



Delft University of Technology

**Document Version**

Final published version

**Licence**

CC BY

**Citation (APA)**

Alhaddad, S. M. S., Manrho, J. R., & Mahgoub, M. A. A. (2026). Scour caused by stationary circular developing water jets in cohesive soils. *Ocean Engineering*, 364, Article 126866. <https://doi.org/10.1016/j.oceaneng.2026.126866>

**Important note**

To cite this publication, please use the final published version (if applicable).  
Please check the document version above.

**Copyright**

In case the licence states "Dutch Copyright Act (Article 25fa)", this publication was made available Green Open Access via the TU Delft Institutional Repository pursuant to Dutch Copyright Act (Article 25fa, the Taverne amendment). This provision does not affect copyright ownership.  
Unless copyright is transferred by contract or statute, it remains with the copyright holder.

**Sharing and reuse**

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

**Takedown policy**

Please contact us and provide details if you believe this document breaches copyrights.  
We will remove access to the work immediately and investigate your claim.

*This work is downloaded from Delft University of Technology.*



## Research paper

## Scour caused by stationary circular developing water jets in cohesive soils

Said Alhaddad<sup>ID\*</sup>, Julian Manrho<sup>ID</sup>, Mosaab Mahgoub<sup>ID</sup>

Department of Maritime and Transport Technology, Faculty of Mechanical Engineering, Delft University of Technology, Leeghwaterstraat, Delft, 2628 CN, The Netherlands

## ARTICLE INFO

## Keywords:

Scour  
Submerged water jets  
Stationary water jets  
Cohesive soil  
Dredging  
Cable trenching

## ABSTRACT

Cohesive soil scour occurs in numerous hydraulic and geotechnical applications, yet it has received markedly less attention than scour in non-cohesive sediments. This study advances the understanding of scour processes induced by a vertical, stationary, circular, developing, low-pressure water jet impinging on cohesive soils. A series of small-scale laboratory experiments was conducted using jet pressures ranging from 4.3 to 10 kPa, with two tests extended until equilibrium scour depths were reached. The cohesive soil tested had an undrained shear strength between 4.5 and 5.9 kPa. The influence of key jet parameters, including nozzle diameter and stand-off distance, on soil erosion was investigated through measurements of erosion depth, erosion width, and erosion volume. The repeatability of cavities formed by stationary circular jets in cohesive soils was also examined. Additionally, a semi-theoretical formulation is proposed to predict the equilibrium scour depth. Unlike existing predictive models, the proposed formulation does not require soil-specific calibration parameters. The model was validated using data from the present experiments as well as independent datasets, demonstrating its robustness across different test conditions.

## 1. Introduction

Erosion caused by subaqueous water jets is increasingly observed across a wide range of engineering contexts, including subsea cable trenching (Warringa et al., 2019; Alhaddad, 2026), wastewater treatment systems (Sharp and Joseph, 2009), deep-sea mining (Liu et al., 2023; Alhaddad et al., 2024), and other marine and hydraulic engineering applications. A detailed understanding of the erosion mechanisms associated with submerged jets is critical for advancing the design and performance of hydraulic and offshore engineering systems. However, the complex coupling between flow dynamics and soil response has prevented the establishment of a theoretical framework for jet-induced erosion. In particular, erosion processes in cohesive soil remain insufficiently investigated compared to those in non-cohesive soil. Circular impinging jets can generate intense localized shear stresses and normal stresses on cohesive beds, producing scour holes and mass erosion failures that are still difficult to predict reliably.

Three main mechanisms are commonly distinguished in jet-induced erosion of cohesive soils: mass erosion, surface erosion and flake erosion (Mazurek et al., 2001; Palermo et al., 2024). Mass erosion is a large-scale failure process involving the detachment and removal of cohesive soil lumps of varying sizes, and it is responsible for the greatest increases in scour hole dimensions. Winterwerp and Van Kesteren (2004) described this mechanism as an undrained soil failure process

in which pressure gradients induce cracking within the soil, ultimately causing large soil lumps to detach. In contrast, surface erosion is a more gradual process and is generally treated as a drained soil-mechanical process. Mazurek et al. (2001) described surface erosion as a particle-by-particle removal mechanism and observed that it was commonly accompanied by the formation of a sediment cloud within the experimental water tank. In flake erosion, thin soil flakes are dislodged.

Over recent few decades, a range of dimensionless analysis approaches has been applied to examine the evolution of characteristic dimensions of holes in cohesive soils (e.g., Mazurek et al., 2001; Dong et al., 2020; Qiu et al., 2024). Mazurek et al. (2001) proposed that two distinct scour hole morphologies correspond to different impinging jet regimes, namely weakly deflected and strongly deflected jets. “Weak deflection” holes are shallow and wide and have small ( $SOD/D$ ) values, and “strong deflection” holes are narrow and deep and have large ( $SOD/D$ ) values, where  $SOD$  is the stand-off distance and  $D$  is the nozzle diameter. The authors differentiated between the two regimes based on the value of an excess shear stress term  $(X - X_c)/X_c$ , where  $X$  is a parameter describing the hydraulic properties of jet and  $X_c$  is the value of  $X$  at which mass erosion first occurs. Dong et al. (2020) investigated the critical conditions governing the onset of scour and systematically evaluated the influence of key parameters

\* Corresponding author.

E-mail address: [s.m.s.alhaddad@tudelft.nl](mailto:s.m.s.alhaddad@tudelft.nl) (S. Alhaddad).

– including nozzle diameter, jet velocity, impact height, scour duration, moisture content, and critical shear stress – on the resulting scour hole dimensions. Qiu et al. (2024) also analyzed the effects of jet velocity, impingement height, and nozzle diameter on scour hole geometry.

Although jet-induced scour in cohesive sediments has been examined in several studies, most have focused on high-pressure water jets and scour generated by fully developed jets. In contrast, erosion processes associated with developing low-pressure water jets in cohesive soils remain insufficiently explored. Low-pressure water jets are used in different applications, such as Mass Flow Excavation Method (MFE) and Water Injection Dredging (WID) (Sigwald et al., 2015). In contrast to conventional dredging operations, MFE utilizes high-volume, low-pressure flow to excavate and relocate sediment without direct interaction with the seabed. This method can be applied in cohesive and non-cohesive sediment and is well-suited for applications such as subsea pipeline de-burial, cable route preparation, and decommissioning of offshore structures. In WID, substantial volumes of low-pressure water are injected directly into the sediment bed. This process decreases the bulk density of the seabed material, resuspending it and generating turbidity currents the transport the sediment away from the dredging location (Fuller et al., 2024).

This study advances the understanding of scour processes induced by a circular, developing, low-pressure water jet impinging on cohesive soils. A total of eleven small-scale laboratory experiments were conducted on such jets (jet pressure = 4.3–10 kPa), two of which were extended until equilibrium scour depths were achieved. To ensure that experiments start with developing water jets, the stand-off distances (*SOD*) were maintained between 1 and 2.2 times the nozzle diameter *D*, which are shorter than the potential core lengths proposed by Lee and Chu (2012) ( $6.2D$ ) and reported by Hashiehbaf et al. (2015) ( $4D$ ). The unique conditions of our experiments yield datasets that critically contribute to the existing body of experimental data on cohesive soil scour. Based on the underlying physics governing vertical jet development and experimental data, a semi-theoretical formula is proposed to predict the equilibrium scour depth. In contrast to existing predictive models, the proposed formula does not require calibration parameters specific to soil type. The formula was validated using experimental data from the present study as well as independent datasets from two previously published experimental investigations. In addition, the repeatability of scour cavity geometries generated by stationary circular jets in cohesive soils was examined, addressing a gap in the existing literature.

## 2. Laboratory experiments

In this section, we describe the experimental setup, instrumentation, test procedure and characterization of clay, respectively.

### 2.1. Experimental setup

The experiments were conducted in a rectangular glass tank with internal dimensions of 3.0 m in length, 0.2 m in width, and 0.4 m in depth (see Fig. 1). Circular nozzles of various diameters (5, 6.5, 8, and 10 mm) were designed specifically for this study and fabricated using resin-based 3D printing to ensure precise geometry and repeatability. A laser scanner was mounted on a motorized carriage capable of moving along custom rails installed at the top of the flume.

### 2.2. Instrumentation

The experimental setup included an acoustic flow meter installed in-line with the jet supply hose to continuously monitor the flow rate, ensuring that the target jet velocity was accurately maintained for each experiment. Flow rate control was achieved using a variable-frequency drive, which allowed precise adjustment of the pump speed. To quantify the resulting cavity geometry, an optical sensor (LLT3002-430) was used. This sensor can capture detailed profiles with up to 1024 measurement points per scan at frequencies up to 10 kHz, providing high-resolution measurements of cavity depth and width.

### 2.3. Test procedure and data acquisition

Each test was conducted following a standardized procedure to ensure repeatability and consistency of results.

- Cohesive soil was prepared by mixing dry clay powder with the required amount of water until a homogeneous mixture was obtained. The undrained shear strength of the prepared clay was then measured.
- The clay was placed inside a cylindrical bucket (height = 15.5 cm), and the clay surface was leveled using a spatula.
- The bucket was positioned at the center of the water flume. The jet nozzle was mounted on the mobile carriage at a specified stand-off distance (*SOD*), measured with a caliper.
- The flume was filled with water to a height of 10 cm above the soil surface.
- The experiment was initiated by simultaneously switching on the water pump and the preset timer. When the timer completed its cycle, the experiment was paused for momentary cavity measurements.
- Water was drained from the tank to enable laser-based cavity profiling, as the laser was operated above water. Any remaining water within the cavity was carefully removed using a graduated syringe.
- The mobile carriage was translated along the flume at a controlled velocity (circa 2 cm/s) so that the mounted laser scanner could map the cavity at a constant scanning speed with a sampling frequency of 25 Hz.
- The cavity volume was measured by slowly filling the cavity with water using a graduated syringe.
- Water was supplied to the flume again, and the previous steps were repeated to obtain the next momentary cavity measurements.

Table 1 summarizes the experiments conducted in this study, including the jetting conditions and the undrained shear strength of the clay.

### 2.4. Characterization of clay

The cohesive soil used in this study was prepared by mixing water with clay powder. The particle density of the clay powder was measured as 2800 kg/m<sup>3</sup>. To ensure uniform consistency, water was gradually added to the powder under continuous stirring. The standardized soil preparation process produced samples that were homogeneous and uniform in water content, particle size distribution, and mechanical properties. Prior to each test, the undrained shear strength of the prepared clay was measured and documented. The grain size distribution of the clay is presented in Fig. 2, while characterizing properties of the material are summarized in Table 2.

## 3. Experimental results

This section presents and discusses the experimental results. Hereafter, ‘cavity depth’ is used as an abbreviated term for the maximum scour depth, and ‘cavity width’ for the maximum scour width in the transverse direction.

### 3.1. General description of results

In stationary water jetting, jet duration is a crucial parameter influencing the resulting cavity shape. Selected examples of test results are presented in Fig. 3 (temporal evolution of scour dimensions). Most soil excavation occurs during the initial phase of testing. Subsequently, smaller soil fragments are eroded, and the main geometric features of the scour hole exhibit only gradual growth. Consequently, jet efficiency

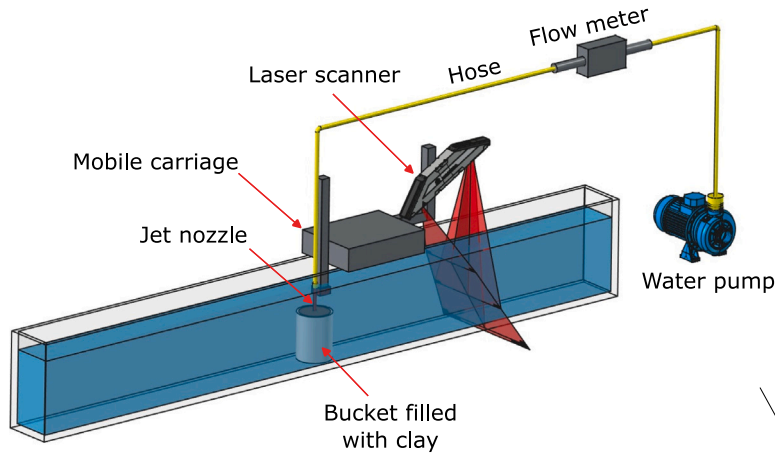


Fig. 1. Schematic representation of the experimental setup illustrating its components.

Table 1

A summary of the experiments conducted within this study.  $D$  is the nozzle diameter,  $SOD$  is the stand-off distance,  $s_u$  is the soil undrained shear strength,  $Q$  is the flow rate through the nozzle,  $u_0$  is the jet exit velocity,  $p_0$  is the jet pressure at the nozzle exit, and  $r$  denotes a repeat test.

| Test #         | $D$ (mm) | $SOD/D$ | $SOD$ (mm) | $s_u$ (kPa) | $Q$ (l/min) | $u_0$ (m/s) | $p_0/s_u$ |
|----------------|----------|---------|------------|-------------|-------------|-------------|-----------|
| 1              | 5        | 1.0     | 5          | 5.69        | 5.28        | 4.48        | 1.8       |
| 2              | 5        | 2.2     | 11         | 4.51        | 4.74        | 4.02        | 1.8       |
| 2r             | 5        | 2.2     | 11         | 4.57        | 4.74        | 4.02        | 1.8       |
| 3 <sup>a</sup> | 5        | 2.0     | 10         | 5.80        | 4.22        | 3.59        | 1.1       |
| 4              | 5        | 2.0     | 10         | 5.80        | 3.44        | 2.92        | 0.7       |
| 5              | 8        | 1.0     | 8          | 5.62        | 10.15       | 3.37        | 1.0       |
| 6              | 8        | 2.0     | 16         | 5.90        | 10.15       | 3.37        | 1.0       |
| 6r             | 8        | 2.0     | 16         | 5.61        | 10.15       | 3.37        | 1.0       |
| 7              | 10       | 1.0     | 10         | 5.52        | 15.55       | 3.30        | 1.0       |
| 8              | 10       | 2.0     | 20         | 5.54        | 15.55       | 3.30        | 1.0       |
| 9 <sup>a</sup> | 6.5      | 1.5     | 10         | 5.65        | 7.80        | 3.92        | 1.4       |

<sup>a</sup> These tests were conducted until reaching the equilibrium cavity depth.

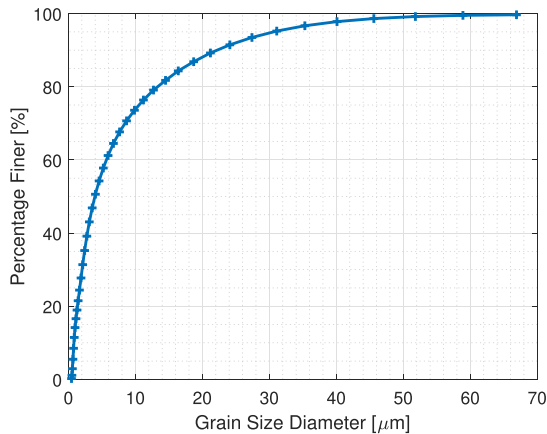


Fig. 2. Cumulative grain size distribution of the clay used in the experiments.

Table 2

Properties of the clay used in the experiments.

| $d_{10}$ [μm] | $d_{30}$ [μm] | $d_{50}$ [μm] | $d_{60}$ [μm] | $d_{90}$ [μm] | $\rho_s$ [kg/m <sup>3</sup> ] |
|---------------|---------------|---------------|---------------|---------------|-------------------------------|
| 0.8           | 2             | 4             | 5.6           | 22            | 2800                          |

decreases as the jet duration increases. It should be noted that water jetting was performed at the same location on the clay surface throughout each experiment, and the jet time is treated as cumulative operating time. We observed that the location of the maximum scour depth can

deviate from the jet centerline, which may be attributed to mass failure mechanisms, particularly during the early stages of erosion, resulting in asymmetrical scour hole geometries (Mazurek et al., 2001). Results of Test 6r and Test 9 show that the equilibrium scour width is reached much faster than the equilibrium scour depth. The latter was already reached within the duration of Test 9, whereas it was not reached in Test 6r.

The left panel of Fig. 4 shows an approximately logarithmic trend for the temporal evolution of scour depth. In all our tests, the scour volume increased monotonically with the scour depth. The right panel of Fig. 4 shows the scour volume plotted against the scour depth for Tests 1, 6r, and 9, where an almost linear correlation is observed.

### 3.2. Repeatability of experiments

There is a paucity of studies analyzing the repeatability of cavities formed by stationary circular jets in cohesive soils. To address this gap, two experiments – Test 2 and Test 6 – were each performed twice, with the repeated tests denoted as Test 2r and Test 6r, respectively. The same procedures for clay preparation and experimental operation were strictly followed to ensure accurate replication. In this section, we systematically assess variability of the scour outcomes when the same conditions are repeated using our measurements and data from two previous studies.

The normalized root mean square deviation (NRMSD) can be used to quantify the repeatability of the cavity measurements, which reads:

$$\text{NRMSD} (\%) = \frac{\sqrt{\frac{1}{N} \sum_{i=1}^N [X_1(t_i) - X_2(t_i)]^2}}{\frac{1}{2N} \sum_{i=1}^N [X_1(t_i) + X_2(t_i)]} \times 100 \quad (1)$$

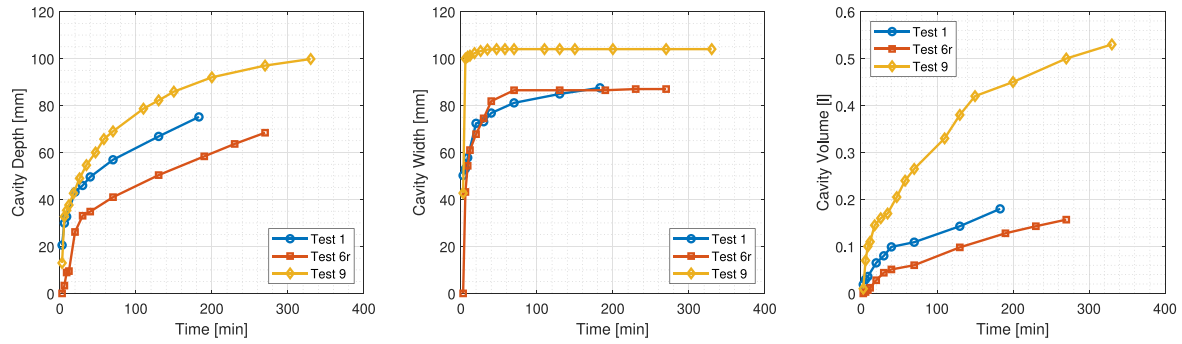


Fig. 3. Temporal cavity depth evolution (left), width evolution (middle) and volume evolution (right) for Tests 1, 6r, and 9.

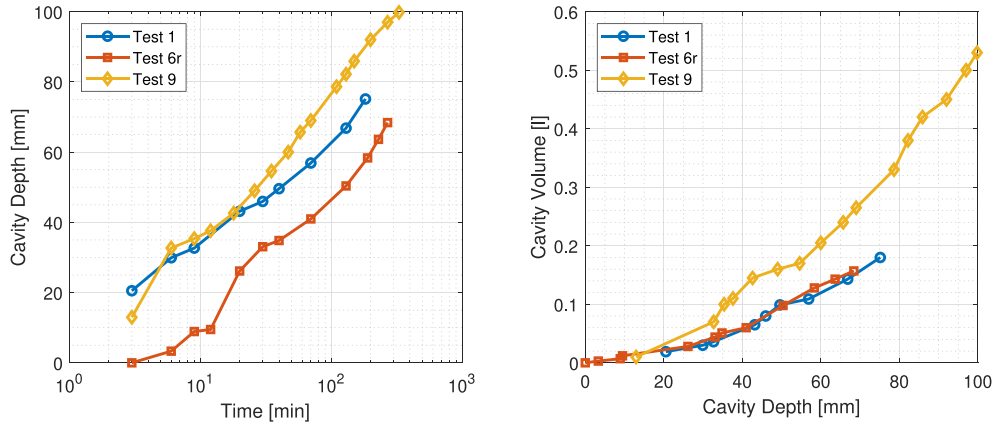


Fig. 4. Temporal cavity depth evolution in semi-logarithmic scale (left) and scour volume plotted against the cavity depth (right) for Tests 1, 6r, and 9.

where  $X_1$  and  $X_2$  represent the measured quantities obtained from the original and repeated tests, respectively,  $t_i$  denotes the common measurement times, and  $N$  is the total number of samples. The normalization by the mean value renders the NRMSD dimensionless, facilitating a quantitative assessment of experimental repeatability.

### 3.2.1. Test 2

Fig. 5 presents the temporal evolution of cavity volume and depth for Test 2 and Test 2r. The results exhibit the same trends over time, but deviations in the values are observed between the two tests. The temporal evolution of the erosion depths for Test 2 and Test 2r are not reported because they could not be retrieved; the laser elevation was insufficient to capture the temporal maximum cavity depth.

The repeatability of cavity volume and width for Test 2 was quantified using Eq. (1), yielding NRMSD values of 14% for volume and 6% for width. This indicates a good repeatability for width and a moderate level of variability between the repeated tests in terms of cavity volume. A deviation of 14% suggests that while the overall trend of volume evolution is reproducible, cumulative differences in erosion lead to divergence over time. This level of variability is reasonable for erosion experiments in cohesive soils, where small early-stage differences can amplify as the process evolves.

To gain further insight into the resulting cavities, top-view photographs from Test 2 and its repeat (Test 2r) at four time points (6, 20, 70, and 130 min) are provided in Fig. 6. Differences between the two cavity shapes are evident. By the end of the tests, the cavity in Test 2r evolved into a more circular shape, whereas the cavity in Test 2 developed an oval geometry.

### 3.2.2. Test 6

The temporal evolution of cavity depth, volume, and width for Test 6 and its repeat (Test 6r) is shown in Fig. 7. The results also

exhibit the same trends over time, but deviations in the values are observed among the two tests. Both tests reached an equilibrium width at approximately the same jet duration, but the equilibrium width values differ. The NRMSD values for cavity depth, volume, and width were computed using common measurement times and were found to be 25%, 50%, and 17%, respectively. The relatively large NRMSD for cavity volume highlights the strong sensitivity of integrated erosion metrics to small differences in the early stages of scour development. Given the cumulative nature of the erosion process, such deviations can amplify over time, leading to increased divergence in the later stages of cavity evolution.

For further insight, top-view photographs from both tests at four time points (6, 12, 130, and 190 min) are presented in Fig. 8. Differences in cavity shape are evident. By the end of the tests, the cavity in Test 6 evolved into a more circular form, whereas the cavity in Test 6r developed an oval shape.

### 3.2.3. Former studies

While there are almost no studies that explicitly examine the repeatability of cavity/scour formation under vertical stationary circular jets in cohesive soils, data of repeated tests is available in some studies (e.g., Janmaat, 2020 and Palermo et al., 2024). We computed the NRMSD values for cavity depth, volume, and width for a test by Palermo et al. (2024), obtaining values of 30%, 38%, and 29%, respectively. We also calculated the NRMSD values for the cavity depth for a test reported by Janmaat (2020) and was found to be 30%; repeated volume and width measurements are unavailable for this test. The variability observed among repeated tests in these studies is consistent with that found in the present work.

### 3.2.4. Conclusion on repeatability

Overall, the repeatability analysis indicates that while the general trends of cavity evolution are consistent across repeated tests,

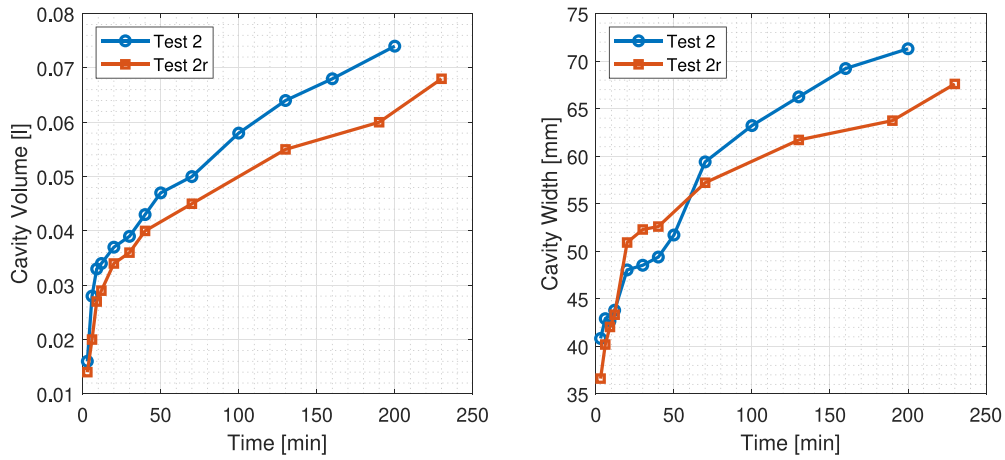


Fig. 5. Temporal evolution of cavity volume and width for Test 2 and its repeat (Test 2r).

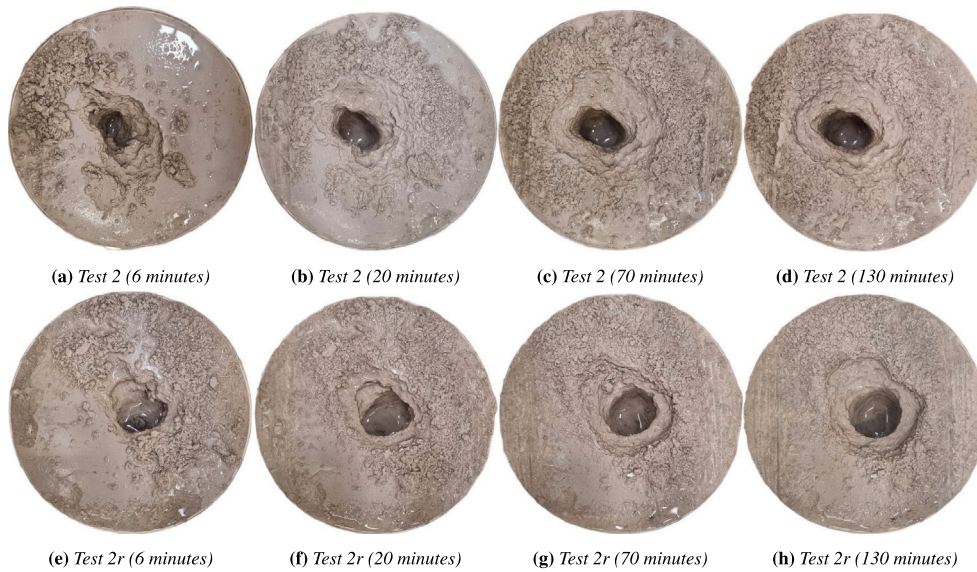


Fig. 6. Top-view images of the cavities formed in Test 2 and Test 2r at 6, 20, 70, and 130 min, showing deviations in cavity shape despite similar testing conditions.

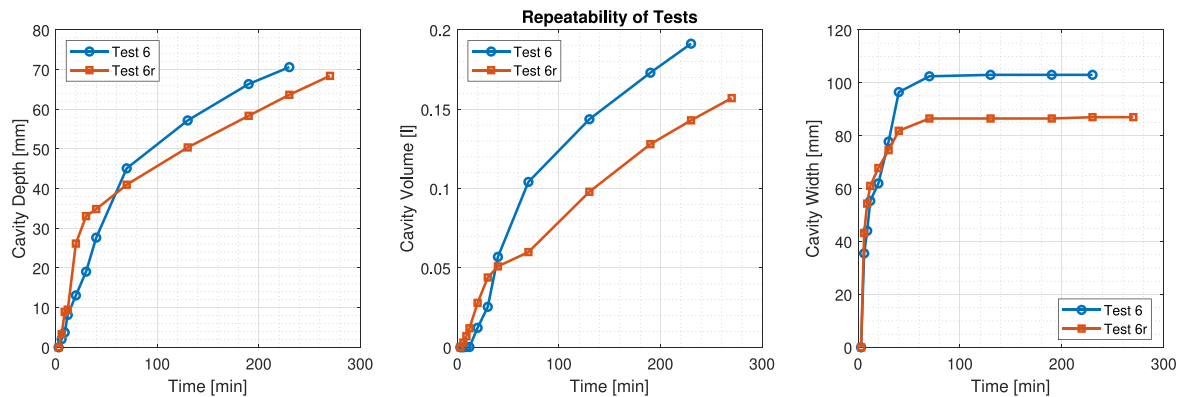
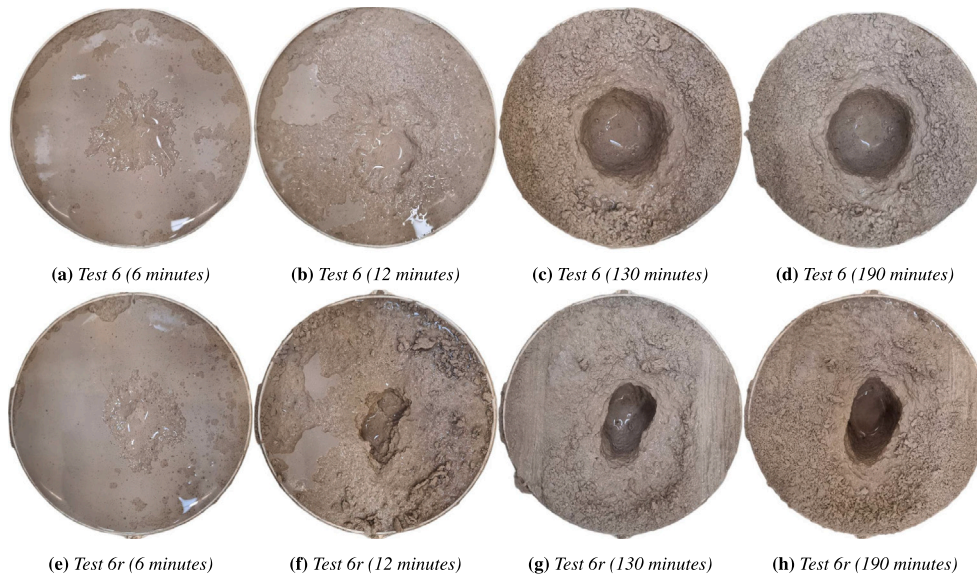


Fig. 7. Temporal evolution of cavity depth, volume and width for Test 6 and its repeat (Test 6r).



**Fig. 8.** Top-view images of the cavities formed in Test 6 and Test 6r at 6, 12, 130, and 190 min, showing deviations in cavity shape despite similar testing conditions.

quantitative differences are unavoidable. NRMSD values show that width is more reliably reproduced than volume and depth, and top-view observations reveal that subtle variations in early-stage erosion can lead to divergent cavity shapes over time. These results highlight the cumulative and sensitive nature of water-jet-induced soil erosion, emphasizing that even carefully controlled experiments can exhibit inherent variability in detailed cavity geometry.

### 3.3. Effect of nozzle diameter and stand-off distance

We first analyze the effect of nozzle diameter on the resulting cavity. Our results show that larger nozzle diameters produce larger cavities in all dimensions—depth, width, and volume (see Fig. 9). This is evident when comparing Test 5 ( $D = 8$  mm) with Test 7 ( $D = 10$  mm), as well as Test 6 ( $D = 8$  mm) with Test 8 ( $D = 10$  mm). This trend can be explained by the fact that increasing the nozzle diameter while maintaining the same exit velocity results in a higher flow rate. The corresponding increase in flow momentum leads to a greater impinging force on the soil, thereby generating a larger cavity (Alhaddad et al., 2024, 2025).

With regard to the stand-off distance, our results show that larger SOD values lead to smaller cavities. This is evident when comparing Test 5 ( $SOD/D = 1$ ) with Test 6 ( $SOD/D = 2$ ), as well as Test 7 ( $SOD/D = 1$ ) with Test 8 ( $SOD/D = 2$ ). This behavior arises because the mean jet velocity immediately above the clay surface is higher when the SOD is smaller, resulting in a more energetic and erosive jet (Alhaddad et al., 2025).

### 3.4. Dimensionless jet pressure lower than unity

The lowest jet pressure applied in our experiments was 4.3 kPa, used in Test 4, corresponding to a dimensionless jet pressure below unity ( $p_0/s_u = 0.74$ ). No distinct cavity was observed during the first 12 min (see Fig. 10); instead, erosion of the clay surface occurred due to wall jets flowing parallel to the clay surface after impingement. Test 4 was repeated for a shorter duration (60 min), and the same behavior was observed.

Fig. 11 compares the resulting cavities of Test 4 and Test 3. In the latter, the dimensionless jet pressure was slightly above unity ( $p_0/s_u = 1.11$ ). All other jetting conditions were identical in both tests. Test 3 produced significantly greater cavity depths than Test 4, with a distinct

cavity forming after only 3 min of jetting. This outcome is expected since the dimensionless jet pressure in Test 3 higher, resulting in a greater flow impingement force. In contrast, Test 4 resulted in a wider cavity, as reduced flow penetration into the clay left more energy available for the wall jets to promote lateral erosion.

## 4. Equilibrium scour depth

Several studies have proposed formulations for estimating the maximum scour depth,  $z_{c,max}$ , in cohesive soils (e.g., Stein et al., 1993; Mazurek et al., 2001; Jain et al., 2021). Such formulations typically include empirical coefficients calibrated using specific datasets to account for soil resistance to erosion. In contrast, and with the aim of developing a broadly applicable formulation that does not rely on soil-specific calibration parameters, we adopt a different approach in this study. A careful analysis of our experimental data, together with data from existing experimental studies, revealed that  $z_{c,max}$  is reached when the dynamic pressure in the center of the jet,  $p_d$ , equals  $0.185 \times s_u$ . To derive an expression for  $z_{c,max}$ , we first revisit the theory of jet flow development.

### 4.1. Flow development theory

Fig. 12 shows the velocity field of a free circular jet, where two regions can be distinguished: the flow development region (developing jet) and the developed flow region (developed jet). The transfer of mass and momentum accelerates the ambient water, whereas the jet velocities decrease with distance from the jet exit. The flow development region (also known as the potential core) is the region where the velocity at the centerline of the jet is equal to jet exit velocity. When the geometrical center of the jet is penetrated by the turbulence, the flow is fully developed.

In the fully developed region, the velocity field follows the Gaussian form:

$$u_j(s, r) = \sqrt{\frac{c_1}{2}} \frac{u_0 D}{s} \exp\left(-c_2 \frac{r^2}{s^2}\right) \quad (2)$$

where  $u_j(s, r)$  is the flow velocity at an axial distance  $s$  and a radial distance  $r$ ,  $u_0$  is the jet exit velocity,  $D$  is the nozzle diameter, and  $c_1$  and  $c_2$  are entrainment coefficients (Fischer, 1979).

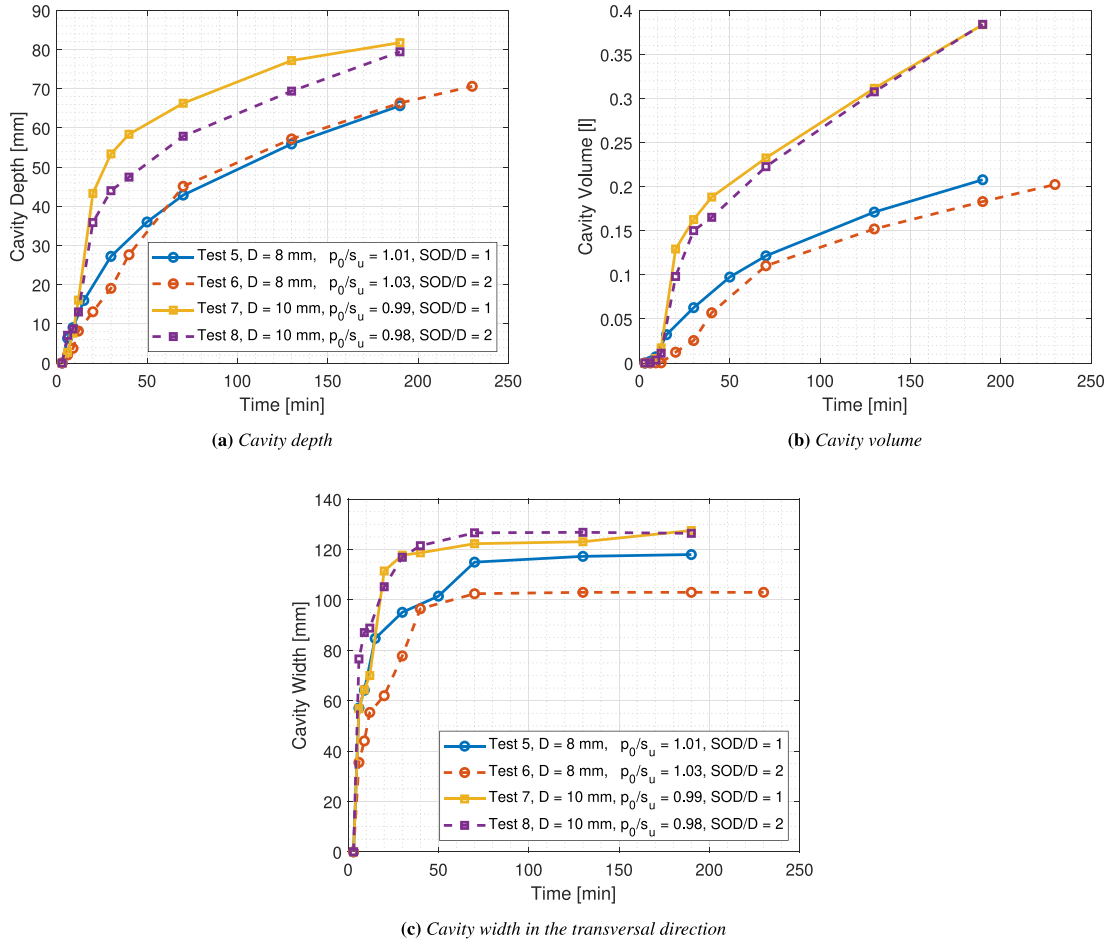


Fig. 9. Effect of nozzle diameter and stand-off distance on the resulting cavity.

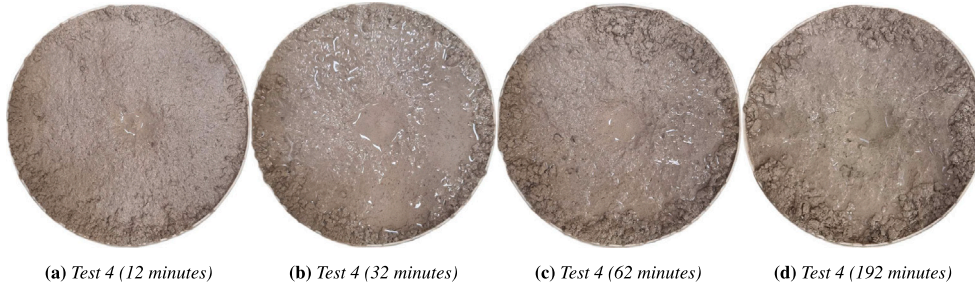


Fig. 10. Top-view images of the cavity formed in Test 4 at 12, 32, 62, and 192 min.

Neglecting the momentum loss and assuming, for analytical simplicity, that the momentum flux at the nozzle exit  $M_0$  is equal to the momentum flux  $M(s)$  renders (Rajaratnam, 1976):

$$M(s) = \rho_w 2\pi \int_0^\infty u_j(s, r)^2 r \cdot dr = M_0 \quad (3)$$

in which

$$M_0 = \rho_w Q_0 u_0 \quad (4)$$

where  $Q_0$  is the flow rate at the nozzle exit, which can be calculated as

$$Q_0 = c_d \frac{1}{4} \pi D^2 u_0 \quad (5)$$

in which  $c_d$  is the nozzle discharge coefficient. Assuming  $c_d = 1$  for simplicity, and substituting Eqs. (2), (4), and (5) into Eq. (3), the

coefficients  $c_1$  and  $c_2$  are found to be equal and can be estimated as 77 (Albertson et al., 1950).

For vertical jets, the point of stagnation pressure intersect with the geometrical center at the bed (Beltaos, 1976) (see Fig. 13). The dynamic pressure in the center of the jet  $p_d$  is a function of the axial jet velocity:

$$p_d = \frac{1}{2} \rho_w u_j(s, 0)^2. \quad (6)$$

When  $s$  is smaller than the potential core length  $s_{pc}$ , the velocity at the centerline of the jet is equal to jet exit velocity, meaning that  $p_d$  can be considered equal to the jet pressure at the nozzle exit  $p_0$ . Combining Eqs. (2) and (6) results in the following relationship for  $p_d$  when  $s \geq s_{pc}$ :

$$p_d = \frac{77}{4} \rho_w u_0^2 \frac{D^2}{s^2} \quad \text{for } s \geq s_{pc} \quad (7)$$

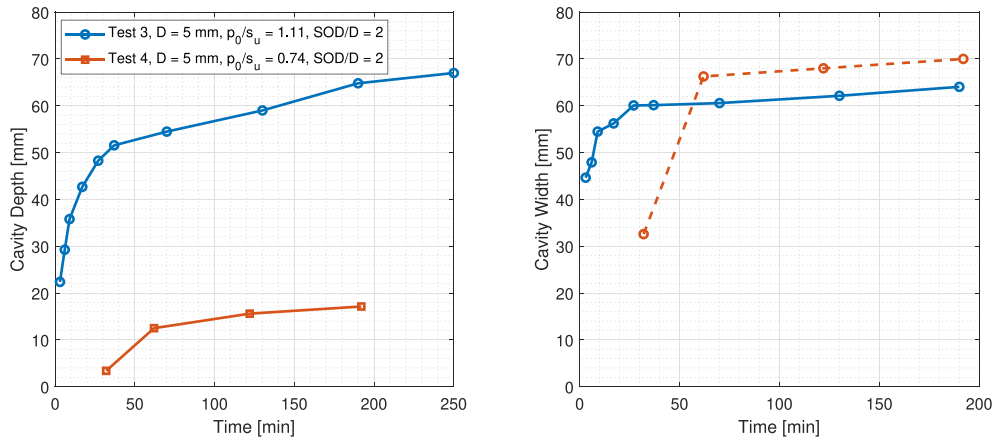


Fig. 11. Comparison between cavity dimensions of Test 3 ( $\rho_0/s_u = 1.11$ ) and Test 4 ( $\rho_0/s_u = 0.74$ ).

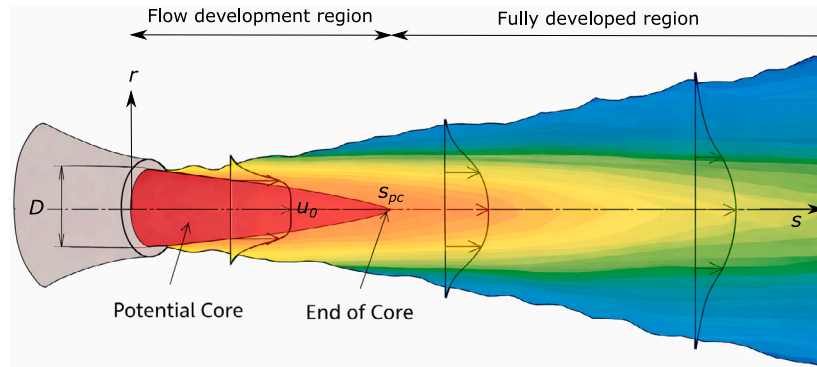


Fig. 12. Schematic diagram showing the velocity field of a free circular jet (modified from Castro and Demuren, 2017).  $D$  is the nozzle diameter,  $s$  is the axial distance and  $r$  is the radial distance.

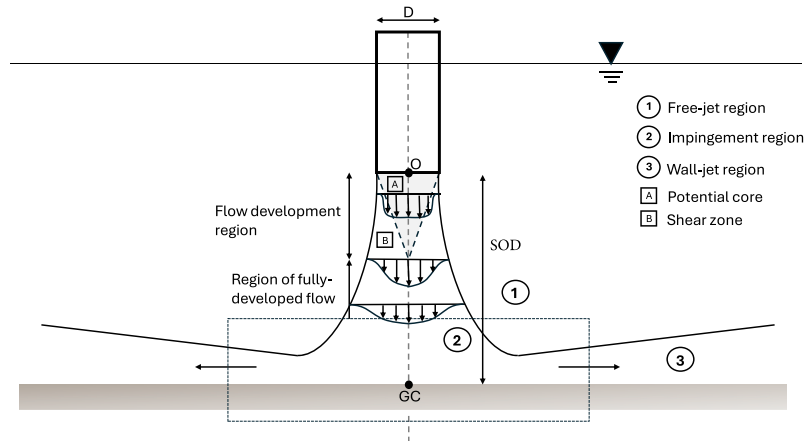


Fig. 13. Flow development of a vertical circular stationary submerged jet impinging on a flat bed (Alhaddad et al., 2025).  $O$  indicates the origin of the jet axis, whereas  $GC$  indicates the geometrical center of the jet (also the stagnation point).

It should be noted that the distance  $s$  increases gradually during the stationary excavation process.

#### 4.2. Equilibrium scour depth formula

The maximum erosion depth  $z_{c,max}$  is defined here as the largest vertical distance, measured from the original undisturbed soil surface down to the deepest point of the cavity once the erosion process has reached equilibrium. As noted earlier, analysis of existing experimental data showed that the maximum cavity depth is reached when  $\frac{p_d}{s_u} =$

0.185. The value of  $s$  at this ratio can be obtained using Eq. (7), after which subtracting SOD yields  $z_{c,max}$  as follows:

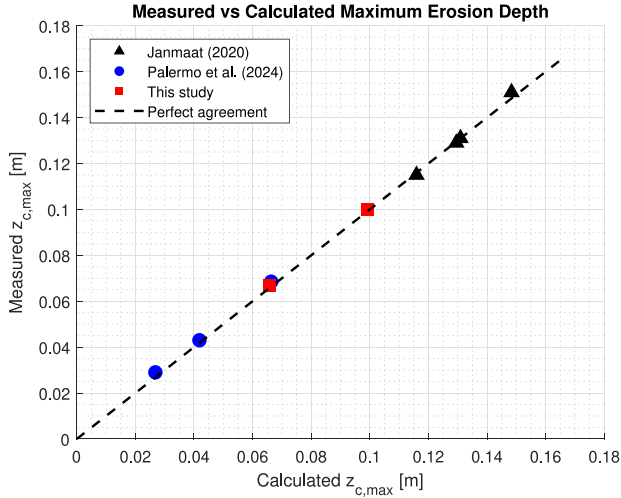
$$z_{c,max} = D u_0 \sqrt{\frac{77 \rho_w}{0.74 s_u}} - SOD \quad (8)$$

It does not escape our attention that using a single type of cohesive soil may limit the applicability of our proposed semi-theoretical formula. We address this point by incorporating experimental data from other studies involving different types of clays. Data on the maximum equilibrium scour depth are scarce in the existing literature due to the

**Table 3**

Jetting conditions for the experiments used to show the predictive capability of Eq. (8).

| Study                 | $P_0/s_u$ | $SOD/D$ |
|-----------------------|-----------|---------|
| Janmaat (2020)        | 0.84      | 7.5     |
|                       | 1.09      | 7.7     |
|                       | 0.93      | 7.4     |
|                       | 0.93      | 7.4     |
| Palermo et al. (2024) | 0.66      | 9.0     |
|                       | 0.84      | 9.0     |
|                       | 1.17      | 9.0     |
| Present study         | 1.11      | 2.0     |
|                       | 1.36      | 1.5     |



**Fig. 14.** Comparison between the measured equilibrium scour depths and the predicted ones using Eq. (8).

very long durations required to reach equilibrium. Consequently, most reported experiments do not attain equilibrium conditions. Nevertheless, we identified suitable datasets in two recent studies (Janmaat, 2020; Palermo et al., 2024) and used them to evaluate the predictive capability of Eq. (8) (see Fig. 14). The results demonstrate high predictive accuracy, with  $R^2 = 0.998$  and a low mean absolute percentage error of 2.1%, confirming close agreement between model predictions and experimental measurements. It is worth noting that the present experiments involve developing jets, whereas the datasets from the two aforementioned studies correspond to fully developed jets ( $SOD/D = 7.4$ – $9.0$ ) (see Table 3). This further demonstrates the robustness of the model across a broad range of test conditions.

## 5. Temporal evolution of scour depth

The prediction of the temporal variation of scour depth in cohesive sediments is challenging owing to their complex erosion characteristics (Pandey et al., 2022). Therefore, scientists and engineers rely on empirical equations to predict scour depths. A number of empirical equations have been proposed in the literature to describe the temporal evolution of scour depth  $z_c$  in cohesive soils (e.g., Ansari et al., 2003; Mazurek et al., 2006; Dong et al., 2020). Recently, Eq. (9) was proposed by Palermo et al. (2024) for the temporal evolution of  $z_c$  based on the maximum achievable scour depth  $z_{c,max}$ :

$$z_c = \left( 1 - \exp \left( A \left( \frac{t \cdot u_0}{d_{50}} \right)^B \right) \right) \cdot z_{c,max} \quad (9)$$

where  $A = -1.968 \times 10^{-5}$ ,  $B = 0.44$ ,  $t$  is time [s] and  $d_{50}$  is the median particle size.

To assess whether Eq. (9) can predict the measured erosion depths in this study, the experimental results were plotted against the corresponding calculated values in the left panel of Fig. 15. Eq. (8) was used to compute  $z_{c,max}$ . Eq. (9) was chosen for this assessment because it has been validated for developing jets, which corresponds to the conditions of our experimental data. Overall, the comparison indicates that Eq. (9) underestimates the erosion depths observed in the present experiments. The best agreement with the experimental data was obtained using  $A = -6.11 \times 10^{-7}$  and  $B = 0.63$  (see the right panel of Fig. 15). The discrepancy between the values of  $A$  and  $B$  reported by Palermo et al. (2024) and those obtained in this study suggests that additional parameters influencing the erosion process should be accounted for in Eq. (9). Scour by circular jets in cohesive soils is mainly governed by an interplay of hydraulic loading and soil mechanical properties. While the undrained shear strength and median particle size were used in the calculations, they may not suffice to characterize the cohesive soil behavior in question.

Given that physical models represent real prototypes at reduced scale, they may be affected by scaling. Reynolds number, which expresses the ratio of inertial to viscous forces, is an important parameter in this context. Mazurek et al. (2001) found that scour formulas developed for cohesive soils are applicable only to jets with Reynolds numbers greater than approximately 10,000. In the present study, Reynolds numbers ranged from 14,617 to 33,002. Accordingly, Reynolds number is unlikely to have affected the reported results, since all tests were performed at  $Re > 10,000$ . Nonetheless, further analysis of this issue remains warranted.

## 6. Conclusion

In this study, we investigated the scour process caused by vertical, stationary, circular, developing, low-pressure water jets impinging on cohesive soils. We carried out small-scale laboratory experiments using jet pressures ranging from 4.3 to 10 kPa and soil undrained shear strengths between 4.5 and 5.9 kPa, corresponding to dimensionless jet pressures of 0.7–1.8. Two tests were extended until equilibrium scour depths were reached. To ensure that the stand-off distance remained within the potential core of the jet, the ratio between stand-off distance and nozzle diameter was maintained between 1 and 2.2. Temporal scour evolution was assessed by halting the jet at selected intervals and measuring the resulting scour hole geometry (depth, width, and volume).

The repeatability of scour cavity formation in cohesive soils was also examined, addressing a notable gap in the literature. While general trends in cavity evolution were consistent across repeated tests, quantitative differences were observed. Statistical analysis indicated that cavity width is more reliably reproduced than depth and volume, and top-view observations revealed that subtle variations during early-stage erosion can lead to divergent cavity shapes over time. The influence of nozzle diameter and stand-off distance on soil erosion was also assessed. Larger nozzle diameters consistently produced larger cavities in all dimensions, while increasing stand-off distance resulted in smaller cavities.

Based on the underlying physics of vertical jet development and experimental data, a semi-theoretical formulation was developed to predict equilibrium scour depth. Unlike existing predictive models, the proposed formulation does not require soil-specific calibration parameters. Validation using both the present experimental data and independent datasets demonstrated the robustness of the model across a range of test conditions, providing a reliable tool for predicting jet-induced erosion in cohesive soils. Regarding the temporal evolution of erosion depth, existing knowledge remains insufficient to develop a predictive formulation applicable across different types of cohesive soils.

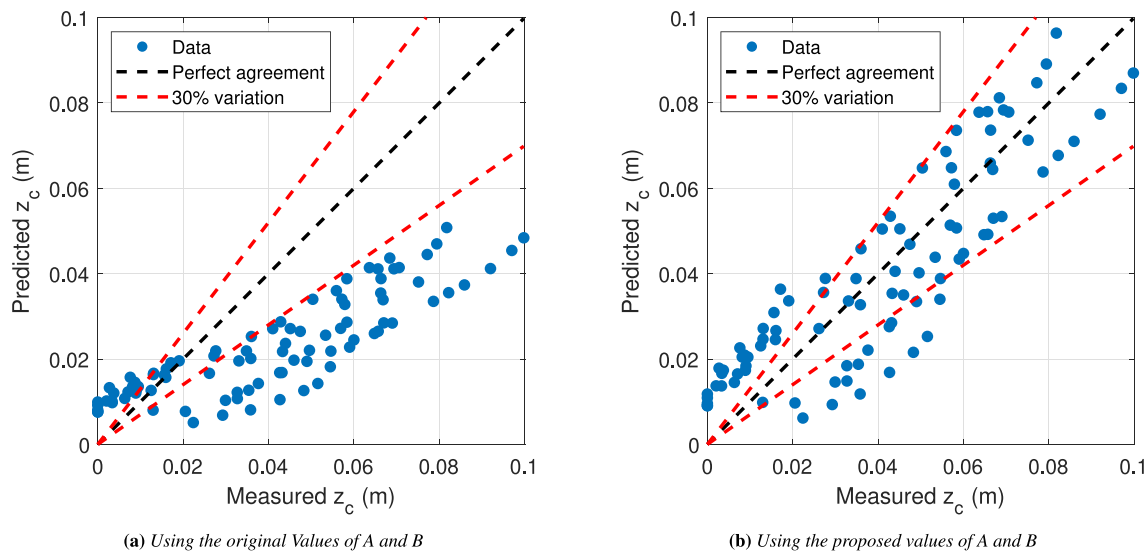


Fig. 15. Measured against calculated (with Eq. (9)) scour depths.

### CRediT authorship contribution statement

**Said Alhaddad:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Julian Manrho:** Visualization, Methodology, Data curation. **Mosaab Mahgoub:** Visualization, Methodology.

### 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.

### References

- Albertson, M., Dai, Y., Jensen, R.A., Rouse, H., 1950. Diffusion of submerged jets. *Trans. Am. Soc. Civ. Eng.* 115 (1), 639–664.
- Alhaddad, S., 2026. Breaching of sidewalls in submarine cable trenches: The role of ambient sediment concentration. *Ocean Eng.* 363, 126504.
- Alhaddad, S., Snyder, A., Bult, S.V., Keetels, G., 2025. Experimental investigation of cohesive soil erosion caused by translating submerged inclined water jets. *Appl. Ocean Res.* 157, 104486.
- Alhaddad, S., Suleman, M., Kirichek, A., Chassagne, C., 2024. Experimental investigation of cohesive soil erosion and suspension caused by a coandă-effect-based polymetallic-nodule collector. *Results Eng.* 22, 102231.
- Ansari, S.A., Kothiyari, U.C., Raju, K.G.R., 2003. Influence of cohesion on scour under submerged circular vertical jets. *J. Hydraul. Eng.* 129 (12), 1014–1019.
- Beltaos, S., 1976. Oblique impingement of circular turbulent jets. *J. Hydraul. Res.* 14, 17–36.
- Castro, N.D., Demuren, A.O., 2017. Large eddy simulation of turbulent axially rotating pipe and swirling jet flows. *Proc. Inst. Mech. Eng. Part C: J. Mech. Eng. Sci.* 231 (9), 1749–1761.
- Dong, C., Yu, G., Zhang, H., Zhang, M., 2020. Scouring by submerged steady water jet vertically impinging on a cohesive bed. *Ocean Eng.* 196, 106781.
- Fischer, H.B., 1979. *Mixing in Inland and Coastal Waters*. Academic Press.
- Fuller, W.P., Wagner, R.J., Lewis, R.E., 2024. US hydrodynamic dredging challenges and opportunities. *Transp. Res. Rec.* 2678 (7), 487–500.
- Hashiehbaf, A., Baramade, A., Agrawal, A., Romano, G.P., 2015. Experimental investigation on an axisymmetric turbulent jet impinging on a concave surface. *Int. J. Heat Fluid Flow* 53, 167–182.
- Jain, R., Lodhi, A.S., Oliveto, G., Pandey, M., 2021. Influence of cohesion on scour at piers founded in clay–sand–gravel mixtures. *J. Irrig. Drain. Eng.* 147 (10), 04021046.
- Janmaat, R., 2020. *Cohesive Soil Erosion by a Low Pressure Vertically Impinging Jet* (Master's thesis). Delft University of Technology.
- Lee, J.H.-w., Chu, V., 2012. *Turbulent Jets and Plumes: A Lagrangian Approach*. Springer Science & Business Media.
- Liu, X., Chen, X., Wei, J., Jin, S., Gao, X., Sun, G., Yan, J., Lu, Q., 2023. Study on sediment erosion generated by a deep-sea polymetallic-nodule collector based on double-row jet. *Ocean Eng.* 285, 115220.
- Mazurek, K., Rajaratnam, N., Sego, D., 2001. Scour of cohesive soil by submerged circular turbulent impinging jets. *J. Hydraul. Eng.* 127 (7), 598–606.
- Mazurek, K., Rajaratnam, N., Sego, D., Verheij, H., Hoffmans, G., 2006. Time development of scour in a cohesive material due to a submerged circular turbulent impinging jet. In: *ICSE-3, 3rd International Conference on Scour and Erosion*. Amsterdam, the Netherlands.
- Palermo, M., Di Nardi, J., Bombardelli, F.A., Pagliara, S., 2024. Scour due to circular jets in cohesive soils: Physical evidence from three-dimensional laboratory tests. *Phys. Fluids* 36 (9).
- Pandey, M., Jamei, M., Ahmadianfar, I., Karbasi, M., Lodhi, A., Chu, X., 2022. Assessment of scouring around spur dike in cohesive sediment mixtures: A comparative study on three rigorous machine learning models. *J. Hydrol.* 606, 127330.
- Qiu, Y., Lan, X., Yang, Z., Wang, G., Liu, J., 2024. Study on the mechanism of soil erosion by submerged water jet vertical scouring in cohesive soils. *Ocean Eng.* 311, 118919.
- Rajaratnam, N., 1976. *Turbulent Jets*, vol. 5, Elsevier.
- Sharp, J., Joseph, L., 2009. Hydraulic and sustainable waste water disposal in rural coastal communities. In: *Hydraulic Structures, Equipment and Water Data Acquisition Systems*. In: *Encyclopedia of Life Supporting Systems*, vol. 3, pp. 127–138.
- Sigwald, R., Ledoux, S., Spencer, K., 2015. *Water Injection Dredging Guidance Document*. Technical report, GEODE group: Groupe D'Etudes et D'Observation sur les Dragages et L'Environnement.
- Stein, O., Julien, P., Alonso, C., 1993. Mechanics of jet scour downstream of a headcut. *J. Hydraul. Res.* 31 (6), 723–738.
- Warringa, S., Rhee, V., Miedema, S., Lupea, C., Visser, C., 2019. Modelling the waterjet cable trenching process on sand dunes. In: *Proceedings of the 22nd World Dredging Conference*, Shanghai, China. pp. 22–26.
- Winterwerp, J.C., Van Kesteren, W.G., 2004. *Introduction to the Physics of Cohesive Sediment Dynamics in the Marine Environment*, vol. 56, Elsevier.