Soluble Filament 3D Printing: A Game-Changer for Experimental Studies on Piping Stability

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Abstract

Internal erosion is a common incident associated with nearly half of all dam dysfunctions and failures. This phenomenon occurs when soil particles are washed out of the soil mass by seepage via a preferential pathway. When the seepage is strong enough, the flow can wash out coarse particles and form an elongated void referred to as a “pipe”. Although many analytical assessment methods have been proposed, laboratory testing using representative soil samples remains the most reliable approach. Experimental studies on the stability of piping and erosion rate commonly use preformed or pre-drilled straight holes, which do not adequately represent realistic piping scenarios. This paper presents a worth-spreading validated approach using 3D printing soluble filament to form pipes within reconstituted soil specimens. 3D printing technology helps to form the pipe at any size and shape, while the soluble filament dissolves in water without inducing significant mechanical disturbance to the surrounding soil. Transparent hydrogels were used to observe the dissolution process of 3D-printed pipe walls, and the approach was further verified using cohesive soils. Test results confirmed that the formation of pipes using 3D soluble filament has negligible impacts on soil pipe stability.

Keywords chosen from ICE Publishing list

Internal erosion; experiment; 3D printing; additive manufacture; soluble; PVA; BOVH; clayey.

List of notations (examples below)

ABS is Acrylonitrile Butadiene Styrene
BVOH is Butenediol Vinyl Alcohol
PLA is PolyLactic Acid
PVA is PolyVinyl Alcohol
USCS is Unified Soil Classification System
d_{50} is the mean particle size

Introduction

Internal erosion is an insidious hazard, which often develops through three main underground stages: initial mobilisation, fine transportation, and piping. Analytical assessments often focus on the onset condition of erosion to assess whether fine particles could be washed out of the soil skeleton (To and Scheuermann, 2021, To et al., Submitted 2014). However, if only fine and loose particles are washed out, the soil might still be stable in its primary fabric structure (Goldin et al., 1992, Fannin and Slangen, 2014, To et al., 2015). Internal erosion becomes critical when seepage removes coarse particles and forms a pipe (Bridle, 2016). If the pipe is unstable and collapses, the resulting volume change may lead to ground subsidence or sinkholes. It was evidenced that piping could affect large areas of more than 10 km^2 (Bernatek-Jakiel and Poesen, 2018, Baxter, 2007). If the pipe remains stable, it can propagate upstream and trigger other serious failures such as slope sliding. A statistics pointed out that internal erosion was associated with nearly half of all dam failures and dysfunctions in the last century (Foster et al., 2000).

Numerical simulation of piping often use multi-phase mesh-free models (Ma et al., 2024) or mesh refinement techniques (Robbins and Griffiths, 2021). These approaches rely heavily on constitutive models and experimental data. Field tests on internal erosion that use vertical straight boreholes could be unstable, as the borehole and collapse during the test (Shidlovskaya et al., 2023). At the laboratory scale, most experimental studies focus on either erosion rate (Pallanza et al., 2023, Briaud et al., 2001, Regazzoni and Marot, 2011) or deformation of a straight hole in soil samples (Wan and Fell, 2004, Cai et al., 2023). One study proposed using 3D-printing filament as substitutes for soil (Yoneda, 2019). However, acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) are not erodible under typical hydraulic gradients, and resin exhibits fundamentally different hydro-mechanical behaviours compared with soils.

Conventional laboratory methods usually drill or punch through thin soil samples to form a straight hole (Haghighi et al., 2013). When small pipe diameters are required, thin and smooth steel wires could be pushed and pulled through the soil. These techniques could disrupt the pipe surface, as the additional shear may mechanically damage or smear the thin soil layer surrounding the pipe. Pipes formed in soils with little or no cohesion are particularly prone to collapse. In short, the study on pipes of complicated shapes in soil has been impractical before this study.

This paper presents a new preparation method that allows pipes to be pre-formed in reconstituted soil samples. A thin pipe wall is 3D printed with soluble materials and embedded in the soil. Then, the pipe wall is dissolved under a low hydraulic gradient. After the dissolution, only a hollow soil pipe remained. This slow and gentle process causes minimum disturbance to the pipe stability, and therefore, it will not influence the results of erosion tests. The dissolution of pipe walls was observed using a clear acrylic box and transparent hydrogel beads. Later, the new approach was validated with a laboratory soil.

Material selection

The initial authorial idea was to use some fast-dissolving materials like pulverised salt (NaCl) or sugar ($C_6H_{12}O_6$) because they can dissolve within minutes in a gentle flow of water. However, forming a small cylindrical pipe from powdered materials within soil requires a layer-by-layer construction procedure. This procedure is challenging, time-consuming, and inaccurate. If the hollow soil pipe does not have a circular cross-section, it cannot form an arch and collapse quickly after dissolution. Therefore, additive manufacturing, known as 3D printing, was employed to improve efficiency and geometric accuracy.

Two commonly used soluble filaments PVA - polyvinyl alcohol $(C_2H_4O)_n$ - and BVOH - butenediol vinyl alcohol $(-C_2H_4O-)_m(-C_3H_7O_2-)_n$ - were considered (Table 1). As these two filaments are often used as water-soluble support materials, they were used to print the hollow models with no support in this study.

Table 1. PVA and BVOH properties

Property	PVA	BVOH
Density	1.0 ±0.02 kg/l	1.14±0.02 kg/l
Young modulus	3500 MPa	2200 MPa
Tensile breaking stress	78 MPa	45 MPa
Melting temperature	163ºC	175ºC
Vicat softening temperature	60.2ºC	92ºC
Price	40 AUD/1kg roll	70 AUD/350g roll

Long circular pipe walls could be printed by sections and stuck together using water and a light hand pressure within a few seconds. In fact, both PVA and BVOH are commonly used as interfacial adhesives as they become highly sticky when moistened. Even when the attached pipe walls were released from 1 m above ground level, the sections neither broke nor detached. Because no printing support was used, pipe walls with complex cross-section should be printed in vertical direction and in sections. However, this study printed only hollow circular pipe walls. More information about printing setup in this study is provided in Table 2.

Table 2. Printing setup

Parameter	**Value**	**Justification / comments**
Printer model	UltiMaker S5	Common in creative laboratories
Nozzle diameter	0.25 mm	The available nozzle diameters are 0.2, 0.25, 0.4, 0.6, and 0.8mm.
Layer resolution	60 microns	Standard of the printer
Printing temperature	190^{o}C	The temperature can vary slightly during the printing process. Hence, it should be set significantly higher than the melting temperature
Printing speed	30 mm/s	Typical speed for PVA and BVOH
Infill rate	100%	The thin pipe wall does not allow a smaller infill
Printing type	Single layer	Default
Build plate	Glass	Minimise impact of detachment with cooler
Ambient temperature	22^{o}C	Laboratory temperature
Raft and support	No	PVA and BVOH are support materials.

All tests used the same mild hydraulic gradient of 0.1 and were repeated several times (Table 3). The pipes tested below were 200 mm long. The flow varies overtime and too small to be monitored automatically with electromagnetic flowmeter. Manual estimation with beaker showed that the flow velocities of water in powder and hollow pipes were about 0.9 and 25 litre per hour, respectively.

Table 3. Dissolving time of various materials

Materials	Pipe	Dissolving time
Sugar powder (<50µm)	In 10mm inner diameter plastic tube	< 10 minutes
Salt powder (<50µm)	In 10mm inner diameter plastic tube	< 7 minutes
PVA	10mm inner diameter. 1mm thickness	~ 82-95 minutes

BVOH	10mm inner diameter. 1mm thickness	~ 34-57 minutes

The dissolution of sugar and salt powders was significantly faster than the 3D-printing filaments (Table 3). Despite the low seepage velocity, a significant proportion of sugar and salt was washed out before fully dissolving. However, as discussed earlier, forming unsupported pipes from powder materials is challenging. In contrast, pipe walls made of PVA or BVOH required much longer dissolution times, but 3D-printed technique allowed pipes to be fabricated in almost any shape at a typical resolution of 0.25 mm. Considering cost and availability in standard 3D-printing laboratories, PVA was selected for further test presented in the following sections.

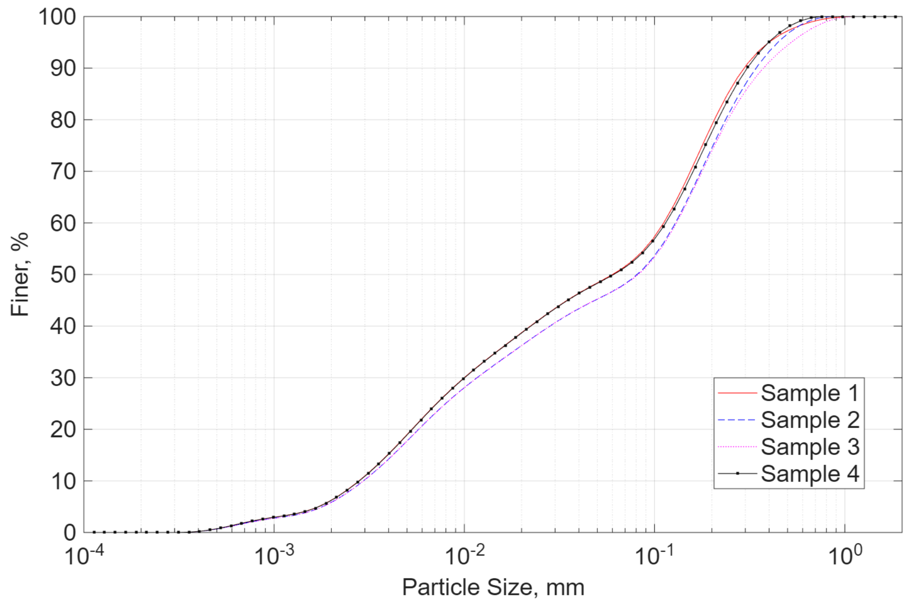

Figure 1. Soil Particle Size Distribution.

Although vertical pipes can be formed in granular soils (To and Price, 2021), horizontal pipes in non-cohesive soils often collapse due to the lack of cohesion, supports, and stress balance. This study employed an available soil that lies at the boundary between fine- and coarse-grained soils according to the Unified Soil Classification System (USCS). As the soil was disturbed and reconstituted, a few soil samples were analysed with a laser diffraction particle size analyser Mastersizer 3000 to ensure the uniformity of the soil. The results showed consistent soil particle size distributions (Figure 1). However, because the d_{50} value was close to the No.200 sieve size, the soil could be classified as either SM (silty sand) or ML (silt with low plasticity) in the USCS. Although the PVA pipe walls were highly durable, they still bent under high force impact. This deformation raised concerns about the maximum compaction achievable in the reconstituted soil. Inadequate compaction may make the soil more susceptible to erosion due to its low shear resistance. To evaluate the quality of the reconstitution, standard direct shear tests (Standards Australia, 2020) were undertaken. The results demonstrated a good agreement of two samples with the same porosity of 0.33 (Figure 2).

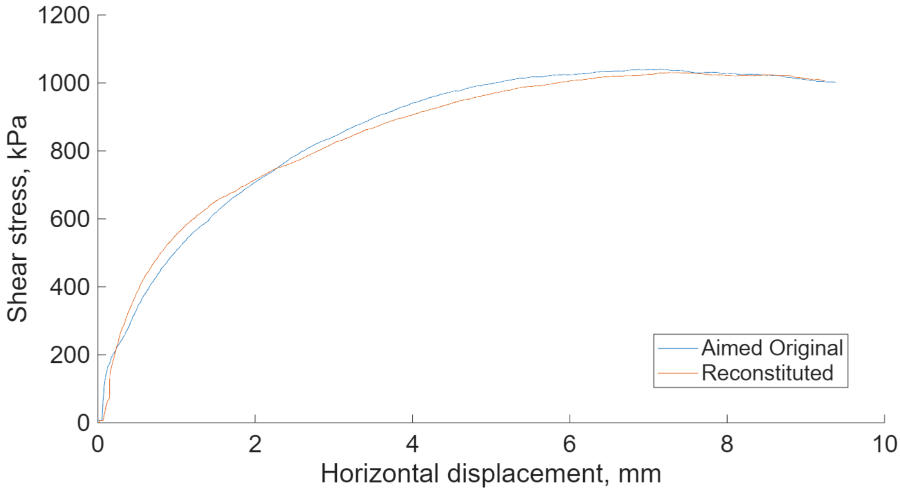

Figure 2. Direct shear test results.

Testing setup

To monitor the dissolving process of the 3D-printed pipe walls, the testing setup employed a transparent acrylic box (Figure 3) and hydrogel beads with diameters of 9-11 mm. As hydrogel has a much higher hydraulic conductivity than soils, an overflow outlet may be added at the back of the acrylic box if required (Figure 4). A rigid lid was created to apply a light load from the top. If a high surcharge stress is required, a smaller metal box should be used. Water was recycled from the water supply pool at the downstream to the top header tank with a submersible pump. The flow was controlled by a 13 mm inlet vale and monitored with a 20-mA flowmeter. Data was recorded every 0.2 seconds by a CR1000X datalogger.

Figure 3. Acrylic box with hydrogels up to the inlet level (left) and dissolving PVA (right).

Firstly, hydrogel beads were filled up to the inlet level. Then, the 3D-printed pipe was inserted to form a closed connection between the inlet and outlet. Subsequently, a 5 cm layer of hydrogel beads was added to ensure that the pressure from the top lid would not damage the pipe. The total filling process required approximately 340 g of hydrogel beads. When the work of PVA pipes was confirmed, a soil was reconstituted and placed carefully in the box instead of hydrogels for the actual test (Figure 5).

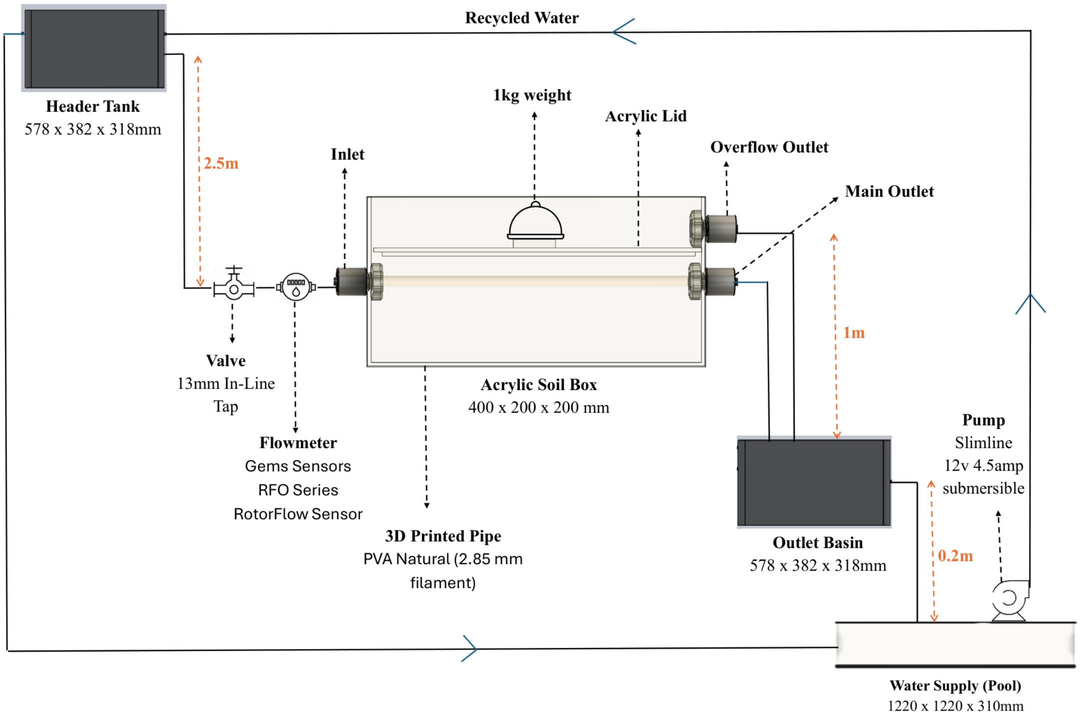

Figure 4. Testing setup.

Figure 5. Bent 3D-printed pipe: after placement (left), before testing (top right) and after erosion (bottom right).

To measure changes in erosion rate over time, eroded fines were collected from the outlet basin (Figure 4 and Figure 6), which also served as the monitoring point for bubbles. When no further bubbles were observed, the pipe wall was considered to be fully dissolved. To confirm this, the test continued for an additional 20 minutes after the bubbles ceased.

Figure 6. Outlet basin with observed bubbles.

Results and discussion

Pipe dissolution

To observe the dissolution time, three different types of pipes (Figure 7) with different parameters (Table 4) were tested in the acrylic box with hydrogel beads. The dissolving process was relatively uniform. In all undertaken tests, pipe dissolution took a long time to reach the outer surface. Then, the full dissolution started at the inlet and progressed slowly towards the outlet. The time from when the dissolution reaches the outer surface at the outlet to the full dissolution of the pipe wall was defined as "shell dissolution" time.

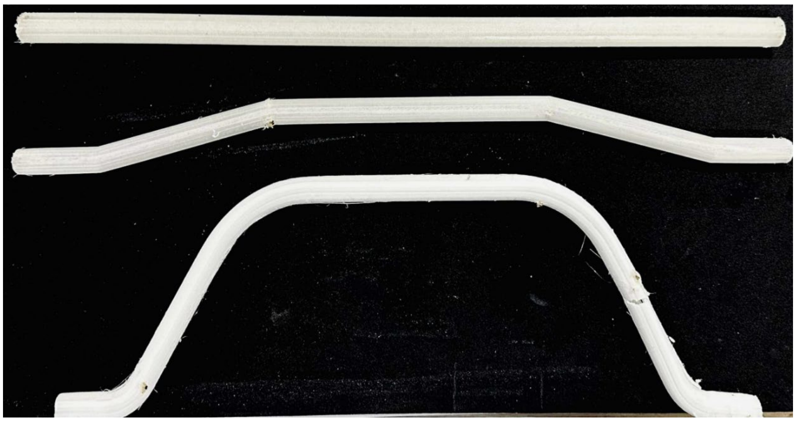

Figure 7. Straight (top), bent (middle), and curved (bottom) pipes.

Table 4. Dissolving time of pipes.

Pipe	Inner diameter (mm)	Wall thickness (mm)	Angle (°)	Curvature (mm)	Total dissolution (min)	Shell dissolution (min)	Mean flowrate (L/min)
Straight	5	1.0			103.07	8.2	4.28
	5	1.5			140.30	8.7	4.65
	5	2.0			180.82	9.7	4.75
	10	1.0			91.82	8.2	4.35
	10	1.5			140.27	9.1	4.72
	10	2.0			183.73	10.3	4.78
Bent	10	1.0	30		91.88	8.2	4.82
	10	1.0	45		117.75	8.4	4.62
	10	1.0	60		140.62	9.1	4.80
	10	1.0	75		166.35	11.6	4.68
Curved	10	1.0		50	140.48	9.5	4.71
	10	1.0		100	125.15	9.2	4.70
	10	1.0		200	99.08	8.9	4.74

The observed data show that the mean flowrates were in a close range for all tested soils. However, the total dissolving times were significantly different. Straight pipes of 2.0 mm wall took approximately double time as the straight pipes of 1.0 mm wall. The pipe bent at 75° took 81% longer than the pipe bent at 30°. Meanwhile, the pipe with 200 mm curvature dissolved 30% faster than the pipe with 50 mm curvature.

Although the shell dissolution time could be considered proportional to the total dissolution time at some level, it did not fluctuate widely as the total dissolution time and remained less than 10 minutes in most of the tests. The thick pipe wall of 2 mm had 25% longer shell dissolution time than the 1mm thin pipe wall. This is interesting because if the pipe walls dissolved uniformly, the dissolution time should be similar.

There were two important notes about dissolution. First, as the hydrogels had high hydraulic conductivities and no cohesion, there was no closed connection between the inlet and main outlet when the pipe wall started disappearing. Therefore, overflow outlet could reduce the mainstream and its shear force. Consequently, the pipe wall dissolution in a hydrogel box might be longer than that observed in soil. Second, a lot of bubbles were generated while PVA was dissolving (Figure 3) because PVA acts like a surfactant. Therefore, the shell dissolution time was estimated approximately. This also raised concerns about the impact of the dissolving process on the stability of pipe.

Pipe stability

Based on insights gained from the hydrogel trial, the study then proceeded to the dissolution in soil. As soil is opaque, pipe stability was assessed indirectly using flow rate. There are two common scenarios can lead to changes in flow rate. First, if the pipe collapses partially or completely, the flow will be temporarily obstructed. Hence, the reading of flow rate will plunge for a moment until the collapsed soil is washed out. Second, if the pipe is enlarged significantly during the long dissolving process, the flow rate will increase gradually. Therefore, the method can be reliable only if the flow is stable. Note that, the shell dissolution time is critical for the preparation, especially coarse granular soils. The PVA support gradually diminishes during this time, and the unbalanced stress could lead to a collapse. If the soil pipe collapses within this time, the preparation is considered unsuccessful. The new approach can be applied to finer soils with higher cohesion. However, the application to poorly graded coarse soil, like coarse sand, may have difficulties due to this collapse. Well graded gravels can interlock to form an arch to keep the pipe stable, but they will need a bigger testing up. In general, coarse soils requires higher seepage force to wash out particles.

The flowmeter data showed that the soil pipes were stable in most tests, except a collapse observed in the test with pipe bent at 75° (Figure 8). In that test, once the 3D printed wall dissolved, the flow exerted a direct thrust at the turning point, causing the soil pipe to collapse. However, such a sharp 75° bend is unlikely in realistic piping development. In all other cases, the flowrate measurement indicated that the use of 3D printed pipe did not adversely affect pipe stability. Minor fluctuations of the results were attributed to measurement resolution rather than pipe deformation.

After the preparation, the hydraulic gradient could be increased to simulate the actual conditions of piping such as in concentrated leak or backward erosion.

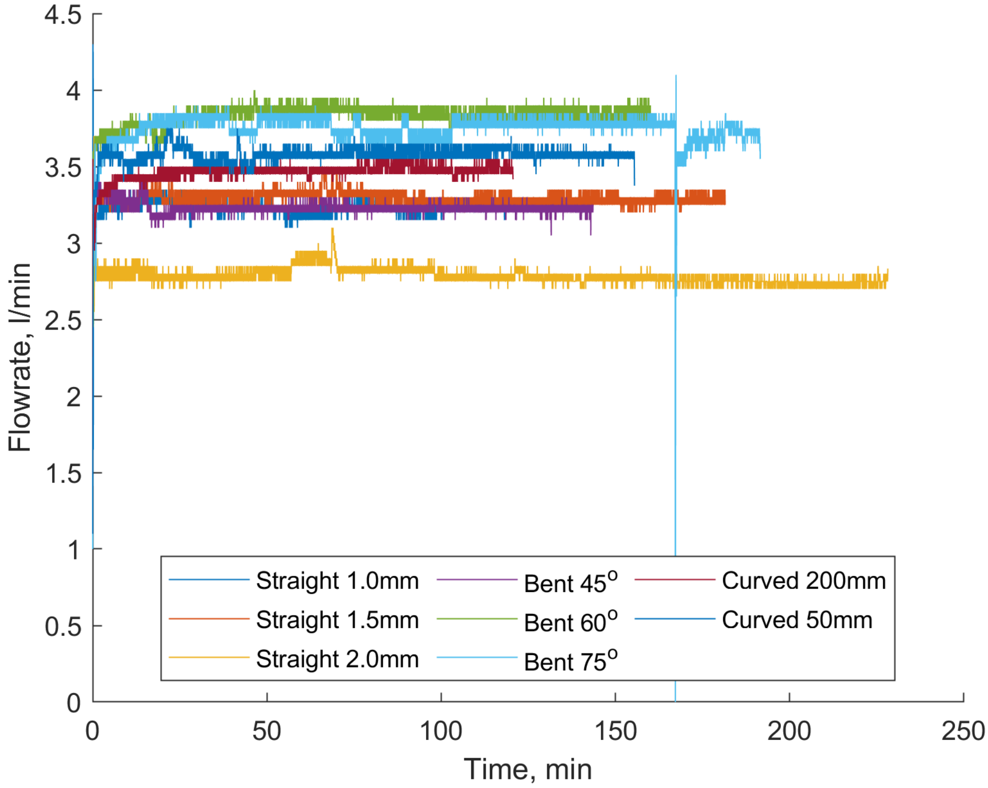

Figure 8. Flowrate of piping in soil.

Conclusions

The paper has presented a worth-spreading approach to pre-form complex soil pipes for erosion tests. The new preparation technique opens the possibility of testing free-form soil pipes that could be bent, curved, split, joined, or irregular. This is the first approach of its kind and can facilitate further research on realistic development mechanism, erosion rate laws, progression speed, and residual strength of soil pipes. The new approach also helps to indicate whether a cohesive soil can form piping or create subsidence.

The new preparation approach can be applied well to cohesive soils with some extend to fine granular soils. However, the application on coarse soils are limited as other traditional preparations. In the future, more details about the influence of pipe shape on susceptibility to soil erosion will be investigated.

Application

The paper presented a new way to make pre-formed piping for internal erosion tests. The detailed process and general guidance help laboratories to conduct investigation on complicated piping development in soils, a task that was impractical before this study.

Acknowledgements

The authors would like to acknowledge the technicians Jarrah May, Julian Nylen, and Joesf Kunta in JCU Create laboratory for their endless support with equipment manufacturing.

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