Effect of Water Content on Internal Erosion of an Unsaturated Slope

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ABSTRACT

Soil piping is the gradual and progressive erosion of soil grains, causing a void (open pipe) to form as water flows through the soil. In dam engineering, this type of internal erosion is often referred to as concentrated leak erosion and has been a cause of failure at multiple dams. Soil piping has also been observed in many landslides and contributes significantly to soil degradation in hillslopes and agricultural areas. Despite these many important impacts, there is still limited understanding of how soil pipes develop and progress and what factors control pipe stability. One of the significant challenges with analyzing soil piping, or concentrated leak erosion, is that it typically occurs in the vadose zone, where unsaturated conditions are present. However, most studies examining internal erosion have focused on saturated conditions, and few studies have examined the role unsaturated hydraulic properties (i.e., air entry value, matric suction, etc.) may play in the likelihood of internal erosion. Consequently, this study aims to explore the mechanisms controlling the erosion rate within soil pipes from the perspective of unsaturated soil mechanics. Bench-scale experiments were performed to examine the formation and progression of an eroded pipe in a small slope constructed at different water contents. Soil samples were also tested to measure its unsaturated hydraulic properties. The results show that the likelihood of pipe formation varies with the moisture content and, therefore, suction in the soil, as does the potential for pipe collapse. This demonstrates that unsaturated soil properties are key to understanding the formation and progression of piping in slopes.

INTRODUCTION

Internal erosion remains a challenging problem for the geotechnical community and is commonly cited as a leading cause of dam failures (Foster et al. 2000, Richards and Reddy 2007, Robbins and Griffiths 2018). Internal erosion is also heavily studied within the soil science and hydrology communities as internal erosion can be a significant contributor to soil degradation and create preferential flow paths within the soil, thereby significantly influencing contaminant transport and watershed hydrology (Swanson et al. 1989, Wilson et al. 2012, Bernatek-Jakiel and Poesen 2018). Within the dams community, internal erosion is divided into four categories: backwards erosion, internal instability, contact erosion, and concentrated leak erosion (ICOLD 2015). Concentrated leak erosion occurs when flow is concentrated at an opening in the soil (i.e., crack, void, macropore), and the previously existing opening enlarges due to erosion by the concentrated flow (ICOLD 2015). This same erosion process is often referred to as soil piping within the soil science community and has been reported in almost all climates and continents (Bernatek-Jakiel and Poesen 2018). When soil piping occurs in slopes (Figure 1), the conduits can act as a natural drain which may increase slope stability if the conduits remain open or may decrease stability if the conduits collapse (Wilson et al. 2012, Sharma 2015).

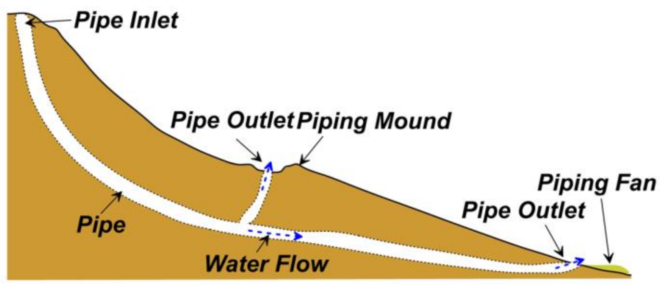

Figure 1. Diagram illustrating piping-related features in slopes (after Bernatek-Jakiel and Poesen, 2018) and a photograph of eroded sand at a soil pipe outlet at a landslide site in west Alabama (after Montgomery et al. 2020).

In the context of this study, soil piping is defined as a gradual, progressive erosion of soil particles, causing a void (open pipe) to form by water flowing through the soil (Sun et al. 2012). The formed pipes act as conduits for water, solutes, dissolved gases and sediments (Bernatek-Jakiel and Poesen 2018). Soil piping is a multi-staged process and can by subdivided into initiation and continuation of erosion, progression to form a pipe, and failure (USBR and USACE 2015). The initiation of erosion occurs at an opening in the soil, which might be a crack caused by differential settlement or desiccation, a void left behind by decayed tree roots or animal activity, or an opening into a drainage pipe or dam conduit. As flow begins to concentrate into this opening, the flowing water may begin to erode the soil causing it to enlarge. If the flow continues to occur at a high enough rate to erode the soil and the void or crack can remain open, the erosion process can progress. In a water-retaining structure (e.g., dam or levee), the void may be eroded back to the reservoir or river, leading to a breach. In a slope, failure may be defined by the collapse of the void leading to the formation of sinkholes or gullies or by the initiation of a landslide (Figure 1). The soil piping process is therefore controlled by the combined effects of the material properties, hydraulic loading, and effective stress conditions (Garner and Fannin 2010).

For soil piping to progress, the soil must be able to support an open void or crack. This limits the piping process to cohesive soils and unsaturated soils with sufficient suction to maintain an open void. Most instances of soil piping and concentrated leak erosion occur within the vadose zone (Figure 2), so understanding the role of the unsaturated properties and suction in the erosion process is important. Many studies have been conducted on the stability of unsaturated slopes (e.g., Ng and Shi 1998, Lu and Godt 2008, Rahardjo et al. 2018, 2019, Liu et al., 2020). However, relatively few studies have considered the role unsaturated hydromechanical properties (i.e., air entry value, matric suction, etc.) may play in the likelihood of piping. Previous experimental studies on piping have primarily used small-scale soil beds with either artificial or naturally formed pipes (Wilson 2011, Sun et al. 2012, Wilson and Fox 2013, Sharma et al. 2015, Yamasaki et al. 2017, Tanaka et al. 2019). These studies investigated the effects of slope angle, hydraulic gradient, and pipe type on soil pipe erodibility and slope stability. Other studies have focused on the role of compaction conditions on the erodibility of samples (e.g., Khoshghalb et al. 2021), but to the best of author's knowledge, none of the previous studies have directly examined the role of suction on the progression of pipe erosion or collapse.

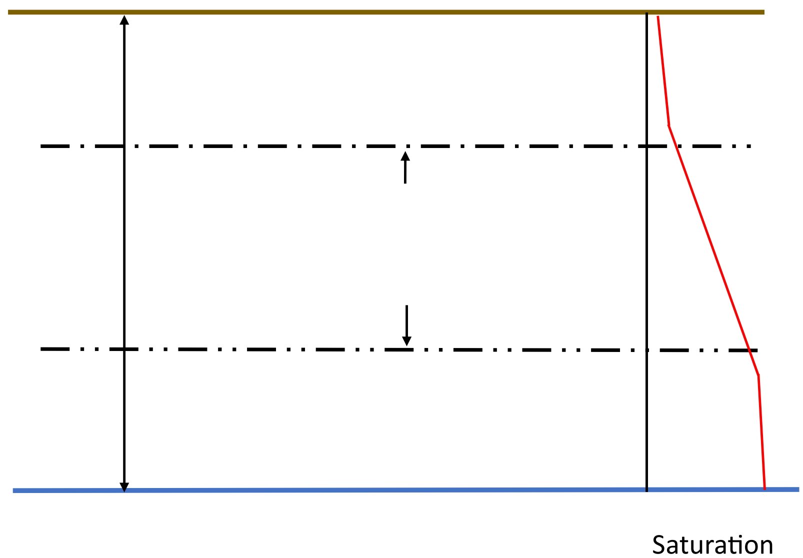

Figure 2. Illustration of changes in saturation and distribution of pore air and water in the vadose zone (after Fredlund 2021).

In this study, bench-scale experiments are performed to examine the progression of soil piping in an unsaturated slope. Small slopes with pre-existing voids were constructed at different water contents and subjected to concentrated flow to examine the ability of the soil to hold a pipe and for that pipe to expand in size. Samples of the soil were also tested to measure the soil-water characteristic curve. The hydrological and mechanical properties of an unsaturated soil largely depend on the degree of saturation, which ultimately influences the suction and effective stress of the soil. Therefore, the effect of the initial state of the soil on piping needs to be investigated. The results show that the likelihood of pipe formation varies with the moisture content and, therefore, suction in the soil, as does the potential for pipe collapse. This demonstrates that unsaturated soil properties are key to understanding the formation and progression of piping in slopes. Future work is needed to expand these results and explore the combined effects of soil type, flow rate, effective stress level, and saturation of the likelihood of pipe formation and collapse.

METHODOLOGY

Materials

The model slope was constructed using a fill soil from the local area (Auburn, Alabama, USA). The soil classifies as a clayey sand (SC) with a fines content of 21.5% as determined by wet sieving. The soil has a liquid limit of 67 and a plasticity index of 20. The grain size distribution of the soil is shown in Figure 3. All tests were performed at a dry density of approximately 1.5 g/cm^3. The soil-water characteristic curve for the clayey sand was measured using the HYPROP 2 and WP4 from the Meter Environment Company. The HYPROP was used to measure the curve at a low suction level (less than 100 kPa), while the WP4 was used to measure suction at very dry states (greater than 3000 kPa). The results from this test are shown in Figure 4.

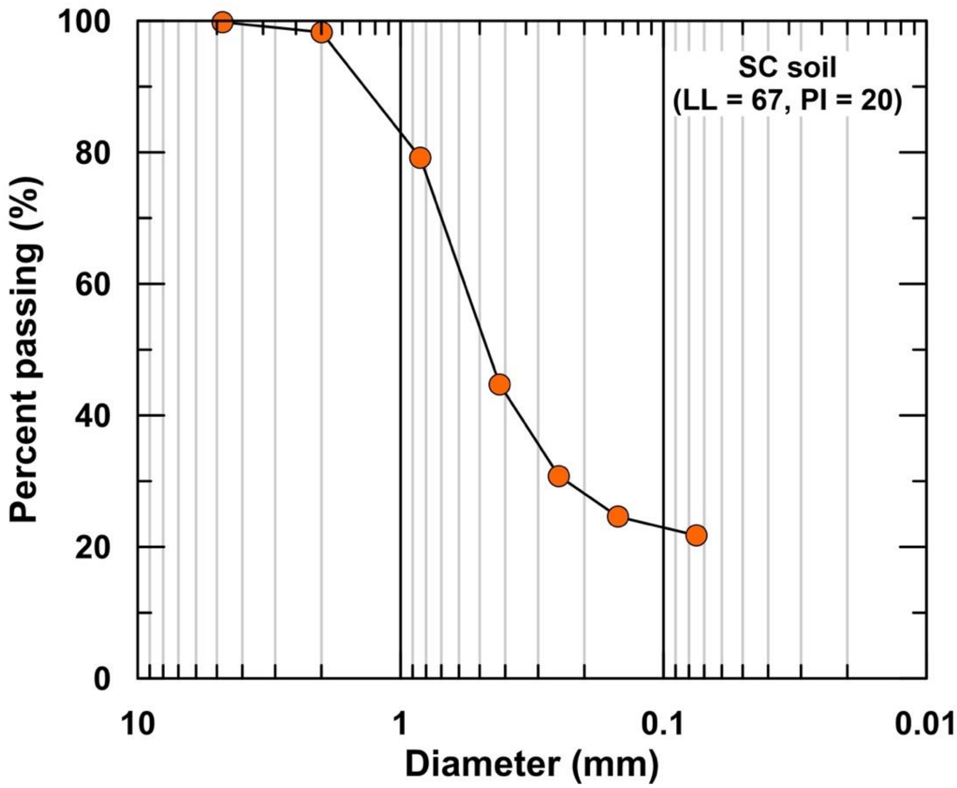

Figure 3. Grain size distribution curve of the SC soil sample

As the SWCC measurements provide discrete points, a model was fit to provide a continuous curve. The data show a clear bimodal pattern, so the bimodal Fredlund and Xing model (1994) was selected and fit the data (Figure 4). The bimodal SWCC is closely related to the dual-porosity structure of the soil as water drains from the two major pore series gradually. The water content decreases sharply in the first drainage region from the largest pores and decreases gradually in the second. The whole drainage process on the bimodal SWCC is divided into four stages based on the role of the pore water. The stage before the first AEV is defined as Stage A. In Stage A, all the pores are filled with water. When the suction is larger than the first AEV, the bulk water drains from the interaggregate pores in Stage B, in which the free water forms a continuous phase. As soil suction increases, the drainage of the meniscus water in the interaggregate pores follows. A large increase in matric suction only results in a slight change in the water content. This stage is defined as Stage C and can be referred to as the first residual state. After that, the pore water becomes discontinuous except for the water bounded between the particles and the clay aggregates in the form of water bridges. Furthermore, the water stored in the intra-aggregate pores begins to drain (Stage D), the second drainage region. The clay aggregates subsequently become unsaturated. The corresponding stages are also labelled in the drying SWCC in Figure 4.

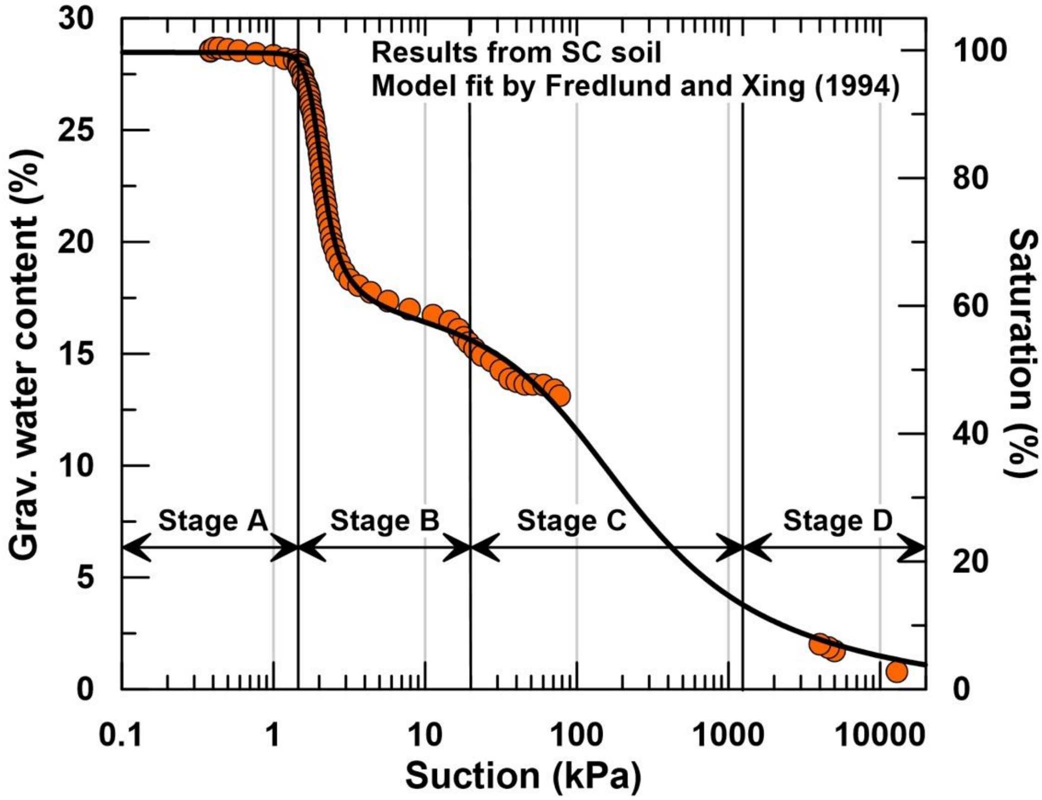

Figure 4. SWCC using Bimodal Fredlund and Xing (1994) model for the SC sample along with different stages of the bimodal curve.

Bench-scale model

A bench-scale slope was used for the current study to collect data to design larger experiments. The model slope was 44 cm long and 17 cm tall at the highest point with a width of 28 cm. The slope was constructed to resemble a pipe existing into a gully or other drainage feature. A gentle slope (1:5) was used for the first 30 cm, with a 1:1.3 slope being used near the toe. A typical cross-section is shown in Figure 5. A small thickness of modeling clay (4 cm at the thickest point and decreasing to zero at the toe of the slope) was placed along the base of the slope to simulate a hydraulic barrier. Tests were performed at initial gravimetric water contents of 5%, 9%, 10%, 20%, 25% and 30% by thoroughly mixing the soil with the desired amount of water. Samples were collected before compaction to verify the achieved water content. Tests could not be performed at higher or lower water contents due to the soil consistency being too dry or too wet, respectively, to form the slope. Tests were performed shortly after completing compaction and all steps were done in a temperature-regulated laboratory, so any moisture loss due to evaporation is expected to be minimal. The slope was then compacted in 5-cm lifts using a hand tamper to target a dry density of approximately 1.5 g/cm^3, which was achieved using the Ladd (1977) under-compaction method.

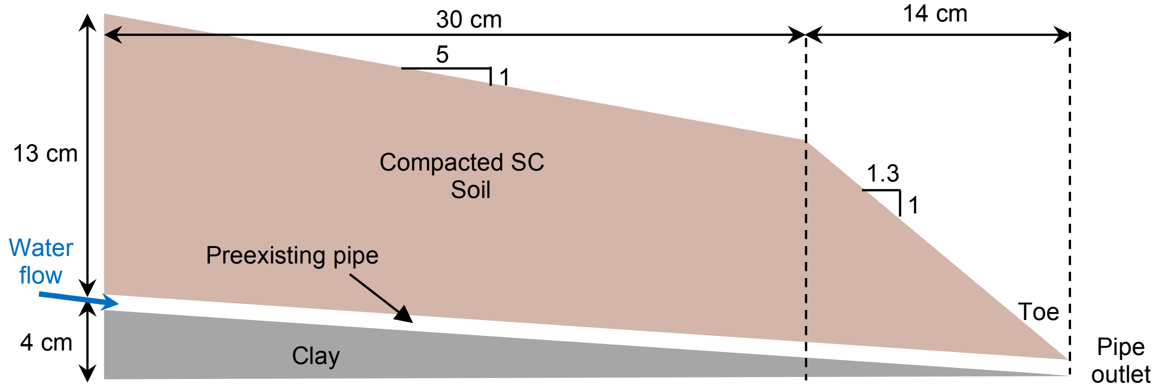

Figure 5. Cross-section of the model slope showing the two soil layers and the location of pre-existing 5 mm pipe that was created during construction.

A pre-existing conduit was created in the slope by placing a small metal tube (5 mm diameter) in the slope during the compaction process (similar to Nieber et al. 2019). This tube is meant to simulate a pre-existing macropore in the slope. The tube was placed at the top of the clay layer and exited at the toe of the slope (Figure 5, Figure 6a). This tube was meant to replicate a macropore or other pre-existing defect that would be enlarged through erosion. Before performing the test, the tube was removed by pulling it out of the slope slowly, being careful to maintain alignment with the soil and avoid disturbance. This was successful for all tests except those performed at 30% water content. In this case, the soil was saturated (Figure 4) and unable to support the pipe after the test pipe has been pulled out.

To simulate a subsurface seepage into a soil pipe, water was introduced to the upslope side of the void through a tube inserted into the box wall. A valve was used to gradually increase the flow to the desired rate (approximately 10 cm^3/s in this study). This flow rate was selected based on the erodibility of the soil and a constant flow rate was used (as opposed to a constant head or gradient condition) as this is considered more representative of the conditions expected within a slope where pipeflow will be driven primarily by infiltration. A video camera was set up in front of the model to record erosion patterns at the toe of the slope and slope movements during the test. Measurements of the height and width of the eroded pipe were also collected periodically usually a ruler.

RESULTS

Tests were conducted at different initial water contents and observations were recorded on the rate of pipe enlargement and the time before a collapse occurred. The observations fell into three categories. In the first category, the soil could support the initial pipe after the tube was removed, but the pipe collapsed soon after starting the flow of water. This was the case for tests performed at 5% and 9% initial water content. In the second category, the soil was able to support the initial pipe and the pipe enlarged with the continued flow (Figure 6b). This occurred for tests performed for initial water contents between 10 and 25%. In the third category, the soil could not support the initial pipe, which either partially or fully collapsed after the molding tube was removed. This was the case for the test performed at 30% water content and tests at higher water contents were unsuccessful due to the soft consistency of the soil.

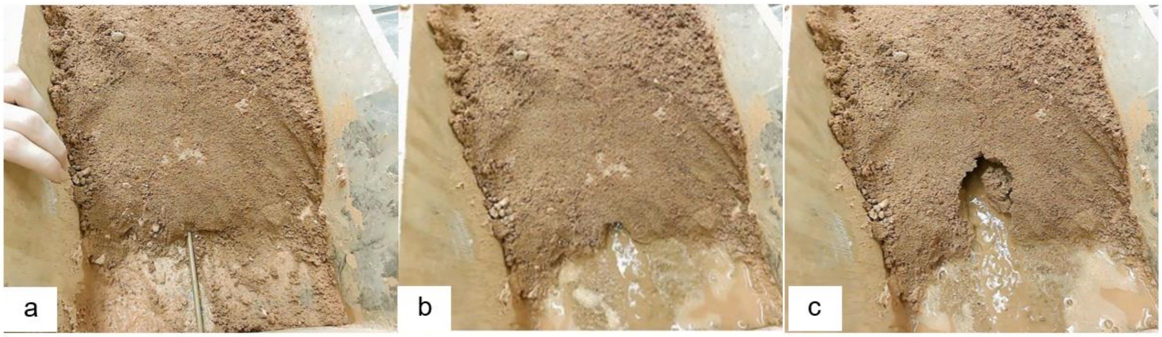

Figure 6. Progression of erosion in the test at an initial water content of 10% showing (a) removal of the metal tube used to form a pre-existing pipe, (b) the pipe expanding as erosion progresses, and (c) partial collapse of the roof over the pipe.

For the tests in the second category, some differences were observed in the response of the slope. For the tests at 10% initial water content, significant erosion occurred during the first five minutes of flow, resulting in a collapse of the pipe roof near the toe of the slope (Figure 6c). These collapses continued to progress further up the slope as erosion continued, with the pipe eventually reaching a diameter of 10 cm and a height of 8.5 cm after approximately 18 minutes. For tests performed at 15, 20, and 25% initial water contents, the pipe initially eroded but stabilized at a width of approximately 2.5 cm and a height of between 2 and 2.5 cm as measured at the toe of the slope. These after the pipe quickly enlarged during flow, and a progressive collapse began starting with the soil forming a roof over the bottom of the pipe. For the test at 20% initial water content, the flow rate was increased to 15 cm^3/s after 15 minutes, but no further erosion was observed.

DISCUSSION

The erosion results presented in this study show that the progression of piping is likely for water contents greater than 10% and less than 25%-30%. This range of moisture contents covers Stages B and C of the SWCC (Figure 4). At water contents greater than 28%, the soil becomes saturated, and the suction decreases to near zero. This loss of suction limits the ability of the soil to hold a roof over the pipe. At water contents less than 10%, the suction is still high, but the soil becomes to become very dry and is prone to collapse upon wetting. Lu et al. (2009) measured the tensile strength of several unsaturated sand and found that the peak level of tensile strength occurred between saturations of approximately 30% and 95%. For the current soil, this would correspond to water contents of 9% and 27%, which is consistent with the range of water contents over which piping was able to progress in the experiments. This result suggests that the suction conditions are directly related to likely of progression of this erosion mechanism and that the range of water contents at which erosion is likely to progress may be predicted from the SWCC. Future experiments will seek to directly measure suction during the tests to confirm this finding.

This set of experiments represents the first work in a larger study examining soil piping in slopes and the relation between soil piping and landslide initiation. The current study has highlighted the role that suction plays in the piping process. However, additional work is needed to examine the role of suction in likelihood of internal erosion progression for other soil types, different compaction conditions, and different effective stress levels. Both the SWCC and soil strength are known to be stress dependent and so a range of slope heights will be needed to assess these effects. Planned future experiments will also examine different slope conditions and measure the mass of eroded material to characterize how the erosion rate varies throughout the experiment.

CONCLUSION

This study examined the effect of water content in a soil pipe on an unsaturated model slope. The SWCC for the clayey sand (SC) used in the model slope was determined using HYPROP and WP4 to measure the SWCC across a range of suction levels. A pre-existing pipe was created in the model slope using a small metal tube placed during compaction and removed before testing. A constant flow of water was then applied to the upslope side of the pipe to determine the likelihood of progression of erosion and collapse of the pipe roof. The test was performed at water contents ranging from 5% to 30%, but the erosion of the pipe was only able to progress for water contents between 10 and 25%. This range of water contents is consistent with the range of saturation levels over which the highest tensile strength is expected (Lu et al. 2009).

The current study has highlighted the role that unsaturated soil properties play in the likelihood of soil piping or concentrated leak erosion. While previous studies have focused on the effects of compaction level and molding water content on the erodibility of a soil, few studies have explicitly examined the role that soil suction plays in the piping process. As soil piping and concentrated leak erosion are commonly observed in the vadose zone, an understanding on how unsaturated soil properties affect the erosion process is critical to developing physics-based approaches to evaluating soil piping. This study represents the first step towards this goal, and future studies are planned to extend these findings to a wider range of soil types, hydraulic gradients, pipe type and effective stress levels.

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