Experimental assessment of soil effects on the leakage discharge from polyethylene pipes
Milad Latifi, Seyyed Taghi (Omid) Naeeni and Amir Mahdavi

ABSTRACT
Leaking water from pipes depends on several factors such as pressure, pipe material, types of cracks and holes and also regime of flow through cracks. The effects of these factors on the leakage have been investigated by several researchers. However, few studies have been found considering the effects of soil around the pipes on the leakage discharge. Here, the leakage from polyethylene pipes is simulated in the laboratory, selecting several soils with different specifications. The leak discharge equation is adjusted to evaluate the effects of soil characteristics. Accordingly, grain diameter greater than 10% and 50% passing, coefficient of uniformity, coefficient of curvature, liquidity limit, plastic limit, plasticity index and hydraulic permeability have been considered to represent the soil properties. It is observed that the leakage is changed in accordance with most of the above parameters. The effects of grain diameter greater than 50% passing, plastic limit and hydraulic permeability are higher on the leakage, comparing to those of other parameters. However, no meaningful relationship is observed between the leakage and some parameters. The effects of significant characteristics are shown by the equations presented in this study.

Key words | leaky coupling, orifice, polyethylene pipes, soil properties, water leakage

INTRODUCTION
Nowadays, the shortage of qualified drinking water is a crisis which threatens substantial parts of the world. High cost of constructing dams, transmission pipelines, water treatment plants and water distribution networks have motivated the engineers to prevent the leakage and loss of valuable fresh water. Water leakage may also threaten the sustainability of the resources in arid and semi-arid areas. Leakage is physical escaping of water form network or service pipes through holes, longitudinal or transversal cracks, and bursts of pipes, valves and fittings. In this regard, several researches have been conducted on the leakage phenomenon to present a relationship for describing leakage discharge. The leakage from pipes is affected by different factors such as leak hydraulics (water pressure in pipes, area and shape of hole or crack), pipe material behaviors, soil hydraulics and water demands (van Zyl & Clayton 2007).

The effects of pressure on the leakage
Considering the effects of different factors on the pipe leakage, mentioned above, the researchers have particularly focused on the water pressure. The theoretical equation of leakage-pressure has been expressed with respect to the Orifice concept. The velocity of water outlet from an orifice is computed using Bernoulli equation and defined as follows:

\[ V = \sqrt{2gh} \quad (1) \]

where \( V \) = theoretical outlet velocity from orifice; \( g \) = gravity acceleration; and \( h \) = water pressure head at orifice. The cross section area of orifice is multiplied by the obtained velocity (Equation (1)) to calculate the theoretical discharge of leakage. In Equation (1), energy loss is
neglected; therefore, correction coefficient \((C_L)\) is multiplied by theoretical velocity to gain the real velocity. Considering the effects of orifice edges as well as the roughness of hole span, the contracted area is calculated by applying the correction coefficient \((C_L)\) in the real cross section area. The multiplication of \(C_r\) and \(C_\ell\) coefficients is used as discharge constant \((C_d)\) in the leakage-pressure equation, Streeter et al. (1998), and defined as follows:

\[
Q = C_d A \sqrt{2gh} \tag{2}
\]

where \(Q\) = leakage discharge; \(C_d\) = discharge constant; \(A\) = hole or crack area. This equation is the basis of leakage-pressure equation, proposed by the International Water Association (IWA) water loss task force (Thornton 2003) as:

\[
Q = C P^{n_1}, \tag{3}
\]

where \(P\) = water pressure at leakage position; \(C\) = a coefficient; and \(n_1\) = an exponent. The relationship between leakage and pressure is not a new issue and its power law form has been demonstrated through several experiments (Thornton & Lambert 2005). The exponent of pressure is considered as 0.5, based on the theory of leakage-pressure equation as well as the relation obtained from Bernoulli equation. However, according to the relevant investigations, this value can be 0.5–2.5 (Lambert 2001; Farley & Trow 2003; Thornton & Lambert 2005).

Germanopoulos (1985) proposed a formula to calculate the leakage discharge in the water distribution networks, assuming uniform distribution of leakage in the pipes, presented as follows:

\[
Q_L = C_L \times L \times (P_{av})^{1.18} \tag{4}
\]

where \(Q_L\) = leakage discharge from the pipe; \(L\) = pipe length; \(P_{av}\) = average pressure of the pipe; and \(C_L\) = leakage constant coefficient. This factor relates leakage per length to the service pressure. Jowitt & Xu (1990) and Araujo et al. (2003) expressed that \(C_L\) depends on the system characteristics (e.g. age and deterioration of the pipe and soil properties, etc.).

The effects of opening shape on the leakage discharge

Many researchers have conducted experiments to evaluate the effects of opening shape and size on the leak discharge. Ashcroft & Taylor (1985) carried out tests on slits on the polyethylene pipes and found the \(n_1\) values in the range 1.23–1.97. Sendil & Al Dhowalia (1992) conducted in-field tests and obtained the exponent of Equation (5) between 0.54 and 1.61.

May (1994) presented Fixed and Variable Area Discharge (FAVAD) theory based on his experiments and it expressed as follows:

\[
Q = C_d \sqrt{2g(A_0 h^{0.5} + m h^{1.5})} \tag{5}
\]

where \(A_0\) = initial leakage area; and \(m\) = head-area slope. In this theory, two kinds of leak areas are considered: (1) fixed areas which act like orifices (initial leak areas); (2) variable areas which can be expanded with changing the pressure values. Cassa et al. (2010) modified the theory and assumed that all leaks have areas that vary linearly with pressure, and that it is only the extent of the variations that differs.

Lambert (2002) proposed the leakage exponent values of 0.5–2.5, considering the type of dominant bursts (0.5 for holes; 1.5 for longitudinal cracks; and 2–2.5 for radial openings). Plastic pipes have \(n_1\) values of 1.5 or even higher, with respect to their potential for longitudinal cracks and crack expansion under higher pressures. Hence, metal and other rigid pipes have the exponent \((n_1)\) of almost 0.5. Giustolisi et al. (2008) suggested the exponent \((n_1)\) of 0.5–1.5, considering the type of leak holes and properties of pipe (e.g. material and rigidity).

van Zyl (2004) proposed the bellow equation to compute the leakage discharge:

\[
Q = C_d \frac{\pi d_0^2}{4} \sqrt{2g \left( H^{1/2} + \frac{2c_0gD}{3tE} H^{3/2} + \frac{c_0^2g^2D^2}{9t^2E^2} H^{5/2} \right)} \tag{6}
\]

where \(d_0\) = original hole diameter; \(D\) = pipe diameter; \(t\) = pipe wall thickness; \(E\) = elasticity modulus; \(H\) = pressure
head; $\rho =$ water density; and $c =$ a constant. In Equation (6), the leakage exponent varies from 0.5 to 2.5, considering the field observations.

Ardakian & Ghazali (2004) measured the leakage and pressure simultaneously in an existing water network and found the exponents of 1.10–1.18. Greyvenstein & Van Zyl (2007) studied the relationship between pressure and leak rate in the failed pipes. They presented the exponent ($n_1$) of 0.79–1.04 for AC pipes with longitudinal cracks, 1.90–2.30 for steel pipes with corrosion clusters, 0.52 for steel and uPVC pipes with round holes, 1.38–1.85 for uPVC pipes with longitudinal cracks and 0.41–0.55 for uPVC pipes with circumferential cracks. De Paola & Giugni (2012) measured the leakage from installed copper nozzles in steel and ductile iron pipes. They found the exponent ($n_1$) values of 0.35–0.7 for different tests. De Marchis et al. (2016) carried out experimental tests on different pipe material rigidities and crack sizes. They found the exponents and coefficients of Equations (3) and (5) for the test. They also ignored the effect of soil on the leakage from pipes. Fox et al. (2017) used a laboratory set to study the behavior of leakage in viscoelastic pipes. In addition to pressure head and leak flow rate, they experimentally measured leak area and axial strain in each test.

The effects of soil around the pipe on the leakage

The effects of soil properties have also been assessed on the leakage by the researchers. Germanopoulos & Jowitt (1989) mentioned that the leakage is affected by the movement and characteristics of the soil in which the pipes are laid. Rajani & Zhan (1996) investigated the effects of soil properties and soil moisture on the pipes breakage. They investigated the structural aspects of soil effects on the pipe deformation in the frost conditions, but not the effects of soil on the leak discharge. Some other scientists studied the effects of soil properties on the pipe deterioration (Kleiner & Rajani 2001; Seica et al. 2002; Sadiq et al. 2004; Najjaran et al. 2006; Xu et al. 2014).

van Zyl & Clayton (2007) assessed the effects of soil properties on the leak rate using Darcy law and suggested the formula for calculating the leakage discharge as follows:

$$Q = F \cdot k \cdot h$$

(7)

where $F =$ the shape factor for the soil flow region; $k =$ the coefficient of permeability of the soil; and $h =$ the head of the water in the pipe. They admitted that this equation is supported by the assumptions which are not generally valid for seepage around a water pipe. Reynolds number, mentioned in previous works, represents high flow velocities and turbulent flow regime. However, Darcy law is based on the laminar regime and very low velocities ($10^{-8}$ to $10^{-2}$ m/sec). Therefore, using Darcy law may lead to inaccurate results.

van Zyl et al. (2013) experimentally studied the effect of soil fluidization phenomenon on the leakage discharge using glass ballotini as a substitute soil. They found that head loss from a leaking pipe is divided into three components: (1) through orifice; (2) in the fluidised/mobile bed zones; and (3) through static soil. The results showed that fluidized and mobile zones are extended almost independent of orifice size. Head loss mostly occurs descendingly in the fluidised and mobile zones, significantly in the orifice and slightly in the static soil. Schwaller & van Zyl (2014) studied the pressure–leakage response of water distribution systems based on the individual leak behavior, presenting several parameters significantly effective in the leakage exponent. They did not consider soil properties in their research.

Noack & Ulanicki (2006) numerically modeled ideal leakage of a circular orifice using Darcy-Weisbach equation and a 2-D soil model, represented by the standard diffusion equation. They determined the effects of soil diffusibility on the pipe leakage specifications by combining the mentioned equations and presenting in the form of one general steady state model. They also found the $n_1$ exponent for various soils. The obtained value of exponent was nearly 1 for very low permeability; i.e. the outflow was not following the square root law. However, as permeability increased, the exponent decreased until reaching 0.5; i.e. the pipe outflow was following the square root law. They carried out several experiments on a test rig with clay and normal soils. By fitting a power law form curve to the data obtained from the test rig, the exponent values were 0.3 for normal soil and 0.5 for clay type soil. The values were different from those of numerical model.

van Zyl (2014) predicted that while soils around a leak might affect pressure–leakage relationship, it is unlikely that any soil will be able to contain the pressures that are
commonly found in water distribution systems. Therefore, soils slightly affect the pressure-response of the leakage. Walski & Beztz (2004) presented theoretical equations and compared their order of magnitudes. They concluded that both soil and orifice losses were effective in the pressure-response of leakage with the predominance of the former in some cases. They defined a dimensionless factor, OS, which indicates the dominance of soil or orifice. When OS is around the order of magnitude of 1, then both the soil and orifice loss are equally effective. In case of very small OS (OS < 0.01), the soil losses are dominant and when the OS is very large (OS > 100), then the orifice loss predominates. Fox et al. (2016) studied the effects of an idealized (invariable) external porous media on the leakage behavior of longitudinal slits in polyethylene pipe. They showed that using a consolidated porous media around the pipe resulted in a different pressure-leakage relationship, less than that of an equivalent leak into air or water. Also, they investigated the effects of constraining the porous media with a geotextile fabric on the leakage.

As mentioned, different researches have been conducted on the factors effective in the leakage discharge, such as pipe internal pressure, pipe material, cracks types, pipe roughness, flow regime, etc. It has also been attempted to find more precise equations for describing the leak from cracks, breaks and holes with different sizes. Geotechnical properties of the soil around the pipe can influence the amount of leaks due to the nature and mechanism of leakage from pipes. This factor has not been considered in the previous works. In this research, the effects of real soil properties around the pipe on the leak discharge are assessed through a number of experimental tests.

METHODOLOGY

In the present research the effects of soil on the leakage is experimentally studied, considering constant pipe material and hole or leak opening size, and different soils around the pipe. The soils are manually prepared by mixing sieved soils in such a way to cover a wide range of soil types, including coarse and fine soils. The main properties of soil, considered for the purpose, are gradation parameters, permeability, liquidity and plastic limit.

Soil environment has been simulated by a laboratory set in the form of a looped network, including a storage tank, a pump to supply enough pressure, two valves to control the pressure, a pressure gauge and a soil box. A 1.5 kW pump with 62 m nominal pressure and 9,600 Lt/hr discharge is used in the laboratory set, schematically presented in Figure 1(a).

Maximum allowable pressure is considered as 50–60 m in most designing codes of water distribution networks. In the conducted tests, the pressure values at the leak are 15–55 m. The 32 mm steel pipes are used to connect the components of network to a 40-mm PN 10 polyethylene main pipe, passed through the soil box. A high pressure hose is used as backflow pipe to the reservoir. Steel soil box is made with the dimensions of 700 × 500 × 500 mm which is open at top. An analog pressure gauge with the accuracy of 0.1% full scale is calibrated and used in the set which can measure the pressure values of 0–60 m.

Polyethylene pipes, one of the most applicable materials in the urban water distribution networks, are applied to simulate the tests with the field situations of the cities. A 5-cm diameter hole is created in the bottom of the box in order to drain and measure the leaked water. In each test, when outlet flow from the hole reaches its steady state (approximately 30–45 min after start in the present research), the discharged water is collected and weighed. The flow rate is calculated by dividing the measured volume of water by recorded time.

The experiments are conducted in two series, orifice on the pipe and leaky coupling. In the former, a circular hole of 1 mm diameter is drilled on the pipe. Orifice shape is selected to eliminate the effects of expanding of leakage opening. In the latter, a polyethylene coupling with a manually damaged gasket is installed between two 40 mm PE pipes (Figure 1(b)). As the gasket is damaged, leakage occurs in the coupling.

Five different soils are selected for each series of tests. Therefore, 10 rounds of tests are carried out. In each round, the pressure is increased gradually and step-by-step from minimum to maximum and then decreased vice versa by adjusting the valve. Simultaneously, leakage discharge is measured and recorded in each pressure step. The obtained results are discussed in the next section.

Appropriate proportions of the sieved soils are mixed in order to meet the considered gradation. In order to meet
maximum compaction, the water is added in such a way that
the moisture values are between 17% (coarse soils) and 22%
(fine soils). After combination, the soil is poured into the box
in 15-cm layers and compacted using a steel plate and cer-
tain blows of the Proctor hammer.

In the first test of each series, the leakage discharge is
measured in the open air (with no soil). Then, the box is
filled with five soil types with different gradations. Figures 2
and 3 show the gradation diagrams of the soils used in each
series of tests.

Plastic limit (PL) and liquidity limit (LL) of the soils are
estimated according to ASTM D4318-10et (2010). The values
of hydraulic permeability (k) of the soils are measured according
to ASTM D2434-68 (2006), using a device made by Eijkelkamp Co. The soils are classified according to Unified
Soil Classification System (USCS), described in ASTM
D2487-11 (2011). Table 1 presents the values of plastic limit,
liquidity limit, plasticity index, hydraulic permeability and
gradation parameters as well as the classification of the soils.

**RESULTS**

This section focuses on the analysis of results and deriving
the relationships to assess the effects of soil properties on
the leakage discharge. For this purpose, several tests are
conducted in two series, each of which includes five soil
types. Then, pressure–leakage curves are plotted for each
soil type based on the relevant results, Figures 4 and 5.
According to the figures, in each series of tests, maximum
leakage occurs in the absence of soils (leakage to air). More-
over, under the same pressures, the leakage is higher in the
coarse soils, compared to that of fine ones. The main
hypothesis of this research is presented by the following
relationship:

\[ Q = f(P, S) \]  

where \( Q \) is leakage discharge from pipe; \( P \) is interior
pressure of the pipe; and \( S \) is a characteristic of the soil.
The characteristics, considered in this research are: grain diameter at 10% passing ($d_{10}$), grain diameter at 50% passing ($d_{50}$), coefficient of uniformity ($Cu$), coefficient of curvature ($Cc$), plastic limit ($PL$), liquidity limit ($LL$), plasticity index ($PI$) and hydraulic permeability ($k$).

As mentioned earlier, in the previous studies, power law is used to represent the pressure–leakage relationship (Equation (3)). According to FAVAD concept, increasing the pressure can increase the leakage area and raising the $n_1$ exponent. It is assumed that soil
properties only affect the coefficient of leakage, not the exponent. This is also expressed by Jowitt & Xu (1993) and Araujo et al. (2003). So, all properties are maintained constant and only the soil properties and pressure are variable in the tests. Hence, it is assumed that the below equation can describe the effects of soil on the leakage discharge:

\[ Q = C' S^p \frac{P^q}{C} \]  

(9)

where \( C' S^p \) is the substitution of \( C \) in Equation (3). In this research, suitable soil characteristics \( (S) \) and proper

---

**Table 1** Properties of soils used in the tests

<table>
<thead>
<tr>
<th>Test Set</th>
<th>Soil Number</th>
<th>( D_{10} ) (mm)</th>
<th>( D_{50} ) (mm)</th>
<th>( C_u )</th>
<th>( C_c ) (–)</th>
<th>Liquidity limit (%)</th>
<th>Plastic limit (%)</th>
<th>Plasticity index (%)</th>
<th>Hydraulic conductivity (m/sec)</th>
<th>Soil type (USCS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leakage form orifice</td>
<td>Soil #1</td>
<td>0.09</td>
<td>0.23</td>
<td>3.00</td>
<td>1.33</td>
<td>24.0</td>
<td>10.3</td>
<td>13.7</td>
<td>1.05 \times 10^{-4}</td>
<td>SP-SC</td>
</tr>
<tr>
<td></td>
<td>Soil #2</td>
<td>0.11</td>
<td>0.55</td>
<td>5.18</td>
<td>2.07</td>
<td>22.0</td>
<td>11.5</td>
<td>10.5</td>
<td>2.52 \times 10^{-3}</td>
<td>SP</td>
</tr>
<tr>
<td></td>
<td>Soil #3</td>
<td>0.26</td>
<td>1.20</td>
<td>6.15</td>
<td>1.54</td>
<td>25.4</td>
<td>15.8</td>
<td>9.6</td>
<td>5.09 \times 10^{-3}</td>
<td>SW</td>
</tr>
<tr>
<td></td>
<td>Soil #4</td>
<td>0.18</td>
<td>0.46</td>
<td>2.94</td>
<td>0.71</td>
<td>17.4</td>
<td>11.1</td>
<td>6.3</td>
<td>2.30 \times 10^{-5}</td>
<td>SP-SM</td>
</tr>
<tr>
<td></td>
<td>Soil #5</td>
<td>0.12</td>
<td>0.80</td>
<td>11.67</td>
<td>0.54</td>
<td>22.5</td>
<td>14.6</td>
<td>7.9</td>
<td>9.50 \times 10^{-5}</td>
<td>SP</td>
</tr>
<tr>
<td>Leakage form leaky coupling</td>
<td>Soil #6</td>
<td>0.085</td>
<td>0.13</td>
<td>3.29</td>
<td>1.52</td>
<td>21.2</td>
<td>8.6</td>
<td>12.6</td>
<td>2.20 \times 10^{-5}</td>
<td>SP-SC</td>
</tr>
<tr>
<td></td>
<td>Soil #7</td>
<td>0.195</td>
<td>1.90</td>
<td>9.74</td>
<td>0.97</td>
<td>24.8</td>
<td>15.6</td>
<td>9.2</td>
<td>4.68 \times 10^{-3}</td>
<td>SW</td>
</tr>
<tr>
<td></td>
<td>Soil #8</td>
<td>0.13</td>
<td>0.51</td>
<td>4.62</td>
<td>0.74</td>
<td>25.3</td>
<td>17.4</td>
<td>5.7</td>
<td>9.10 \times 10^{-5}</td>
<td>SP-SM</td>
</tr>
<tr>
<td></td>
<td>Soil #9</td>
<td>0.08</td>
<td>0.52</td>
<td>8.13</td>
<td>0.85</td>
<td>23.8</td>
<td>15.8</td>
<td>8.0</td>
<td>1.67 \times 10^{-4}</td>
<td>SC</td>
</tr>
<tr>
<td></td>
<td>Soil #10</td>
<td>0.17</td>
<td>0.62</td>
<td>4.71</td>
<td>0.46</td>
<td>25.3</td>
<td>13.2</td>
<td>12.1</td>
<td>2.84 \times 10^{-3}</td>
<td>SP</td>
</tr>
</tbody>
</table>

SP, Poorly graded sand; SC, Clayey sand; SW, Well-graded sand, fine to coarse sand; SM, Silty sand.

**Figure 4** Leakage discharge from orifice in various pressures.
value of $n_2$ are estimated by determining the relationship between soil properties and leakage.

**Leakage from orifice**

Equations (10)–(15), derived from power regression, present the relationship between pressure and leakage from orifice.

\[
\begin{align*}
Q &= 4.1401P^{0.5599} \quad R^2 = 0.9928, \text{RMSE} = 1.68\% \quad \text{Free Air} \\
Q &= 3.2713P^{0.5443} \quad R^2 = 0.9778, \text{RMSE} = 3.08\% \quad \text{Soil \# 1} \\
Q &= 3.1733P^{0.5995} \quad R^2 = 0.9610, \text{RMSE} = 5.86\% \quad \text{Soil \# 2} \\
Q &= 4.2345P^{0.5336} \quad R^2 = 0.9903, \text{RMSE} = 2.41\% \quad \text{Soil \# 3}
\end{align*}
\]

\[Q = 3.3175P^{0.5777} \quad R^2 = 0.9928, \text{RMSE} = 2.23\% \quad \text{Soil \# 4} \]
\[Q = 2.8720P^{0.6101} \quad R^2 = 0.9900, \text{RMSE} = 3.20\% \quad \text{Soil \# 5}
\]

In the above equations, the values of correlation coefficient ($R^2$) and root mean square error (RMSE) are greater than 0.96 and less than 6%, respectively, which indicates that power law is properly describing the leakage–pressure relationship. Besides, the values of exponents are close and in the range of 0.53–0.61. Although, theoretically, it is expected to find exponent close to 0.50 for free air tests, it is derived close to 0.56. It may be due to the elasticity of the polyethylene pipes which may lead to a slight increase in the exponent. Also, researchers have found the same results, e.g. Thornton & Lambert (2005) and De Paola & Giugni (2012). To understand the effects of soil on the relationship, the above equations are converted to the ones with similar
Soil exponents. In this regard, identical exponents are calculated for all soils through minimizing the square errors, which changes the coefficients of the equations. The values of coefficient, exponent and correlation factor are obtained for leakage–pressure relationship and presented in Table 2. It should be noted that the aforementioned equations are diverted in such a way to have identical exponents ($n_1 = 0.5745$) in different soils.

**Leakage from leaky coupling**

Equations (16)–(21) are derived from the results of the tests conducted on leaky coupling and are presented as follows:

\[
Q = 15.1006P^{0.4410} \quad R^2 = 0.9936, \quad RMSE = 1.53\% \quad \text{Free Air}
\]

(16)

\[
Q = 10.5142P^{0.4133} \quad R^2 = 0.9616, \quad RMSE = 3.24\% \quad \text{Soil \# 6}
\]

(17)

\[
Q = 12.3397P^{0.4542} \quad R^2 = 0.9662, \quad RMSE = 3.46\% \quad \text{Soil \# 7}
\]

(18)

\[
Q = 10.5310P^{0.4701} \quad R^2 = 0.9731, \quad RMSE = 2.87\% \quad \text{Soil \# 8}
\]

(19)

\[
Q = 9.3866P^{0.4829} \quad R^2 = 0.9572, \quad RMSE = 3.92\% \quad \text{Soil \# 9}
\]

(20)

\[
Q = 11.8228P^{0.4541} \quad R^2 = 0.9672, \quad RMSE = 3.28\% \quad \text{Soil \# 10}
\]

(21)

In these tests, the values of $R^2$ and RMSE are greater than 0.95 and less than 4%, respectively, indicating the appropriate power correlation between leakage and pressure. Also, the values of power exponent are less than 0.5 and in the range of 0.41–0.48, which indicates a leak opening contracting with increasing pressure (Greyvenstein & Van Zyl 2007; Cassa & Van Zyl 2013). Based on the coupling structure, by increasing the pressure, the gasket is compressed and the leak area decreases. Also, the close values of exponents confirm the assumption of Equation (9). Accordingly, the same exponent is derived for all soils with different coefficients through minimizing the square errors. Equations (17)–(21) have been used to derive the coefficients, exponents and correlation factors for leakage–pressure relationships considering the same exponent values ($n_1 = 0.4569$) in different soils, Table 3.

**The relationship between leakage and soil properties**

The relationship between coefficient $C$ and soil properties is studied to find the proper representative characteristics of the soil and its exponent. Figures 6 and 7 illustrate the relationship between coefficient $C$ and soil grain diameter at 10% passing ($d_{10}$) and 50% passing ($d_{50}$), respectively.

According to the figures, $C$ coefficient increases with the increase of $d_{10}$ and $d_{50}$, representing the increase of leakage. Moreover, the leakage changes with changing the soil gradation. In case of $d_{10}$, $C$ coefficient changes more rapidly in leaky coupling, compared to that of orifice. Furthermore, leaky coupling has higher exponent in comparison to that of orifice. However, no significant difference is observed in the exponents of $d_{50}$ in orifice and leaky coupling.

The values of correlation coefficients ($R^2$) between $d_{10}$ and $C$ are high in both series of tests: $R^2 = 0.80$ for leaky coupling and $R^2 = 0.61$ for orifice. Concerning $d_{50}$, these

### Table 2 | Coefficients, exponents and correlation coefficients for leakage–pressure relationship in orifice

<table>
<thead>
<tr>
<th>Soil</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>#4</th>
<th>#5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C$</td>
<td>2.9333</td>
<td>3.4712</td>
<td>3.6536</td>
<td>3.3555</td>
<td>3.2656</td>
</tr>
<tr>
<td>$n_1$</td>
<td>0.5745</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.9752</td>
<td>0.9597</td>
<td>0.9861</td>
<td>0.9928</td>
<td>0.9861</td>
</tr>
<tr>
<td>RMSE (%)</td>
<td>3.65</td>
<td>5.80</td>
<td>3.10</td>
<td>2.27</td>
<td>3.80</td>
</tr>
</tbody>
</table>

### Table 3 | Coefficients, exponents and correlation coefficients for leakage–pressure relationship in leaky coupling

<table>
<thead>
<tr>
<th>Soil</th>
<th>#6</th>
<th>#7</th>
<th>#8</th>
<th>#9</th>
<th>#10</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C$</td>
<td>8.9959</td>
<td>12.2189</td>
<td>11.0421</td>
<td>10.3029</td>
<td>11.7052</td>
</tr>
<tr>
<td>$n_1$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.4569</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.9521</td>
<td>0.9661</td>
<td>0.9724</td>
<td>0.9547</td>
<td>0.9672</td>
</tr>
<tr>
<td>RMSE (%)</td>
<td>3.76</td>
<td>3.47</td>
<td>2.90</td>
<td>4.06</td>
<td>3.27</td>
</tr>
</tbody>
</table>

Downloaded from https://iwaponline.com/ws/article-pdf/18/2/539/207101/ws018020539.pdf by guest
**Figure 6** | The relationship between coefficient C and soil grain diameter at 10% passing ($d_{10}$).

**Figure 7** | The relationship between coefficient C and soil grain diameter at 50% passing ($d_{50}$).
values are still higher, comparing to those of $d_{10}$, $R^2 = 0.87$ for orifice and $R^2 = 0.74$ for leaky coupling. Therefore, it can be concluded that soil gradation size affects the leakage discharge from pipes; and $d_{50}$ is a better representative of soil gradation characteristics.

The coefficients of uniformity and curvature are used to determine well or poor grading of the soil. According to USCS for sand soils, the soil is well graded if $C_u \geq 6$ and $1 < C_c < 3$; otherwise, it is poor graded (ASTM D2487-11). Well graded soils may be expected to resist longer against water flow, and therefore lead to lower leakage, compared to poor graded ones. Then, $C$ coefficient is compared with uniformity ($C_u$) and curvature ($C_c$) coefficients and presented in Figures 8 and 9, respectively. According to Figure 8, no meaningful relationship exists between $C_u$ and $C$ ($R^2 = 0.12$) in the leakage from orifice. The correlation coefficient is higher in the leaky coupling, compared to that of orifice, but yet not enough to derive a meaningful relationship, either.

Based on Figure 9, in the leakage from orifice, the correlation coefficient is very low ($R^2 = 0.05$), indicating the existence of no meaningful relationship between $C_c$ and $C$. $R^2$ has low value in the leakage from leaky coupling ($R^2 = 0.46$), showing an inverse relation between $C_c$ and leakage.

Atterberg limits indicate the behavior and consistency of soil in different moistures. These limits are used to distinguish between clay and silt and determine their types in the soils. Considerable effects of plastic properties of soil may be expected on the leakage from pipes. Figure 10 shows the relation between liquidity limit ($LL$) and $C$ coefficient. Concerning the leakage from orifice, no meaningful relation is observed between liquidity limit and leakage ($R^2 = 0$). Conversely, a power relation with the exponent of 1.57 and correlation coefficient of 0.83 is found in the leakage from leaky coupling. Regarding the contradictory results, obtained for orifice and leaky coupling, no definite decision can be made about the relation between $LL$ and coefficient $C$.

The relationship between plastic limit ($PL$) and $C$ is presented by a power equation in Figure 11. The values of correlation coefficient and exponent are 0.41 and 0.28, in leakage from orifice, respectively, and 0.52 and 0.31 in the leaky coupling, respectively.
By increasing the plasticity index (PI), lower permeability is expected in the soil which means lower leakage. Figure 12 shows the relationship between PI and C coefficient. According to this figure, in both series of tests, C coefficient decreases with the increase of plasticity index. Low values of correlation coefficient (0.06 for orifice...
Figure 11 | The relationship between plastic limit (PL) of soils and $C$ coefficient.

\[
C = 4.7869 \times (PL)^{0.3103} \\
R^2 = 0.5168
\]

Figure 12 | The relationship between plasticity limit (PI) of soils and $C$ coefficient.

\[
C = 1.6299 \times (PI)^{0.2826} \\
R^2 = 0.4092
\]

\[
C = 13.257 \times (PI)^{0.093} \\
R^2 = 0.063
\]

\[
C = 4.3335 \times (PI)^{-0.119} \\
R^2 = 0.1806
\]
and 0.18 for leaky coupling) undermine the validity of the equations.

Comparing the results of Atterberg limits, it is concluded that plastic limit has the best fitness with the experimental results and is the best representative of plastic properties of the soil.

Figure 13 shows the relationship between hydraulic permeability coefficient (k) and C. Hydraulic permeability coefficient with a wide range of values is often shown by a semi-log diagram. The mentioned relationship is properly described by logarithmic equation in the leakages from orifice ($R^2 = 0.43$) and leaky coupling ($R^2 = 0.84$). Therefore, hydraulic permeability coefficient can be used as another soil characteristic for estimating the leakage from pipes.

Considering the above equations, the relationship between soil properties, pipe pressure and leakage from pipes can be expressed as follows:

$$Q = 3.5518 (d_{50})^{0.1133} P^{0.5745} \quad R^2 = 0.7357$$  \hspace{1cm} (22)

Leakage from orifice

$$Q = 11.657 (d_{50})^{0.1176} P^{0.4569} \quad R^2 = 0.8687$$  \hspace{1cm} (23)

Leakage from leaky coupling

$$Q = 1.6299 (PL)^{0.2826} P^{0.5745} \quad R^2 = 0.4092$$  \hspace{1cm} (24)

Leakage from orifice

$$Q = 4.7869 (PL)^{0.3103} P^{0.4569} \quad R^2 = 0.5168$$  \hspace{1cm} (25)

Leakage from leaky coupling

$$Q = 0.0761 (Ln(k) + 51.9093) P^{0.5745} \quad R^2 = 0.4355$$  \hspace{1cm} (26)

Leakage from orifice

$$Q = 0.5026 (Ln(k) + 29.5842) P^{0.4569} \quad R^2 = 0.8366$$  \hspace{1cm} (27)

Leakage from leaky coupling

where $P$ is pressure (m); $d_{50}$ is grain diameter at 50% passing (mm); $PL$ is plastic limit (%); and $k$ is hydraulic permeability (m/s).
CONCLUSION

In this study, the effects of soil characteristics have been investigated on the leakage discharge from pipes. The main hypothesis of the research is that the properties of soil surrounding the pipe affect the leakage rate. The leakage from pipes is simulated in the laboratory considering different soil types. Accordingly, different leak types are evaluated using five soil types around a pipe with a 1 mm diameter orifice, as well as a leaky coupling. The same exponent of pressure is calculated in the leakage–pressure equation for all soils in each types of leakage (orifice and leaky coupling). Then, the relations are obtained for leakage discharge in terms of soil characteristics considering \( d_{10} \) and \( d_{50} \) parameters, coefficient of uniformity, coefficient of curvature, liquidity limit, plastic limit, plasticity index and hydraulic permeability of soil. According to the obtained results, the leakage is changed with changing the mentioned parameters of surrounding soil, proving the main hypothesis of this research. Moreover, the leakage is higher in the coarse soils comparing to that of fine soils. Besides, lower leakage is observed in the soils with more plastic limits, which may be due to the higher portion of fine particles of soil and its resistance against water drainage. Based on the results, the leakage from pipes decreases with increasing the cohesion of coarse soils as well as the increase of fine part of the soil and the ratio of soil clay to silts. Also, the higher the hydraulic permeability, the higher the leakage. Therefore, the hydraulic permeability can be considered as an effective parameter in the leakage rate.

It is concluded that the leakage values, estimated by the laboratory relations which obtained from leakage measuring in the absence of soils (outlet to free air), are higher, compared to those of field conditions. Therefore, in dealing with leakage modelling in water distribution systems, considering the influence of water moving through the soil is necessary. Also, some other limitations on the data were a limitation in box dimensions, number of soil types and pipe materials. Regarding the obtained correlation coefficients, the grain diameter greater than 50% passing \( (d_{50}) \), plastic limit and hydraulic permeability can be considered as the appropriate characteristics of the soil in the leakage relationship.

CONFLICT OF INTEREST

No conflict of interest.

REFERENCES


First received 12 December 2016; accepted in revised form 16 June 2017. Available online 30 June 2017.