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Prediction of leakage flow rate from upward water jets bursting at the ground

Predição da vazão perdida por jatos de água ascendentes aflorantes no solo

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Abstract

This paper presents experimental studies to explore the behavior of upward water jets in granular beds. The test conditions included both the cavity and chimney regime. Combining our results with data available in the literature, it was possible to fit a linear relationship to describe the dimensionless upward water velocity at the bed surface (u/U) as a function of kFr, in which Fr is the Froude number and k is a fitting parameter that was linearly related with the medium particle diameter d. A threshold condition (kFr = 1) was also proposed to predict the onset of the chimney regime, which was consistent with published data. Finally, a simple equation based on d, D and H was derived to predict the real-scale leakage flow rate Q from upward water jets bursting at the ground. The results obtained will potentially help water utilities estimate the water loss from underground pipelines.

Keywords: Experiments; Fluidization; Pipe leakage; Water distribution system.

Resumo

O presente artigo apresenta estudos experimentais com o objetivo de analisar o comportamento de jatos d’água ascendentes em leitos granulares. As condições de teste incluíram tanto o regime da cavidade, quanto o regime de chaminé. Combinando os resultados obtidos com dados disponíveis na literatura, foi possível ajustar uma relação linear para descrever a velocidade ascendente adimensional da água na superfície do leito granular (u/U) em função de kFr, em que Fr é o número de Froude e k é um parâmetro de ajuste linearmente dependente do diâmetro médio da partícula, d. Foi proposta uma condição limite (kFr = 1) para prever o início do regime de chaminé, que se apresenta em concordância com dados publicados. Por fim, uma equação simples baseada em d, D e H foi derivada para prever a taxa de vazamento em escala real, Q, de jatos de água ascendentes que atingem o solo. Os resultados obtidos podem ajudar as concessionárias de água a estimar a perda de água em tubulações enterradas.

Palavras-chave: Experimentos; Fluidização; Vazamento de tubulação; Sistema de distribuição de água.

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INTRODUCTION

Leakages from water distribution systems are a global problem, which are responsible for substantial losses of the water supplied (Shao et al., 2019; Yu et al., 2019; Silva et al., 2021). These leakages are classified into two categories: background leakages and bursts. While background leakages cause relatively small water losses and are not easily detected, as they are confined in the soil layer, bursts cause massive water losses and can be visualized at the ground (van Zyl et al., 2013; Schulz et al., 2021).

Previous researchers investigated both experimentally and theoretically the dynamics of upward water jets in granular beds (van Zyl et al., 2013; Ergun, 1952; Zoueshtiagh & Merlen, 2007; Philippe & Badiane, 2013; Alsaydalani & Clayton, 2014; Cui et al., 2014; Bailey & Van Zyl, 2015; Montella et al., 2016; He et al., 2017; Schulz et al., 2021). These studies revealed that depending on the jet flow rate, basically three subsequent flow regimes are generated: static bed; fluidized cavity; and fluidized chimney bursting at the bed surface. While some studies assessed the pressure/velocity fields in the cavity regime, others focused on the description of the onset of each flow regime using flow visualization and analytical/theoretical models. More recently, computational fluid dynamics (CFD) has been used to investigate the flow patterns and sand bed erosion processes in the chimney regime (Tang et al., 2017). However, none of the above-mentioned studies provided measurements of upward water velocity in the chimney regime (after full fluidization). Moreover, the methods proposed for estimating the critical leakage flow rate for full fluidization usually depend on parameters that are not easily obtained in the field.

In the present paper, we conduct experimental studies to investigate the behavior of upward water jets in granular beds, covering both the cavity and chimney regimes. The objectives are: (1) to better understand the flow patterns in both regimes; (2) to determine a threshold condition for reaching the chimney regime; (3) to investigate the upward water velocity at the top of the sand bed; and (4) to derive simple correlations to predict the real-scale leakage flow rate from upward water jets bursting at the ground. The results of this study will potentially help water companies quantify the water loss from pipe bursts.

MATERIAL AND METHODS

Experimental setup and procedures

Experiments were performed in a square plexiglass tank, with side of 50 cm and height of 100 cm, as shown schematically in Figure 1. The tank was filled with typical sands used for underground water pipelines up to a height H of 10-20 cm. Sand particle density (ϱs) was 2.65 g/cm^3 and medium grain diameter (d) ranged from 0.27 to 0.31 mm. A centrifugal pump of 2.0 HP gradually injected tap water through a bottom nozzle with diameter D = 1 cm, located at the center of the tank, in order to saturate the sand layer. Then, water was slowly added at the top of the sand bed to form a water layer with a fixed height H' = 10 cm. Finally, the centrifugal pump injected flow rates Q of 139-417 mL/s through the nozzle at a steady-state condition, as water was also

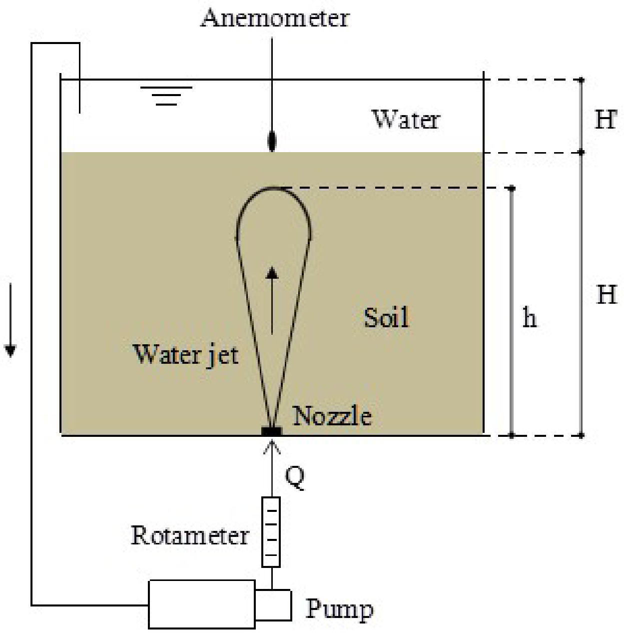

Figure 1. Schematic of experimental setup, indicating the upward water jet in the sand bed.

withdrawn from the water layer above the sand bed. The flow rates Q were controlled by a globe valve and measured using a rotameter (CONAUT, Model 440).

For relatively low values of Q, the cavity regime occurred, as the upward water jet kept confined in the sand bed ($h < H$). On the other hand, for larger values of Q, the chimney regime occurred, since the upward water jet reached the top of the sand bed ($h > H$). For the latter case, the mean upward water velocity at the sand-water interface (u) was measured with an electromagnetic propeller anemometer (Omni Instruments, MiniWater20).

Experimental data analysis

The experimental results were combined with data available in the literature to obtain general correlations to predict: the limiting condition between the cavity and chimney regimes; the upward water velocity at the top of the sand bed; and the leakage flow rate from upward water jets bursting at the ground.

RESULTS AND DISCUSSION

Depending on the flow rate injected through the bottom nozzle, the experimental simulations of the upward water jets in the sand bed reached the cavity or the chimney regime. As we used a centered nozzle at the bottom of the tank, only the chimney regime could be visualized in the experimental setup. Thus, because of water turbidity, the propeller anemometer had to be used (instead of flow visualization) to measure the water jet velocity at the sand bed surface in order to confirm that the chimney regime was reached. Similar flow behaviors (cavity and chimney regimes) were also reported by previous researchers (Philippe & Badiane, 2013; Cui et al., 2014; Montella et al., 2016; He et al., 2017; Schulz et al., 2021).

Figure 2 depicts our experimental results for the upward water jet velocity (u) at the soil-water interface as a function of leakage flow rate (Q), height of the sand bed (H), and medium particle diameter (d). The null values of u represent the cavity regime, in which the height of the water jet is lower than the sand bed height (h < H). On the other hand, the positive values of u represent the chimney regime (h > H), where u consistently increased with Q and d, and decreased with H. This result is in agreement with previous experimental studies, in which the chimney regime was observed visually for larger values of Q and d, and smaller values of H (Zoueshtiagh & Merlen, 2007; Philippe & Badiane, 2013; He et al., 2017).

In Figure 3a we combined in a dimensionless framework our experimental data with that available in the literature (Tang et al., 2017), in order to describe the upward water velocity at the soil-water interface (u/U) as a function of kFr, where U is the nozzle exit velocity, k is a fitting parameter, and Fr is the Froude number, defined as:

$$Fr = \frac{U}{\sqrt{gH}} \tag{1}$$

Curve fitting resulted in k-values of 0.42 and 0.47 for Exps. 1-3 and Exp. 4, respectively. A value of k = 1.20 was also fitted for the data of Tang et al. (2017). This resulted in the following correlation ($R^2 = 0.89$):

$$\frac{u}{U} = 0.015\left(kFr - 1\right) \tag{2}$$

The graphical analysis of the regression residuals indicates that the residuals are distributed randomly around the x-axis, with constant dispersion, suggesting that there are no serious violations of the assumptions of homoscedasticity, null mean and independence from errors. The average of the residuals presented a value of 0.0006, very close to zero. In addition, the Shapiro-Wilk normality test was performed, resulting in W = 0.97 and p-value = 0.70, which indicates that the residuals follow a normal distribution.

Equation 2 suggests that the cavity regime occurs when kFr < 1, while the chimney regime occurs when kFr > 1 [see Figure 3a]. Therefore, a threshold condition can be taken as kFr = 1. It was also possible to derive a second correlation ($R^2 = 0.97$) to describe the fitted values of k as a function of medium particle diameter d (in mm), as depicted in Figure 3b:

$$k = 1.5d \tag{3}$$

The above correlations (2) and (3) are consistent with the physics of the problem, as U scales with the height of the water jet h from energy arguments ($U \sim \sqrt{2gh}$). Thus, Fr can be expressed as a function of h/H. On the other hand, k is linearly related with the medium particle diameter, and can be seen as a function of the hydraulic permeability of the porous medium (Philippe & Badiane, 2013). Hence, the direct relationship between the dimensionless velocity u/U and kFr seems reasonable.

The validation of our threshold condition (kFr = 1) was performed in Figure 4 by using the flow regime diagram and experimental data reported by He et al. (2017). Except for a very few data points (Q ~ 90 mL/s and H = 0.2 m), where kFr was close to 1 (transitional regime), all the other flow conditions were in prefect agreement with the cavity and chimney regimes observed visually by He et al. (2017). This suggests that the following equation derived from the condition kFr = 1 [see Equations 1-3] can be used to predict the real-scale leakage flow rate from upward water jets bursting at the ground (for h = H):

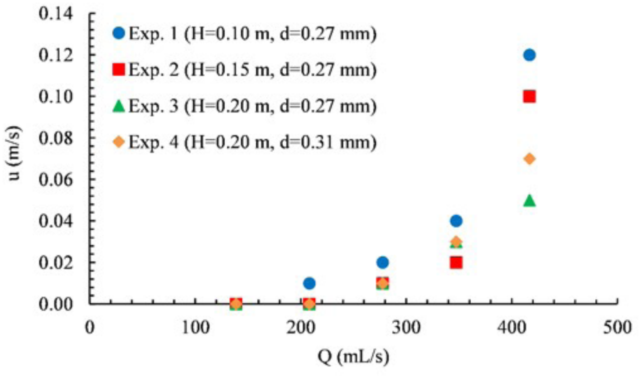

Figure 2. Experimental results of upward water jet velocity (u) at the soil-water interface as a function of leakage flow rate (Q), height of the sand bed (H), and medium particle diameter (d).

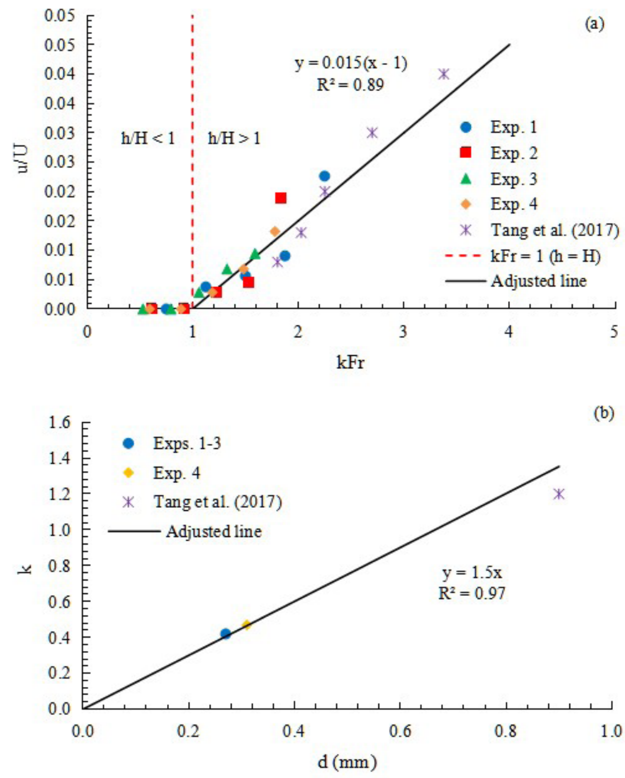

Figure 3. (a) Dimensionless upward water velocity at the soil-water interface (u/U) as a function of the Froude number (kFr), indicating two regimes: cavity regime (h/H < 1) and chimney regime (h/H > 1); (b) Fitting of the constant k as a function of the medium particle diameter (d).

$$Q = \frac{\pi D^2}{6d}\sqrt{gH} \quad (4)$$

in which Q is the leakage flow rate (m^3/s), D is the orifice diameter (m), d is the medium grain diameter (mm), and H is the depth of the leakage opening (m).

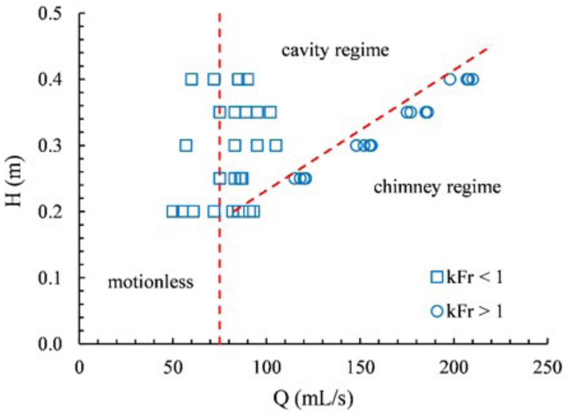

Figure 4. Validation of our threshold condition (kFr = 1) between the cavity and chimney regime with the flow regime diagram and experimental data of He et al. (2017).

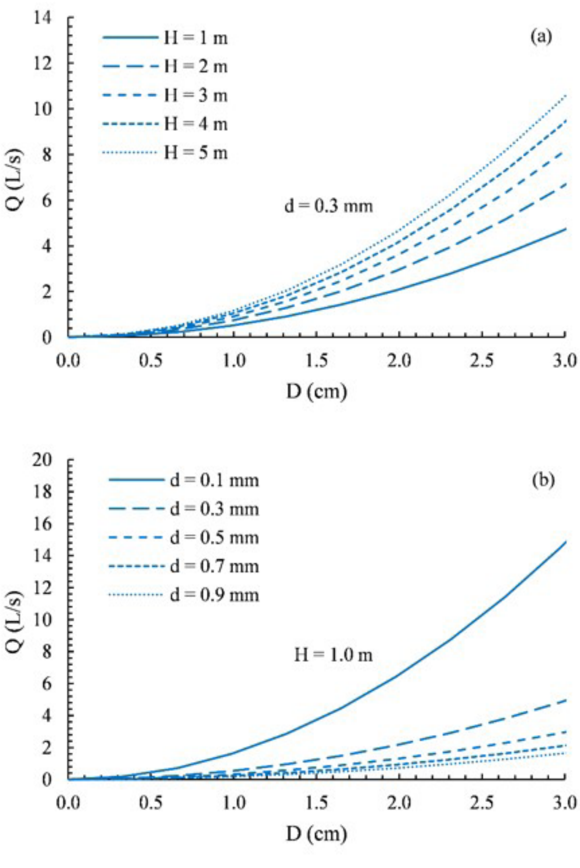

Figure 5. Prediction of leakage flow rate Q as a function of orifice diameter D: (a) effect of orifice depth H, and (b) effect of mean particle diameter d.

Note that Equation 4 is much simpler than previous equations and methods proposed in the literature (Ergun, 1952; Zoueshtiagh & Merlen, 2007; Philippe & Badiane, 2013; Cui et al., 2014; Montella et al., 2016; He et al., 2017; Tang et al., 2017), and can be seen as a predictive tool for practical applications.

Figure 5 shows the prediction of leakage flow rate Q for typical values of orifice diameter D, depth H, and mean particle diameter d, by using the Equation 4. The simulations provided consistent results, which suggest that Figure 5 can be potentially used for water loss management in water distribution systems.

For instance, if a leakage with orifice diameter D = 2 cm is detected in an underground pipeline located at a depth H = 3 m in a porous medium of d = 0.3 mm, Figure 5a provides a leakage flow rate Q = 4 L/s. On the other hand, for D = 1 cm, H = 1 m, and d = 0.1 mm, Figure 5b results in a leakage flow rate Q = 2 L/s.

CONCLUSIONS

In this study we conducted laboratory experiments to investigate the behavior of upward water jets in porous medium. The test conditions included both the cavity and chimney regimes, but the focus was on the determination of the leakage flow rate from upward water jets bursting at the granular bed surface.

The main findings of the study are:

1. Combining our experimental results with published data, it was possible to fit a linear relationship to describe the dimensionless upward water velocity at the soil-water interface (u/U) as a function of kFr, in which Fr is the Froude number based on the nozzle exit velocity U and the depth of the leakage opening H, and k is a fitting parameter;
2. The parameter k was also linearly related with the medium particle diameter d, and was assumed to be a function of the hydraulic permeability of the porous medium. This implies that the lower the value of k, the higher the leakage flow rate Q required for water jet bursting at the ground;
3. A threshold condition (kFr = 1) was proposed to predict the onset of the chimney regime, in which the upward water jet reached the top of the granular bed. This condition was also consistent with data available in the literature;
4. A simple equation was derived to predict the real-scale leakage flow rate from upward water jets bursting at the ground. The results provided in this study will potentially help water utilities quantify the water loss from pipe bursts.

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Authors contributions

Luísa Ciríaco Silva de Oliveira: Data curation, formal analysis, investigation, writing – original draft, writing – review and editing.

Iran Eduardo Lima Neto: Conceptualization, funding acquisition, methodology, project administration, supervision, writing – original draft, writing – review and editing.

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