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# Scouring Damage to Buried Pipes Caused by Leakage Jets: Experimental Study

**S. M. Pike[1], J. E. van Zyl[2], and C. R. I. Clayton[3]**

[1] Department of Civil Engineering, Private Bag X3, Rondebosch 7701, South Africa University of Cape Town, South Africa
[2] Department of Civil Engineering, Private Bag X3, Rondebosch 7701, South Africa University of Cape Town, South Africa
[3] Emeritus Professor, Faculty of Engineering and the Environment, University of Southampton, UK

## Abstract

This paper reports on an experimental study on the scouring of pipe materials on the outside of leaks caused by soil fluidization. A base experiment was designed consisting of a 3 mm diameter hole angled at 45° to the horizontal in a 110 mm diameter unplasticized polyvinyl chloride (uPVC) pipe. Five parameters were investigated in a sensitivity analysis: soil particle size, leakage flow rate, leak orientation, cover depth and pipe material. The development of the scour patterns was measured at regular intervals. It was found that the leak jet orientation had the greatest impact on the scouring rate, followed by the leakage flow rate, sand particle size, pipe material and cover depth.

## Introduction

Non-revenue water is a common problem that burdens water authorities worldwide, the effects of which include loss of revenue and water scarcity aggravation. A large proportion of non-revenue water is comprised of real losses, i.e. water lost through bursts and background leaks from water distribution systems. Underground pipes are commonly buried in selected granular materials specified by building codes. When leaks occur in pressurised pipes, water (or other fluid) exits through the leak openings and into the surrounding soil, often causing localised fluidisation of the soil (van Zyl et al. 2013).

This fluidisation, in turn, has the potential to scour away pipe material adjacent to the leak due to the abrasive action of the soil particles moving across the pipe surface. Fig. 1 shows samples of failed plasticized polyvinyl chloride (PVC ) (a and b) and asbestos cement (c and d) pipes taken from the field with evidence of scouring damage. It is interesting to note in Fig. 1(b) that while this PVC pipe shows scouring damage contiguous with the crack, removal of the black pipe coating over a wider area is also evident.

The aim of this paper is to present the findings of a study that was conducted to investigate scour damage to pipe surfaces adjacent to leaks in a controlled laboratory experiment. An unplasticized polyvinyl chloride (uPVC) pipe section with a round hole drilled at 45° and buried in a container filled with relatively uniform sand was designed as a standard base experiment. The influences of five key factors on the scouring pattern and rate were then investigated. Factors studied were the particle size, cover depth, leakage flow rate, leak orientation and pipe material.

The paper begins with an overview of the current state of knowledge on soil-leak interaction and leakage-induced pipe erosion. The experimental design and methodology are then described, followed by the presentation and discussion of the study findings.

## Soil-leak interaction

Leakage from underground pipes occurs at the interface of two fundamentally different flow regimes: turbulent flow through the leak opening and laminar (Darcy) flow through the soil.

Hydraulically, the flow rate through a hole in a pipe wall is described by the orifice equation (see Finnemore and Franzini (2001)):

$$Q = C_d A \sqrt{2gh} \tag{1}$$

Where $Q$ is the flow rate, $C_d$ the discharge coefficient, $A$ the orifice area, $g$ acceleration due to gravity and $h$ the pressure head differential over the orifice. The orifice equation describes the relationship between pressure differential and flow rate under turbulent flow conditions. (Laminar flow through an orifice is possible, but only occurs at very small flow rates (van Zyl and Clayton 2007) and is thus ignored in this study).

Flow through soils is normally considered to be laminar and is modelled using the Darcy equation (for instance, see (Craig 2004)):

$$Q = KA \cdot \left(\frac{h_s}{L}\right) \tag{2}$$

Where $Q$ is the flow rate, $K$ the soil's hydraulic conductivity, $A$ the cross sectional flow area, $h_s$ head loss and $L$ the length of the flow path.

Walski et al. (2006) studied the incompatibility between the orifice or Darcy equations and proposed a dimensionless soil-orifice number to predict whether the orifice or Darcy flow will dominate the pressure-leakage relationship of leaks in distribution system pipes. They concluded that in most real-word cases the flow behaviour will be dominated by the orifice equation.

Walski et al.'s findings can be understood by noting that there are only two ways in which the soils surrounding a pipe can affect the flow through a leak opening: the first is occlusion, which entails soil particles partially blocking the leak opening, thus reducing the effective flow area. The second is through reducing the head differential over the leak opening by substantially raising the fluid pressure on the outside of the pipe. Both are unlikely to occur to any significant extent in loose granular bedding material, which explains the dominance of the orifice equation.

van Zyl and Clayton (2007) discussed the complexity of the soil-leak interaction and the factors influencing it. They concluded that the leakage flow rate is unlikely to be a linear function of pipe pressure (as would be the case for Darcy flow) due to the interaction of soil particles with the jet and orifice, turbulent flow in the soil, variable geometry of the unconfined flow regime, hydraulic fracturing and piping.

If the jet flows with sufficiently high velocity into an unconfined granular soil bed, i.e. a soil bed that allows sufficient space for soil expansion, local fluidisation of the soil bed occurs (Niven and Khalili 1998; van Zyl and Clayton 2007; Alsaydalani and Clayton 2014). van Zyl et al. (2013) and Bailey (2015) experimentally studied local fluidisation of a vertically upwards water jet in a uniform ballotini (glass beads) bed. Fig. 2 shows the motion of soil particles outside an orifice placed against the glass wall of the container holding the ballotini (van Zyl et al. 2013): the leakage jet and entrained soil particles move rapidly upwards in a vertical 'tube' that opens up in the bed, termed the fluidisation zone. Soil particles are deposited at the top of the fluidized zone and then move slowly down on the outside of the fluidized zone towards the orifice where they are entrained in the leakage jet again. This is called the mobile bed zone.

Van Zyl et al. (2013) also concluded that the flow rate, rather than velocity (and thus the shape of the orifice) determines the size of the fluidisation zone and that the fluidized zone acts as a mechanism to dissipate surplus energy.

Little research has been done on the scouring damage that may be caused by the fluidised zone moving soil particles across the pipe surface outside a leak. Majid et al. (2010) investigated an incident where two failed natural gas pipes were excavated for repair (one medium density polyethylene (MDPE) and one carbon steel). Upon excavation, it was found that the two gas pipes were situated in the fluidisation zone of an adjacent failed asbestos cement water pipe. This soil fluidisation was abrasive enough to scour through the pipe walls of both gas pipes, resulting in their failure.

In a similar incident, Majid and Mohsin (2013) found that a mild steel water pipe had ruptured at a welded joint, causing erosive failure to an adjacent carbon steel pipe conveying natural gas. Majid, Mohsin and Yusof (2012) experimentally investigated the scouring effects on a buried carbon steel pipe situated in the fluidisation zone of an adjacent pipe leak, replicating the first incident. They found that the pipe surface in the centre of the circular scour pattern, where the jet struck the surface perpendicularly, had smooth indentations and that the outer regions of the scour pattern appeared rippled.

## Methodology

### *Experimental Setup*

Fig. 3 and Fig. 4 show the experimental setup used in this study, consisting of three identical reinforced cubic aluminium containers with 700mm long sides. Pipe test samples were 400mm long, 110 mm nominal diameter (ND) pipe sections with both ends closed. The municipal water supply was connected through one of the end caps using a flexible hose with a pressure reducing valve (PRV) and flow meter installed on each of the three setups.

A pipe sample with a manufactured leak orifice was strapped to the base of each of the containers with the orifice on the top pipe surface. The containers were filled with sand to a cover depth of 500mm and then filled with water from the top to saturate the soil. The widths of the containers were chosen to be greater than the cover depths to minimise the effect of the side walls on the settling of the soils. To further mitigate the effect of the side walls, each container was struck firmly ten times on all four sides until settlement and air bubbles leaving the soil bed were no longer visible. Once these preparations were completed, the experimental runs were started by connecting the water supply.

To ensure that each of the three tanks received an identical flow rate, a length of 110 mm uPVC pipe was connected to the water supply through a PRV. The PRV was set to maintain the downstream pressure lower than the minimum diurnal pressure in the water supply to ensure a constant pressure in the pipe. Individual tanks were supplied using identical pipes, each with a flow meter and another PRV to control individual flow rates.

Where the scour damage increased the size of leak orifice itself, the PRV setting was adjusted to maintain a constant flow rate throughout the experimental run. The pressures inside the pipes were approximately 25 to 30m for the base run, which is substantially lower than the pipe's rated operating pressure. Thus the effect of leak area variations with changes in pressure was considered to be negligible even for cases where the wall thickness was substantially reduced due to scouring. No signs of plastic deformation or fracture were observed during any of the experiments conducted.

The scouring damage to the pipe samples were determined by turning off the water supply, emptying the containers and extracting the pipe samples. The length, width and depth of each scour pattern were measured with Vernier callipers. The scouring volume was determined by filling the scoured area with window putty of known density and forming its surface with a curved scraper to match the original curvature of the pipe. The putty was then removed from the scoured area, weighed and converted to a volume.

The pipes were initially inspected after every 20 hours of run time, and sometimes at longer intervals when trends in the scouring pattern were well established. Total experimental run times varied from 60 to 480 hours.

### *Experimental Parameters*

A base experiment was first conducted, followed by a sensitivity analysis in which one experimental parameter was varied at a time.

The base experiment was conducted on a 110 mm Class 9 uPVC pipe with a wall thickness of 4.54 mm and a 3 mm diameter hole drilled at 45° to the horizontal. The angled hole was selected since this was shown to have greater scouring than a 90° jet (Pike 2013). The soil properties are discussed in the following section.

Five parameters were included in the sensitivity analysis: soil particle size, leakage flow rate, leak orientation, cover depth and pipe material. The leak opening shape or size was not included in the sensitivity analysis since van Zyl *et al.*( 2013) showed that it is the jet flow rate rather than velocity that is responsible for the observed fluidisation pattern. Table 1 summarises the parameters of the base experiment, and those that were varied for the sensitivity analysis. In Table 1, Column B represents the base experiment (which was repeated five times), while Columns A and C represent the variation of an experimental parameter.

The experimental setup allowed three experiments to be run in parallel. Thus for each sensitivity experiment, cases A, B and C were runs simultaneously.

It should be noted that for brevity, only a selection of the full set of results obtained in this study have been presented in this paper, thus the results are presented in graphs and tables that were carefully selected to give the fullest possible overview of the study’s results. A detailed description of all the results is available in Pike (2016).

### ***Soil Properties***

The three sands used in this study were all silica sands from the Consol Industrial Mineral mine in Philippi, Western Cape, South Africa (Consol 2014). Previous studies showed that scouring rates increase with increasing particle size (Briaud et al. 2001; Gent et al. 2012). In this study the median grain diameter, $D_{50}$, was used to characterize the soil particle size.

Fig.5 presents microscopic images of the sands used in these experiments. It can be seen that sands A and B consist mostly of highly angular particles with sharp edges and only a few smoother particles in between. The particles of sand C have a lower angularity and smoother edges than the other two sands.

Table 2 summarizes the sands' physical properties, while Fig. 6 shows their particle size distribution.

## Results and Discussion

### *Base experiment*

The base experiment was conducted on a 110mm uPVC pipe with a 3mm hole drilled at 45° and positioned on the top of the pipe. The top of the pipe was buried 500 mm deep in Soil B (Table 2) and a flow rate of 400 L/h was directed through the hole.

The base experiment (Experiment B in each set of runs) was run as part of each of the five experimental runs detailed in Table 1. The base run was used as a reference for each of the parametric sensitivity experiments, and the five base runs allowed the repeatability of the experiment to be investigated.

A tear shaped scouring indentation was observed to form in the pipe material outside the leak opening, with the sharp end of the tear shape pointing in the direction of the angled hole. Fig. 7 shows the leak opening before commencing the experiment and then at 40 and 80 hours of scouring for Experiment 1B. The surface of the scoured area was found to be smooth with no visible scratches, indicating a polishing action.

Fig. 8 to Fig. 11 show the development of the scour volume, maximum depth, width and length with time respectively. All four scouring parameters displayed a growth rate that diminished over time. Logarithmic curves were chosen since they commonly used in scouring studies (for example Cardoso and Bettess 1999; Barbhuiya and Dey 2004; Simarro et al. 2011) and overall provided reasonably good fits to the measured data.

While experiments 2 to 5 displayed similar patterns, experiment 1 displayed slightly lower scouring rates, especially for the scour volume (Fig. 8) and maximum scour depth (Fig. 9). The reason for this is that the walls of the container were not struck, to densify and de-air the sand, after filling it with sand and water as was done for the other experiments. Thus the side walls were likely to have inhibited the settling of the soil in Experiment 1. The trend lines in Fig. 8 to Fig. 11 exclude Experiment 1's data.

An interesting observation was made when excavating the soil after experimental runs: Fig. 12 shows a distinct light-coloured circle was observed on horizontal planes at different levels above the pipe.

An investigation showed that the light colour was caused by the fluidization washing clean the soil particles trapped in the fluidized and mobile bed zones. Careful removal of the soil to different depths allowed three-dimensional profiles of the mobile bed zone to be developed. This was only done for a separate experimental run (Experiment 0), where three tests with vertically upwards jets were buried in the three different soil media described in Table 2. Fig. 13 shows that the height of the mobile bed zone increases with decreasing median soil particle size, despite the slightly different flow rates.

### *Sensitivity Analysis*

#### Experiment 1: Effect of Soil Particle Size

In Experiment 1, the base experiment was run with the three different soils described in Table 2 and Fig. 5 and Fig. 6. The soil used in the base run (Experiment 1B) had a median particle size of 1.6 mm, Experiment 1A and 1C had median particle sizes of 2.1mm and 0.75mm respectively.

The development of the scouring volumes over time is shown in Fig. 14 and the scouring patterns after 100 hours in Fig. 15. It is clear that larger soil particles resulted in greater scouring rates, even though it is evident from Fig. 13 that the size of the mobile bed zone decreased with particle size.

### Experiment 2: Effect of Cover Depth

In Experiment 2, the base experiment was run with a cover depth of 500mm (2B), and the other two experiments with cover depths of 400mm (2A) and 300mm (2C) respectively.

The development of the scouring volumes over time are shown in Fig. 16 The results showed that the 500mm cover depth resulted in greater scour than the smaller cover depths, but no significant difference between the scouring patterns of the 300mm and 400mm cover depths.

### Experiment 3: Effect of Leakage Flow Rate

In Experiment 3, the base experiment was run with a flow rate of 400 L/h (3B) and the other two experiments with flow rates of 600 L/h (3A) and 400 L/h (3C) respectively. It has been shown that a greater leakage flow rate increases the size of the fluidisation zone and the velocity of the particles within the fluidisation zone (van Zyl et al. 2013; Alsaydalani and Clayton 2014). Furthermore, increasing particle velocities and leakage flow rates increase the rate of erosion in various applications (Goddard 1994).

The development of the scouring volumes over time is shown in Fig. 17. It is clear that the leak flow rate has a significant impact on the scouring rate.

The progression of the scouring pattern for highest flow rate of 600 L/h pipe (Experiment 3A) is shown in Fig. 18. It can be seen a small second leak opening had formed adjacent to the initial orifice at 102 hours. This opening continued to grow over the remainder of the test as can be seen after 253 h in Fig. 18 (C).

### Experiment 4: Effect of Leak Orientation

In Experiment 4, the base experiment was run with the leak opening oriented at 45° to the horizontal (4B). Another experiment (4A) was run with the leak opening oriented at 0° to the horizontal, directing a jet along the crest of the pipe through a tube imbedded in a pipe collar. The final experiment had a vertical jet, i.e. at 90° to the horizontal.

The horizontal jet displayed the highest scouring rate of all the experiments, scouring a hole through the pipe material in less than 20 hours as shown in Fig. 19. The reason is that the jet moved soil particles most directly across the surface of the pipe, resulting in the largest contact area and highest scouring particle velocities.

To obtain more detail on the scouring progression, the horizontal jet experiment was repeated with a flow rate of 200 L/h and called Experiment 4A(ii). The development of the scouring volumes with time for Experiment 4, including the 400L/h (4A(i)) and 200L/h (4A(ii)) flow rate experiments, are shown in Fig. 20.

The base and vertical leak experimental results at a flow rate of 400L/h are also shown in Fig. 19. The vertical leak experiment (4C) displayed the lowest scouring rate up to approximately 140 hours, after which the scouring rate increased dramatically. This step change coincided with the maximum scour depth reaching the pipe wall thickness and starting to enlarge the hole diameter (at the end of the experiment (299.5 hours), the leak opening had increased from 3mm to 4.7mm). This point may have resulted in a change in the scouring flow pattern and gradual increases in flow rate between inspections.

### Experiment 5: Effect of Pipe Material

In Experiment 5, the base experiment on uPVC pipes was repeated for high density polyethylene (HDPE) and steel pipe materials. Different pipe materials vary in hardness, and hence exhibit different resistance to abrasion (Goddard 1994; Ha et al. 1998; Yang and Hlavacek 1999).

The progression of the scour volume in the three materials is shown in Fig. 21. The figure shows that uPVC eroded at the greatest rate, followed by steel and then HDPE.

Fig. 22 shows the scour patterns of the three materials after 80 hours. An interesting feature of the steel pipe's scour pattern is that the influence of the soil-leak interaction is visible on a much wider area than the measurable local scouring directly outside the leak opening. In this area the coating of the steel pipe was removed and the underlying steel polished to different levels of smoothness. The wider area shows sharp boundaries on the upstream and lateral sides of the leak opening, but a more gradual variation from the naked metal to the undisturbed coating on the downstream side. The variation in scouring depth over the whole affected area provides an indication of the variation in intensity of the soil movement. Careful inspection of the other pipe materials showed evidence of the same wider scouring pattern, although it was harder to identify than on the steel pipe. However, the wider scouring pattern is clearly shown on a coated uPVC pipe sample taken from the field in Fig. 1 (b).

## ***Discussion***

A tornado plot of the range of scouring volumes after 180 hours in the sensitivity analysis is shown in Fig. 23. The graph shows that the leak orientation clearly has the greatest influence on the scouring rate with a jet across the pipe surface causing by far the greatest scouring. The leak orientation is followed by the flow rate, grain size, pipe material and cover depth in order of their influence on the scouring rate. The cover depth was varied over a small range and was significantly lower than the normal cover depth in practice. Thus further work may show this factor to be more important than this study showed.

The observed scouring of pipe materials outside leaks may have both negative and positive consequences. While the scouring will increase the size of leaks and thus their leakage rate over time, larger leaks are easier to detect and more likely to be discovered and thus repaired. It has been shown that smaller leaks can result in much greater water loss volumes than large leaks due to this factor (Lambert 2001).

Depending on the desirability of leak-induced scouring of pipe materials, practitioners may select pipe and bedding materials that enhance (uPVC and larger bedding grain sizes) or reduces (HDPE and smaller bedding grain sizes) the scouring rate.

The importance of leak orientation emphasises the importance of ensuring that small leaks that are directed across the pipe surface, such leaking seals on bell-and-spigot joints or pipe collars are avoided.

## Conclusions

An experimental investigation has been carried out on the scouring impact of soil-leak interaction on water pipes. The experimental setup consisted of three identical aluminium boxes with a width to height ratio greater than one. A base experiment was set up using a 110mm uPVC pipe with a 3 mm diameter hole at an angle of 45°, buried 500mm deep in a crushed silica sand bedding and with a leakage rate of 400 l/h.

The sensitivity of the erosion rate to soil particle size, cover depth, flow rate, leak orientation and pipe material was then investigated by varying one parameter at a time.

The experiments showed significant erosion of the pipe material, eventually creating new leak openings in the pipe surface. The volume, depth, length and width of the scoured area were found to increase at a diminishing rate with time. It was found that a logarithmic function provided a reasonable description of the scouring parameters with time, although changes in the flow or scouring pattern may be responsible for some of the deviations observed in the scouring patterns.

A sensitivity study showed that the leak jet orientation had the greatest impact on the scouring rate, followed by the leakage flow rate, sand particle size, pipe material and cover depth.

The greatest scouring rate can be expected with a high leakage flow directed across the pipe surface in a deep bed of large soil particles. Conversely the smallest scouring rates can be expected with low leakage flow rates directed vertically upwards in a shallow bed of small particles. HDPE exhibited the lowest erosion rate, followed by steel and then uPVC.

It was observed that the soil in the fluidized and mobile bed zones were washed clean in the scouring process and formed a clearly distinguishable lighter dome in the bedding soil. The shapes of these domes were measured for three different soil particle sizes, showing that larger particles resulted in smaller mobile bed zones while simultaneously displaying larger scouring rates.

Scouring of pipe material clearly affects the way leaks on water supply pipes develop over time and more research is required to better understand both the soil fluidisation and scouring processes. It is recommended that water supply authorities document evidence of scouring found on failed water pipes to facilitate future research into this phenomenon.

**Notation**

The following symbols are used in this paper:

$A$ = Cross sectional flow area

$C_d$ = Discharge coefficient

$D_{50}$ = Median particle size

$g$ = Gravitational acceleration

h = Pressure head

$h_s$ = Headloss through soil

K = Hydraulic conductivity of soil

L = Length of flow path

Q = Volumetric flow rate

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## Figure Captions

Fig. 1. Examples of (a and b) failed PVC and (c and d) asbestos cement from the field. [Image (a) courtesy of de Kater; image (b) courtesy of van Thienen.]

Fig. 2. Local fluidisation patterns caused by water jets at different flow rates (van Zyl et al. 2013): (a) Q=130 l/h; (b) Q=220 l/h; (c) Q=320 l/h.

Fig. 3. Schematic section through the experimental setup

Fig. 4. Delivery pipe feeding into three identical experimental tanks

Fig. 5. The three sands used in this study

Fig. 6. Particle size distributions of the sands used in this study

Fig. 7. The leak opening of the base experiment (a) before commencement of the experiment, (b) after 40 hours and (c) after 80 hours of scouring.

Fig. 8. Development of scour volume with time for the base runs in the five experiments. The trend line only considered experiments 2 to 5.

Fig. 9. Development of scour depth with time for the base runs in the five experiments. The trend line only considered experiments 2 to 5.

Fig. 10. Development of scour width with time for the base runs in the five experiments. The trend line only considered experiments 2 to 5.

Fig. 11. Development of scour length with time for the base runs in the five experiments. The trend line only considered experiments 2 to 5.

Fig. 12. Discoloured zone vertically above orifice

Fig. 13. Shape of mobile bed zones for vertical leak tests

Fig. 14. Pipe material scouring volume for different particle size distributions

Fig. 15. Visual Inspection of Tests 1A, 1B and 1C after 100 hours of scouring

Fig. 16. Pipe material scouring volume for different cover depths

Fig. 17. Pipe material scouring volume for different flow rates

Fig. 18. Visual progression of the scouring pattern for a flow rate of 600 L/h (Experiment 3A)

Fig. 19. Orifice Condition of Experiment 4 at Various Times

Fig. 20. Pipe material scouring volume for leak jets at different angles to the horizontal.

Fig. 21. Pipe material scouring volume for different pipe materials

Fig. 22. Orifice Conditions of Experiment 5 after 80 Hours of Erosion

Fig. 23. Tornado plot of maximum and minimum scour volumes for each experiment at 180 hours

**Table 1.** Parameter values for the base experiment and sensitivity analyses conducted.

| **Number** | **Parameter** | **Experiment ID** | | |
|---|---|---|---|---|
| | | A | B (Base) | C |
| 1 | $D_{50}$ particle size (mm) | 2.1 | **1.6** | 0.75 |
| 2 | Cover depth (mm) | 400 | **500** | 300 |
| 3 | Flow rate (l/h) | 600 | **400** | 200 |
| 4 | Leak angle (°) | 0 | **45** | 90 |
| 5 | Pipe material | Steel | **uPVC** | HDPE |

**Table 2.** Properties of the three sands used in this study

| **Property** | **Unit** | **Sand A** | **Sand B** | **Sand C** |
|---|---|---|---|---|
| $D_{50}$ | mm | 2.1 | 1.6 | 0.75 |
| Particle Density | kg/m$^3$ | 2690 | 2661 | 2690 |
| Coefficient of Uniformity ($D_{60}/D_{10}$) | - | 1.77 | 1.62 | 1.48 |
| Maximum Dry Bulk Density | kg/m$^3$ | 1580 | 1643 | 1790 |
| SEES Form Factor | - | 0.57 | 0.49 | 0.56 |
| Minimum Void Ratio | - | 0.70 | 0.62 | 0.50 |
| Minimum porosity | % | 41.25 | 38.26 | 33.46 |
| Permeability | cm/s | 1.75 | 0.44 | 0.16 |