of the presence of cracks, the leakage- pressure relationship (Eq. (3)) can be written as bellows:

$$Q = aP^{0.5} + bP^{1.5} \qquad a = \sqrt{2g}C_dA_0 \ , \qquad b = \sqrt{2g}C_dm \tag{4}$$

Fitting the observed data (gained from the experiments carried out in this study) on Eq. (4), coefficients a and b are derived. It should be noted that the initial cross section area of leak,A_0, is obtained by multiplying the crack length by its width. Eqs. (5) to (10) show the obtained relationships for calculating pipe leakage with longitudinal crack, while, Eqs. (11) to (16) are obtained for circumferential crack.

$$Q = 7.82\times10^{-7}P^{0.5} + 3.49\times10^{-9}P^{1.5} \qquad R^2 = 0.9903 \qquad Free\ air \tag{5}$$

$$Q = 3.85\times10^{-7}P^{0.5} + 1.81\times10^{-9}P^{1.5} \qquad R^2 = 0.8429 \qquad soil\ \#1 \tag{6}$$

$$Q = 5.06\times10^{-7}P^{0.5} + 1.19\times10^{-9}P^{1.5} \qquad R^2 = 0.7925 \qquad soil\ \#2 \tag{7}$$

$$Q = 6.26\times10^{-7}P^{0.5} + 6.45\times10^{-10}P^{1.5} \qquad R^2 = 0.8612 \qquad soil\ \#3 \tag{8}$$

$$Q = 2.50\times10^{-7}P^{0.5} + 1.97\times10^{-9}P^{1.5} \qquad R^2 = 0.7318 \qquad soil\ \#4 \tag{9}$$

$$Q = 4.49\times10^{-7}P^{0.5} + 1.52\times10^{-9}P^{1.5} \qquad R^2 = 0.8785 \qquad soil\ \#5 \tag{10}$$

$$Q = 7.72\times10^{-7}P^{0.5} + 1.07\times10^{-10}P^{1.5} \qquad R^2 = 0.9825 \qquad Free\ air \tag{11}$$

$$Q = 4.48\times10^{-7}P^{0.5} + 6.26\times10^{-10}P^{1.5} \qquad R^2 = 0.9233 \qquad soil\#6 \tag{12}$$

$$Q = 2.49\times10^{-7}P^{0.5} + 2.48\times10^{-9}P^{1.5} \qquad R^2 = 0.9087 \qquad soil\#7 \tag{13}$$

$$Q = 5.14\times10^{-7}P^{0.5} + 3.82\times10^{-11}P^{1.5} \qquad R^2 = 0.9480 \qquad soil\ \#8 \tag{14}$$

$$Q = 5.75\times10^{-7}P^{0.5} + 1.01\times10^{-11}P^{1.5} \qquad R^2 = 0.9607 \qquad soil\#9 \tag{15}$$

$$Q = 3.07\times10^{-7}P^{0.5} + 2.86\times10^{-9}P^{1.5} \qquad R^2 = 0.9378 \qquad soil\#10 \tag{16}$$

As shown in Eqs. (5) to (16), the coefficients of determination (R^2) of relationships are close to unit, which represents a high correlation between observed results and equations proposed by Cassa et al. [6].

In each of the mentioned equations, having the value of coefficient a and the value of crack initial cross section area, A_0, the coefficient C_d can be calculated for each type of soils. Moreover, by having the value of coefficient b as well as using coefficient C_d which was calculated previously, the value of coefficient m (pressure- leakage area slope) can be estimated for each of the soil types. Parameter C_d is a dimensionless coefficient and is calculated for different soils between 0.1 and 0.35 after the units have been converted. Furthermore, parameter m is a coefficient with length dimension, and after the units have been converted, its values are calculated for different soils between 8.78×10^{-12} and 4.98×10^{-9}.

3.2. Correlation between soil properties and leakage discharge

The relationship between soil properties and leakage discharge is studied to understand the sensitivity of the discharge to soil characteristics. In Fig. 6, the correlation between leakage discharge and main soil properties (median grain size (D_{50}), hydraulic permeability and dry unit weight) is presented for longitudinal crack. Moreover, the linear regressions between leakage discharge and each soil properties are shown in Table 2. By increasing the median grain size and hydraulic permeability of the soil around the longitudinal crack, the leakage discharge increases (Fig. 6a and 6b). This is because of the fact that the larger soil particles let the leaked water flow easier. Also, the high permeability facilitates the leakage flow in soils. As shown in Fig. 6c and Table 2, although there are direct relationships between leakage discharge and dry unit weight of soil, the relationships have low amounts of coefficient of determination. The same results were concluded for circumferential crack.

3.3. Correlation between soil particle sizes and FAVAD coefficients

The correlation between the soils properties and gained values for coefficients C_d and m is studied to find possible relationships. It has been found that there is a significant relationship between some of soil properties and the key coefficients of FAVAD Equation. Figs. 7 and 8 show the relationship between properties of soil particle diameter (D_{10}, D_{30} and D_{50}) and coefficients C_d and m. In Fig. 7, it can be observed that by increasing each of the the particle diameter indexes, D_{10}, D_{30} and D_{50}, the coefficient C_d increases, too. This observation can be justified in this way that if soil particles are larger, the leakage through the particles is easier, and leakage discharge increases as well. Therefore, increasing of discharge coefficient, C_d, makes sense. According to Fig. 8, by increasing the values of D_{10}, D_{30} and D_{50} of soils, the values of m reduces. In coarse soils, soil structure limits the increase of leak area due to increase of pressure. On the contrary, in fine soils, when the pressure increases, leak cross sectional area will increase rapidly.

Eqs. (17) to (28) show the relationship between D_{10}, D_{30} and D_{50} and the coefficients C_d and m.

$$C_d = 0.4855\,(D_{10}) + 0.1137 \qquad R^2 = 0.3208 \qquad \textit{Longitudinal crack} \tag{17}$$

$$C_d = 1.1344\,(D_{10}) + 0.0177 \qquad R^2 = 0.9192 \qquad \textit{Circumferential crack} \tag{18}$$

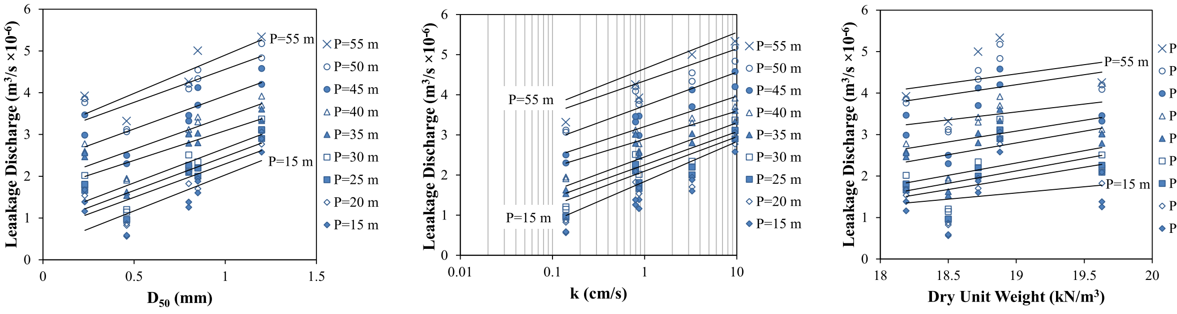
$$m \times 10^9 = -46.052\ (D_{10}) + 9.0304 \qquad R^2 = 0.9190 \qquad \textit{Longitudinal crack} \tag{19}$$

$$m \times 10^9 = -8.4019\ (D_{10}) + 3.4308 \qquad R^2 = 0.2236 \qquad \textit{Circumferential crack} \tag{20}$$

$$C_d = 0.1915\ (D_{30}) + 0.1151 \qquad R^2 = 0.7059 \qquad \textit{Longitudinal crack} \tag{21}$$

$$C_d = 0.3063\ (D_{30}) + 0.0726 \qquad R^2 = 0.7393 \qquad \textit{Circumferential crack} \tag{22}$$

$$m\ \times 10^9 = -3.6802\ (D_{30}) + 3.5693 \qquad R^2 = 0.6070 \qquad \textit{Longitudinal crack} \tag{23}$$

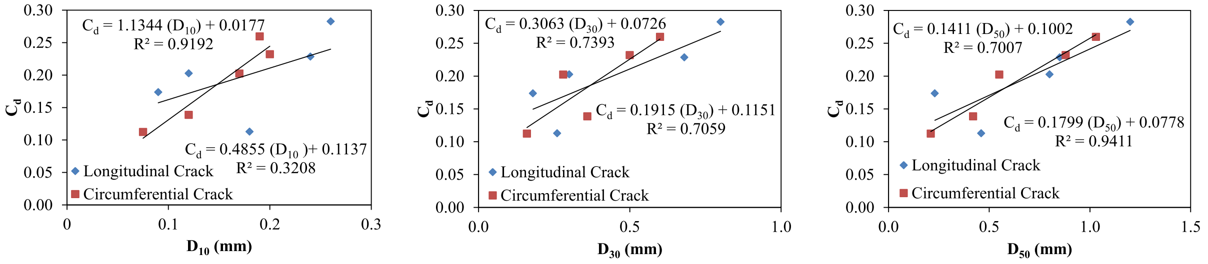


(a) (b) (c)

Fig. 6. Effects of variation in soil parameters on leakage discharge for longitudinal crack.

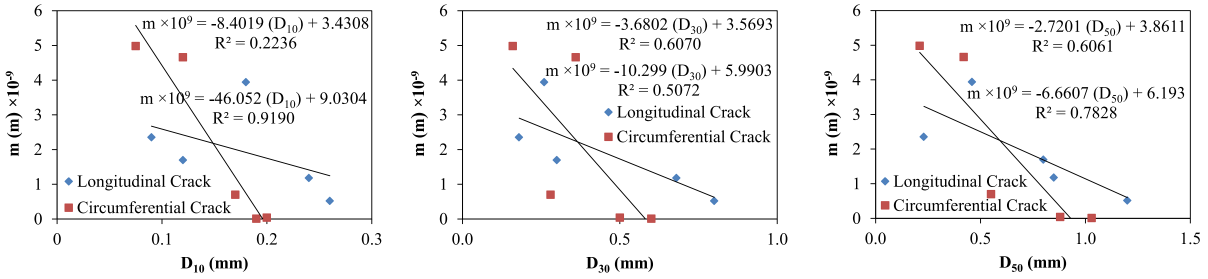
Table 2
Relationship between Leakage discharge and main soil properties (median grain size, hydraulic permeability and dry unit weight) for different pressures in longitudinal crack.

P (m)	Discharge vs median grain size		Discharge vs hydraulic permeability		Discharge vs dry unit weight	
	Relationship	R^2	Relationship	R^2	Relationship	R^2
15	$Q = 1.7205\ (D_{50}) + 0.3099$	0.64	$Q = 0.1925\ k + 0.9624$	0.88	$Q = 0.2993\ (\gamma_d) - 4.0946$	0.04
20	$Q = 1.5973\ (D_{50}) + 0.6978$	0.63	$Q = 0.1662\ k + 1.3403$	0.74	$Q = 0.5378\ (\gamma_d) - 8.2728$	0.15
25	$Q = 1.6222\ (D_{50}) + 0.8470$	0.66	$Q = 0.1605\ k + 1.5241$	0.70	$Q = 0.5952\ (\gamma_d) - 9.1841$	0.18
30	$Q = 1.6562\ (D_{50}) + 1.0141$	0.67	$Q = 0.1648\ k + 1.7025$	0.72	$Q = 0.5922\ (\gamma_d) - 8.9379$	0.18
35	$Q = 1.4193\ (D_{50}) + 1.6701$	0.56	$Q = 0.1357\ k + 2.2764$	0.56	$Q = 0.5676\ (\gamma_d) - 7.9861$	0.19
40	$Q = 1.5554\ (D_{50}) + 1.8685$	0.66	$Q = 0.1473\ k + 2.5369$	0.64	$Q = 0.5219\ (\gamma_d) - 6.8345$	0.15
45	$Q = 1.5875\ (D_{50}) + 2.3385$	0.59	$Q = 0.1627\ k + 2.9846$	0.67	$Q = 0.3795\ (\gamma_d) - 3.6659$	0.07
50	$Q = 1.5798\ (D_{50}) + 2.9790$	0.67	$Q = 0.1548\ k + 3.6427$	0.70	$Q = 0.4820\ (\gamma_d) - 4.9563$	0.13
55	$Q = 1.8338\ (D_{50}) + 3.0672$	0.71	$Q = 0.1757\ k + 3.8492$	0.71	$Q = 0.4477\ (\gamma_d) - 4.0441$	0.09



(a) (b) (c)

Fig. 7. The relationship between coefficient C_d and soil particle diameters at: (a) 10%; (b) 30%; and (c) 50% passing.



(a) (b) (c)

Fig. 8. The relationship between coefficient m and soil particle diameters at: (a) 10%; (b) 30%; and (c) 50% passing.

$$m \times 10^9 = -10.299(D_{30}) + 5.9903 \qquad R^2 = 0.5072 \qquad \textit{Circumferential crack} \tag{24}$$

$$C_d = 0.1411(D_{50}) + 0.1002 \qquad R^2 = 0.7007 \qquad \textit{Longitudinal crack} \tag{25}$$

$$C_d = 0.1799(D_{50}) + 0.0778 \qquad R^2 = 0.9411 \qquad \textit{Circumferential crack} \tag{26}$$

$$m \times 10^9 = -2.7201(D_{50}) + 3.8611 \qquad R^2 = 0.6061 \qquad \textit{Longitudinal crack} \tag{27}$$

$$m \times 10^9 = -6.6607(D_{50}) + 6.1930 \qquad R^2 = 0.7828 \qquad \textit{Circumferential crack} \tag{28}$$

3.4. *Correlation between soil Atterberg limits and FAVAD coefficients*

Fig. 9 shows the relationship between soil plasticity limits and coefficients C_d and m. If plasticity limits of the soils increases, the coefficient C_d and leakage amount decreases. This fact shows the influence of the soil plastic limit on leakage. If the ratio of clay minerals as well as soil plastic limit increases, water drainage around the crack becomes slower, and water pressure around the crack increases as well. Consequently, pressure loss due to water flow across the soil will decrease, which leads to reduction in leakage discharge, as well. Therefore, if the amount of plastic limit increases, soil will show less permeability; accordingly, coefficient C_d and leakage amount will reduce. On the other hand, lack of a trend in observed data indicates that there is not a significant relationship between plastic index (*PI*) and *m* as well as C_d.

It should be noted that the first series of soils (soils No. 1–5) are sandy and lacks plastic limit (*PL*) and liquid limit (*LL*). Eqs. (29) to (32) show the relationship between the soil plasticity limits and the C_d and *m* coefficient.

$$C_d = -0.0105(PL) + 0.3489 \qquad R^2 = 0.5369 \qquad \textit{Circumferential crack} \tag{29}$$

$$m \times 10^9 = 0.4581(PL) - 4.8947 \qquad R^2 = 0.6191 \qquad \textit{Circumferential crack} \tag{30}$$

$$C_d = -0.0117(LL) + 0.4149 \qquad R^2 = 0.5644 \qquad \textit{Circumferential crack} \tag{31}$$

$$m \times 10^9 = 0.3945(LL) - 5.5239 \qquad R^2 = 0.3875 \qquad \textit{Circumferential crack} \tag{32}$$

3.5. Correlation between soil porosity, hydraulic permeability and FAVAD coefficients

Fig. 10 presents the relationship between porosity, hydraulic permeability and coefficients of C_d and *m*. This figure shows that increasing the soil hydraulic permeability and porosity, the amount of coefficient C_d as well as leakage discharge increases. This proves the effects of porosity and hydraulic permeability coefficient on leakage amount from cracks. Due to the fact that fluids move more easily in soils with higher porosity and hydraulic permeability, drainage through these soils are easier, and it causes the more leakage discharge in these soils.

Moreover, if soil porosity and permeability coefficient increases, the amount of coefficient *m* reduces. Due to the fact that in coarser soils porosity and hydraulic permeability coefficient is higher, it can be concluded that in this kind of soils, leak area increase due to pressure increase will be limited; consequently, value of *m* decreases.

Eqs. (33) to (40) show the relationship between hydraulic permeability coefficient and the coefficients C_d and *m*.

$$C_d = 0.0387\ln(k) + 0.1914 \qquad R^2 = 0.9595 \qquad \textit{Longitudinal crack} \tag{33}$$

$$C_d = 0.0375(k) + 0.1166 \qquad R^2 = 0.9818 \qquad \textit{Circumferential crack} \tag{34}$$

$$C_d = 1.4917(n) - 0.1579 \qquad R^2 = 0.4471 \qquad \textit{Longitudinal crack} \tag{35}$$

$$C_d = 2.3378(n) - 0.3534 \qquad R^2 = 0.7368 \qquad \textit{Circumferential crack} \tag{36}$$

$$m \times 10^9 = -0.2562(k) + 2.688 \qquad R^2 = 0.5867 \qquad \textit{Longitudinal crack} \tag{37}$$

$$m \times 10^9 = -1.4244(k) + 4.8256 \qquad R^2 = 0.8600 \qquad \textit{Circumferential crack} \tag{38}$$

$$m \times 10^9 = -29.61(n) + 9.0416 \qquad R^2 = 0.4099 \qquad \textit{Longitudinal crack} \tag{39}$$

$$m \times 10^9 = -80.10(n) + 20.66 \qquad R^2 = 0.5248 \qquad \textit{Circumferential crack} \tag{40}$$

3.6. Correlation between soil dry unit weight and FAVAD coefficients

The relationship between soil dry unit weight (γ_d) and the coefficients of FAVAD equation is investigated (Fig. 11). Results show that in both longitudinal and circumferential cracks, by increasing the dry unit weight, the coefficient of C_d decreases. The more dry unit weight means more compaction, which leads to less discharge coefficient for leakage through the soil. On the other hand, increasing the dry unit weight, the coefficient of *m* increases. Due to the fact that in more compacted soils dry unit weight is higher, it can be concluded that in this kind of soils, leak area increase due to pressure increase is more; accordingly, value of *m* increases. Eqs. (41) to (44) show the relationship between dry unit weight and the coefficients C_d and *m*.

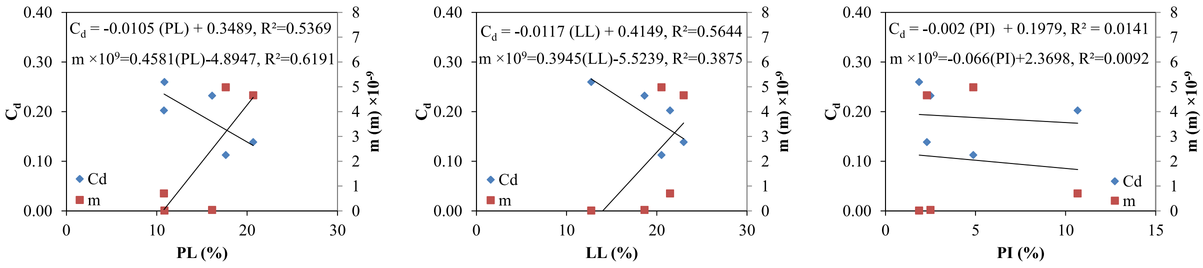
$$C_d = -0.11\,00(\gamma_d) + 2.2666 \qquad R^2 = 0.8833 \qquad \textit{Longitudinal crack} \tag{41}$$

$$C_d = -0.0489(\gamma_d) + 0.8506 \qquad R^2 = 0.9719 \qquad \textit{Circumferential crack} \tag{42}$$

$$m \times 10^9 = 2.3198(\gamma_d) - 41.64 \qquad R^2 = 0.9141 \qquad \textit{Longitudinal crack} \tag{43}$$

$$m \times 10^9 = 1.8778(\gamma_d) - 23.323 \qquad R^2 = 0.8690 \qquad \textit{Circumferential crack} \tag{44}$$

After the graphs were depicted, the correlation between soils various properties and leakage key coefficients were assessed. Subsequently, soil parameters D_{50}, hydraulic permeability coefficient (k) and dry unit weight (γ_d) were selected as the main indexes that have the highest coefficient of determination, based on the results of experimental tests. These parameters are the best representatives for showing the effect of soil properties on the amount of leakage discharge.



(a) (b) (c)

Fig. 9. The relationship between coefficients C_d and m and: (a) *PL*; (b) *LL*; (c) *PI*.

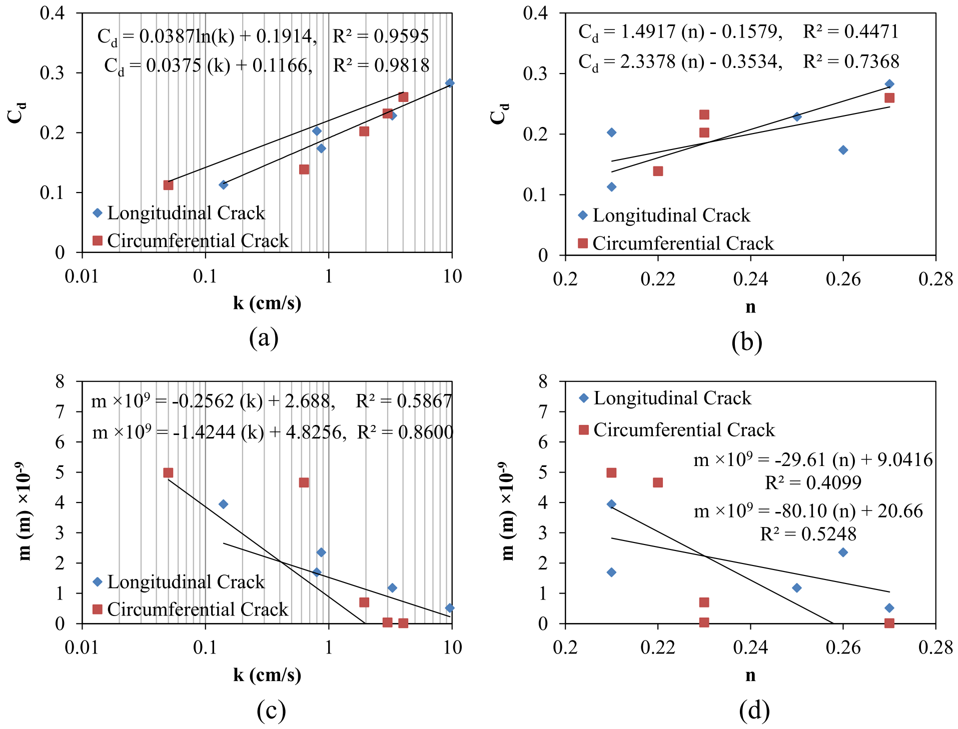
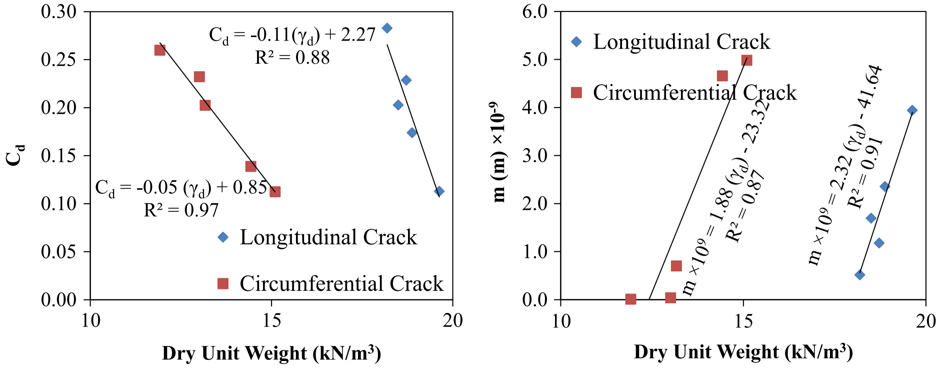


Fig. 10. The relationship between hydraulic permeability coefficient and porosity and: (a-b) C_d; and (c-d) m.



(a) (b)

Fig. 11. The relationship between soil dry unit weight and (a) C_d; and (b) m.

4. Conclusion

In this study, the effects of various properties of the soil around the pipe on leakage discharge were investigated. For this purpose, leakage from polyethylene pipes was simulated in laboratory conditions with longitudinal cracks in presence of five different soil types and in the other time, with circumferential cracks in presence of five other soil types, and leakage amounts were measured. Then, a discharge- pressure relationship was obtained for each type of soils. The results show that the soil properties are effective on the amount of leakage from longitudinal and circumferential cracks. It was also observed that in the presence of soils, the amount of leakage follows the FAVAD theory. By comparing different soil properties, it was found that there is a correlation between parameters soil particle sizes, plasticity limits, and hydraulic permeability of the soils and leakage flowrate. By examining this correlation, it was found that soils D_{50} parameter, hydraulic permeability and dry unit weight are better indicators for introducing soil properties around the cracks. The results of this study help the engineers and managers to estimate the leakage flowrate more precisely. Also, more investigations on different types of pipe materials, soils types, etc. are needed to make it possible to guide the constructors on the required implementations. The authors are sure that more studies will lead to some recommendations on the properties of backfill soils with the aim of decreasing the background leakage.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

[1] ASTM D2434-68, 2006. “Standard test method for permeability of granular soils (Constant head).” D2434-68, ASTM, West Conshohocken, PA. DOI: 10.1520/D2434-68R06.

[2] ASTM D4318-10e1, 2010. “Standard test methods for liquid limit, plastic limit, and plasticity index of soils.” *ASTM International*, West Conshohocken, PA. DOI: 10.1520/D4318.

[3] ASTM D2487-11, 2011. “Standard practice for classification of soils for engineering purposes (Unified soil classification system).” *ASTM International*, West Conshohocken, PA. DOI: 10.1520/D2487-11.

[4] ASTM D698-12e2, 2012. “Standard test methods for laboratory compaction characteristics of soil using standard effort (12400 ft-lbf/ft^3 (600 kN-m/m^3)), *ASTM International*, West Conshohocken, PA. DOI: 10.1520/D0698-12E02.

[5] Coetzer, A.J., van Zyl, J.E., and Clayton, C.R.I. 2006. “Experimental study of the hydraulics of small circular holes in water pipes.” In *Proc., the 8th Annual Symposium on Water Distribution Systems Analysis Symposium*, Cincinnati, Ohio, 27–30 August.

[6] A.M. Cassa, J.E. van Zyl, R.F. Laubscher, A numerical investigation into the effect of pressure on holes and cracks in water supply pipes, J. Urban Water 7 (2) (2010) 109–120, https://doi.org/10.1080/15730620903447613.

[7] M. Di Marchis, B. Milici, Leakage estimation in water distribution network: effect of the shape and size cracks, *Water Res. Manage*. 33 (2019) 1167–1183, https://doi.org/10.1007/s11269-018-2173-4.

[8] M. Farley, S. Trow, Losses in water distribution networks, IWA Publishing, London, 2003.

[9] M. Ferrante, Experimental investigation of the effects of pipe material on the leak head-discharge relationship, J. Hydr. Eng. 138 (8) (2012) 736–743, https://doi.org/10.1061/(ASCE)HY.1943-7900.0000578.

[10] S. Fox, R. Collins, J. Boxall, Physical investigation into the significance of ground conditions on dynamic leakage behaviour, J. Water Supply Res. Technol. AQUA 65 (2) (2016) 103–115, https://doi.org/10.2166/aqua.2015.079.

[11] G. Germanopoulos, P.W. Jowitt, Leakage reduction by excess pressure minimization in a water supply network, Proc. Instit. Civil Engin. 87 (2) (1989) 195–214, https://doi.org/10.1680/iicep.1989.2003.

[12] B. Greyvenstein, J.E. van Zyl, An experimental investigation into the pressure-leakage relationship of some failed water pipes, J. Water Supply Res. Technol. AQUA 56 (2) (2007) 117–124, https://doi.org/10.2166/aqua.2007.065.

[13] Lambert, A. 2000. “What do we know about pressure: leakage relationships in distribution systems?” In *Proc., IWA Conf. System Approach to Leakage Control and Water Distribution Systems Management*, Brno, Czech Republic.

[14] M. Latifi, S.T.O. Naeeni, A. Mahdavi, Experimental assessment of soil effects on the leakage discharge from polyethylene pipes, Water Sci. Technol. Water Supply 18 (2) (2018) 539–554, https://doi.org/10.2166/ws.2017.134.

[15] May, J. 1994. “Pressure dependent leakage.” *World Water Environ. Eng.*, October 10.

[16] C. Noack, B. Ulanicki, “Modelling of soil diffusibility on leakage characteristics of buried pipes”, In Proc Water Distribution Systems Analysis Symposium 2006 (2008) 1–9.

[17] S.M. Pike, J.E. van Zyl, C.R.I. Clayton, Scouring damage to buried pipes caused by leakage jets: experimental study, J. Pipeline Syst. Eng. Pract. 9 (4) (2018) 1–11, https://doi.org/10.1061/(ASCE)PS.1949-1204.0000328.

[18] Thornton, J. 2003. “Managing leakage by managing pressure: a practical approach.” *Water 21*, IWA Water Loss Task Force.

[19] Thornton, J. and Lambert, A. 2005. “Progress in practical predictions of pressure- leakage, pressure- Burst frequency and pressure- Consumption.” In *Proc. IWA Special Conference Leakage 2005*, Halifax, Canada.

[20] J.E. van Zyl, A.M. Cassa, Modeling elastically deforming leaks in water distribution pipes, J. Hydr. Eng. 140 (2) (2014) 182–189, https://doi.org/10.1061/(ASCE)HY.1943-7900.0000813.

[21] M. Latifi, Sh. Mohammadbeigi, K. Farahi Moghadam, S.T.O. Naeeni, F. Kilanehei, Experimental study of pressure and soil effects on fluidization and mobile bed zones around buried leaking pipes, J. Pipeline Syst. Eng. Pract. 13 (4) (2022) 1–9, https://doi.org/10.1061/(ASCE)PS.1949-1204.0000671, 04022034.