External Abrasion Caused by Leakages in Potable Water Distribution System Pipes

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Abstract: External abrasion caused by leaks in pipe connections is a constant risk for water distribution systems (WDSs). Phenomena related to pipe leakages may lead not only to flow losses and pressure drops in locations where they occur but also potential damage in buried pipes due to soil fluidization. The aim of this paper is to demonstrate that pipe failures can be developed by this leakage phenomenon that causes soil fluidization. Through experimental research using a model with pipes of various materials, the impact of a leak in the outer walls of a buried pipe was simulated. Results showed that regardless of the material, size, or any other input variable, every pipeline is vulnerable to external abrasion. A future improved model could be developed using water under pressure to perform simulations, which may lead to further contributions. Results from this study suggest that improving materials should not be the only concern when designing water networks, and particular attention should be paid to enhance the quality of pipe connections. **DOI: 10.1061/(ASCE)PS.1949-1204.0000503.**

Introduction

Currently, for many water utilities the implementation of water distribution systems (WDSs) includes not only the hydraulic and construction cost analysis, but also the operational, maintenance, and rehabilitation activities required throughout their life cycle. The good performance of a WDS can be influenced by the selection of pipe materials and their resistance to damage due to external factors. Deterioration of pipelines is related to the occurrence of chemical, biological, or laboratory phenomena that produce effects with different degrees of severity depending on the response of each pipe material. Some pipelines may end up in possible failures or even in rupture, leading to the malfunction of the system and additional costs for water authorities. Many numerical and experimental studies analyze the effects of pipes that are exposed to aggressive environments, such as corrosion, extreme temperature, abrasion, and fatigue.

Internal abrasion in pipes is a thoroughly studied research topic in urban drainage systems; pipeline failure can be caused by sediments transported in wastewater and stormwater that wear down the inner surface of pipes. However, in WDSs, internal abrasion is rather unusual because the transported water must ensure safe consumption under established water quality standards (i.e., nonpresence of sediment particles). Instead, scouring damage in potable water pipes is mostly due to external abrasion. In the hydraulics of modern WDSs, this has not been considered an important issue.

Different theories try to explain the reason for wear on the outer walls of pipes. For instance, rodents were associated with the abrasion of pipes because orifices observed resembled this animal's attack. Indeed, the National Sanitation Foundation (NSF) developed a series of tests to determine the threat of rodents to PVC pipes. It was noticed that rodents only attacked pipes when the pipes interfered with their path to a food source and that there were no cases of total penetration of pipes, as is usually seen in actual failure situations (National Sanitation Foundation 1955). Therefore, this idea was rejected, and new theories were proposed to explain external abrasion through other mechanisms associated with the structural behavior and hydraulics of pipes.

The most widely accepted theory indicates that interactions between the leaky coupling of pressurized pipes and surrounding soil might be considered as a main cause (Majid et al. 2010). The occurrence of leaks can be defined as the failure of a pipe, which is a common problem that causes inefficient energy distribution and low-pressure conditions throughout networks (Alsaydalani 2017). Many researchers have focused on understanding the influence of various factors in the behavior of leaks because it is important to define the level of damage in pipes (breakages, deformation, or deterioration). Some of the factors studied are associated with leak hydraulics, pipe material and properties, and soil hydraulics. Experimental tests have been carried out to analyze the performance of leakage discharge and the pressure–leakage relationship by including different pipe materials, orifice sizes and shapes, and pressure rates (de Marchis et al. 2016; Alsaydalani 2017). Nevertheless, the models developed ignored the effects of the surrounding soil.

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Hence, other research emphasize dealing with leakage modeling in water distribution systems by considering the influence of soil characteristics on the leakage discharges from pipes. Principally, the interaction between leakages and the surrounding soil has been studied extensively because erosional forms in pipes and in situ fluidization are strongly related to the washing of soil particles produced by these discharges (Mih and Kabir 1983). This also may lead to damage in the foundations of buildings and roads, which impacts the safety of neighboring populations and increases costs for water distribution companies.

Because of this potential damage, it has been necessary to analyze the effects of these events in terms of the structure and hydraulics of both pipes and soil. A research project to analyze the effect of the soil environment around leaking water pipes was carried out by van Zyl et al. (2013) that emphasized the phenomenon of soil fluidization. It was found that extended fluidized and mobile zones are inevitable and almost independent of orifice size. Similarly, Fox et al. (2016) investigated the dynamics of leakage behavior considering the significance of soil conditions. In addition, Latifi et al. (2018) showed through several experimental tests that the geotechnical properties of the soil around a pipe could influence the amount of leakage discharge. Nonetheless, all these previous works focused only on how the performance of leakages changes in relation to the properties of the soil medium that covers the pipes, or vice versa. In those tests, different types of openings were created to simulate leakages, but few were designed to recreate the moment when cracks appear and failure occurs in pipes.

Few studies have evaluated resistance to weariness in different pipe materials and the structural effects caused by leaky couplings. The most recent study performed tests on scouring outside of pipe materials at leaking sites caused by soil fluidization (Pike et al. 2018). Five parameters were investigated in a sensitivity analysis, and it was found that the leak jet orientation had the greatest impact on the scouring rate. Other factors, such as the leakage flow rate, sand particle size, pipe material, and cover depth, were also evaluated with respect to how they impacted the increase in scouring damage on tested pipes.

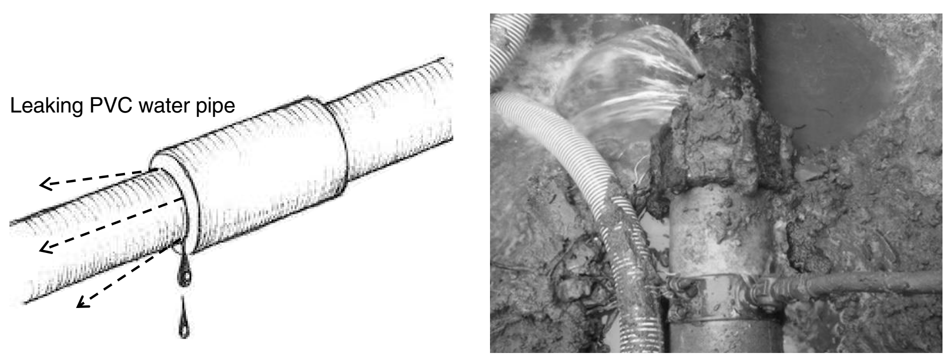
From the results of this research, it is possible to assert that a main cause of external abrasion in pipes could be associated with either leaky joints or defects in couplings between household fittings and pipe mains that were not properly installed during the construction of networks. Therefore, leaks are eventually generated due to the pressure of the water flow inside those pipes (Fig. 1). The water jets discharged at high pressure rates move through the granular material of the soil that covers the pipe and produces swirls that erode the surface of the pipes until the walls end up breaking.

Therefore, the aim of this research is to analyze how external abrasion causes this type of drilling in pipes of water distribution networks (WDNs) through several experimental tests. It also seeks to describe this phenomenon and identify differences in results from the variation of input conditions. To achieve this, a laboratory model was built in the Hydraulic Laboratory of the Universidad de los Andes (Bogotá, Colombia), where the conditions of buried pipes in situ were reproduced. Multiple experiments were performed varying the initial conditions, such as material, pipe sizes, and water pressure. It is important to mention that the only limitation of the simulation was that the model could not be pressurized internally as in a real-life system. However, this does not mean that the results are not accurate, but this fact should not be taken into account when interpreting the findings.

Model Description

The laboratory model seen in Fig. 2 was made up of a tank built with 6.5-mm-thick steel sheets. The dimensions of the tank were 0.7 m wide, 0.75 m high, and 2.5 m long. Initially, the top of the tank was uncovered so the tested pipes and granular material (local soil sample) could be introduced. Soil conditions were exactly the same for all tests, and three lifts of 0.15 m each were used. Compaction was done manually using a single-direction plate, and soil humidity was 10%–14%. Afterwards, a top cover of the same steel material and thickness was built to maintain the internal pressure on the soil and isolate the internal conditions from the outside. To ensure that the soil would be pressurized, a total of 30 screws were used to secure the lid to the tank.

Two steel cover plates 0.3 m wide and 0.4 m high were installed on both the front and back part of the tank. The front cover was built with two types of openings where the test and water supply pipes were placed. The latter was connected on one end to the laboratory water supply system through a series of 76.2-mm (3-in.) galvanized steel pipes using a male threaded adapter [Fig. 3(a)] and from the other end (inside the tank) to a new steel accessory built to allow the simulation of leakage. This was made by designing the accessory with a shape that guaranteed a transition from a circular cross-sectional area of the water supply pipe to a rectangular cross-sectional area that simulated a thin jet of a leaky coupling (2.3×40.9 mm). To guarantee a smooth transition of the water flow without generating a water impact, a 45° short nipple was used. This angle was determined as being suitable for avoiding an abrupt change in water direction and for not increasing the horizontal distance of the contact zone between the test pipe and the



(a) (b)

Fig. 1. (a) Example of potential leaks in a pipe; and (b) how it looks in a real situation.

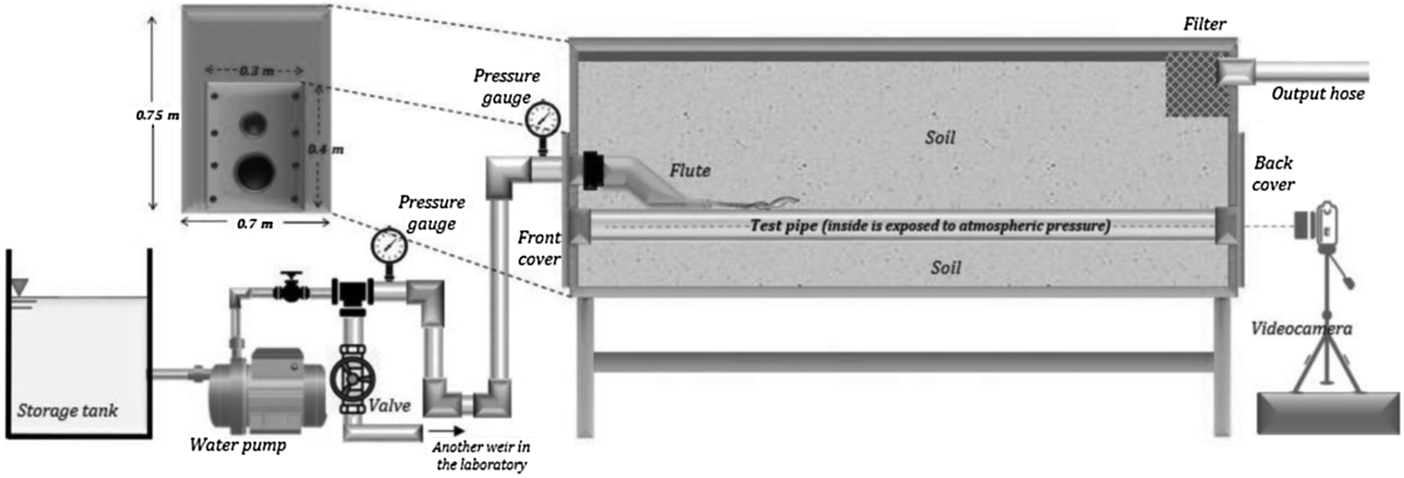


Fig. 2. Experimental setup for testing external abrasion (side view).

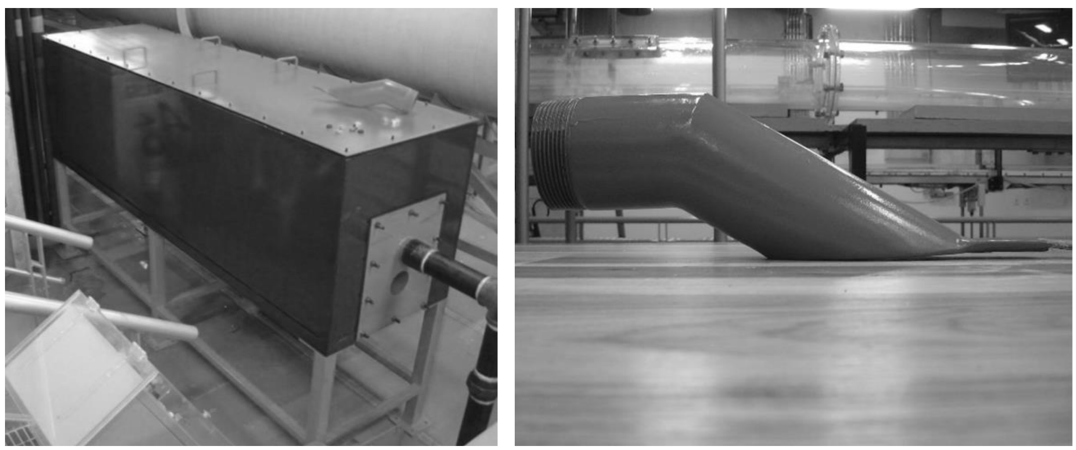


Fig. 3. (a) Experimental setup for testing external abrasion; and (b) lateral view of flute.

simulated leak at the joint. For the purposes of this study, this accessory will be referred to as the *flute* [Fig. 3(b)].

On the other hand, the back cover had only one type of opening to hold the other end of the test pipe. Thus, both ends of each test pipe were exposed to atmospheric conditions and could be monitored from either opening by a video camera.

Because the experiment considered different test pipes with distinct diameters and materials, several side covers were built with the corresponding male unions so the pipes would be held properly in place. The vertical distance between the opening of the test pipe and the one coming from the water supply pipe also varied to ensure that, despite the changes in the diameter and thickness of the test pipes, the nozzle of the flute would always be parallel and sufficiently close to the wall of the pipe [Fig. 4(a)].

Additionally, the design included another 76.2-mm (3-in.) opening in the upper right side of the tank to allow the connection of a hose to remove the excess water from the saturated soil of the model. To avoid significant losses of sand particles through the hose, a filter made with mesh and gravel was placed right before the output opening to retain as much soil material as possible [Fig. 4(b)]. This connection ended in one of the weirs of the laboratory, where the water returned to the supply system.

It is important to mention that to regulate the water pressure entering the tank, a pump was connected to the galvanized steel pipes at the beginning of the assembly and a valve was used to control the water flow required for each test. When it was completely closed, the water was transported toward another weir of the laboratory, but as it was gradually opened, the water flowed toward the model with the desired pressure. Thus, the input conditions were achieved without exceeding the capacity of the pump.

Instrumentation consisted of two pressure gauges [electronic Kobold MAN-LD (KOBOLD Messring GmbH, Hofheim, Germany) [range 0–100 kPa (0–1 bar)], accuracy $\pm 0.1\%$) and a bourdon gauge [range 0–1.1 MPa (0–160 psi)], accuracy $\pm 1\%$)], a video camera, and an ultrasonic micrometer. The first pressure gauge was placed right before the entrance of the model to obtain the water pressure at the output of the flute. However, to increase the reliability of the data, the second gauge was placed a few millimeters after the valve, close to the pump. During the tests, it was found that both measures were quite similar as water flow was relatively small and head losses were negligible. Hence, only readings of the electronic gauge were reported as results.

The video camera was used to continuously record the interior of the test pipes to observe the exact moment when the failure

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(a) (b)

Fig. 4. (a) Flute placed for pipe test; and (b) gravel filter to avoid sediment loss through output pipe.

occurred in each test pipe. This helped to keep exact track of the time in order to stablish the duration of the tests from the beginning until each pipe failed. Finally, the ultrasonic micrometer (The Woodlands, Texas) Check-Line TI-007 (range 0.15–25.4 mm, accuracy $\pm$ 0.001 mm) was used to measure only the thickness of the PVC pipes in the damaged area. The micrometer uses a sensor that emits electronic signals to the material and then records the time it takes the signal to return. A digital device receives the readings and associates the reduction of wall thickness in terms of a variable such as the function of the wave velocity moving through the material tested.

Tests

A total of 13 tests were carried out using pipes with diameters of 101.6, 152.4, and 203.2 mm (4, 6, and 8 in., respectively) and made of different materials such as PVC (with biaxially oriented particles), polyethylene, and ductile iron. These pipe properties were selected because they are commonly used for local WDNs and couplings in household connections, in accordance with local regulations. The values for the input parameters for each test are presented in Table 1.

Taking into account the real conditions of a WDN, test pressures ranged between 50 and 200 kPa [5.8 and 20.4 m of water gauge (mH2O)] depending on the material and diameter of the pipe. For trials with polyethylene and PVC pipes, pressure values of 50, 90, and 120 kPa were initially considered, while for ductile iron pipes, 150 and 200 kPa were used. At the beginning of each test, the pressure was first verified with both manometers in order to choose the right value for each type of pipe. Because polyethylene and PVC pipes with the largest diameter [203.2 mm (8 in.)] have greater wall thicknesses, higher test pressures had to be considered using values of 150 and 200 kPa. Therefore, realistic conditions were intended to be simulated by ensuring that the pressures were not over- or underestimated for each type of test pipe.

As for the soil environment surrounding the test pipe, a sample with properties similar to those of the infill soil commonly used in local interventions once pipes are installed was used. According to the Unified Soil Classification System (USCS), the test soil was well-graded sand with gravel (SW).

The sample was uneven and very well graded, containing sand particles of a wide range of sizes and a smaller portion of gravel and silty material, as can be seen in the soil gradation curve in Fig. 5. The coefficient of uniformity (Cu) was 8.78 and curvature coefficient (Cc) was 0.524.

The assembly consisted of installing the 2.5-m test pipes in the tank with their corresponding fittings and alternating both side covers whenever the diameter of the selected pipes changed. Some pipes had bell-and-spigot (rubber rings) ends, while others did not, so it was necessary to use either dresser couplings or a hermetic seal with neoprene on a smaller opening. After verifying that the test pipes were properly placed and secured, the soil sample was added and compacted using methods of compaction commonly seen in field labor. However, neither power tools nor international

Table 1. Values of input parameters for external abrasion tests

Test number	Material	Thickness (mm)	Nominal diameter (in.)	Nominal diameter (mm)	Test pressure (kPa)	Test pressure (mH_2O)
1	PVC	2.75	4	101.6	92	9.4
2	PVC	2.75	4	101.6	117	11.9
3	PVC	2.75	4	101.6	57	5.8
4	PVC	2.75	4	101.6	57	5.8
5	PVC	4.12	6	152.4	117	11.9
6	PVC	4.12	6	152.4	92	9.4
7	Ductile iron	9.97	6	152.4	200	20.4
8	Ductile iron	9.97	6	152.4	155	15.8
9	PVC	5.49	8	203.2	155	15.8
10	PVC	5.49	8	203.2	117	11.9
11	Polyethylene	11.95	8	203.2	155	15.8
12	Polyethylene	11.95	8	203.2	200	20.4
13	Ductile iron	9.97	6	152.4	155	15.8

Fig. 5. Soil gradation curve of sample used in model.

Fig. 6. (a) Soil compaction method; and (b) soil medium progressively compacted.

standards, such as the Proctor compaction test, were used. Fig. 6(a) shows how the compaction was done using handmade tools and nonstandardized regulations until the tank was completely filled with the soil material [Fig. 6(b)], and then the upper cover was placed and hermetically sealed. Then the electronic gauge was installed, the pump turned on, and the valve opened to the desired pressure. Finally, the video camera was located to the side of the tank to record the inner part of the test pipe.

The tests were then developed until each pipe failed, i.e., the moment cracks appeared on the top surface of the pipe near the jet impact zone; this was determined by using the video camera recordings to detect the exact time at which water and soil started to enter the test pipe. These time measurements were different for each tested pipe. Because of the cracks, a soil fluidization phenomenon occurred and water with sediment particles started passing through the hole. Right after this, the pump was turned off so both the water flow and video recording stopped, then each test pipe was internally disassembled. The soil sample was removed without affecting the pipe walls, and pictures of the results obtained were taken. Finally, the tested pipe was uninstalled to measure and analyze the dimensions of the failure before moving to the next test pipe.

Two types of scouring damage were observed through all the tests, such as holes caused by the piercing of the pipes and a damaged area surrounding it. Failure measurements of both the width and length of the hole and the damaged area were registered using an electronic caliper [Fig. 7(a)]. Fig. 7(b) shows the typical shape seen in most of the failures of tested pipes, although each pipe presented slight changes in the areas affected by the wear. For PVC pipes, the wall thickness in the damaged area was also measured using the ultrasonic micrometer. Finally, an additional granulometric analysis of soil was carried out when a significant amount of soil material got inside the tested pipes.

Results and Analysis

The results obtained from each test showed that failures were inevitable regardless of the surface material of the tested pipe, caused by the interaction of many input variables such as pressure, test time until failure, diameter, and wall thickness. All tested pipes presented scouring damage due to the impact of the simulated leakage jet and scouring of soil particles against the pipe. The deterioration process started with the weariness of the walls of the pipes caused

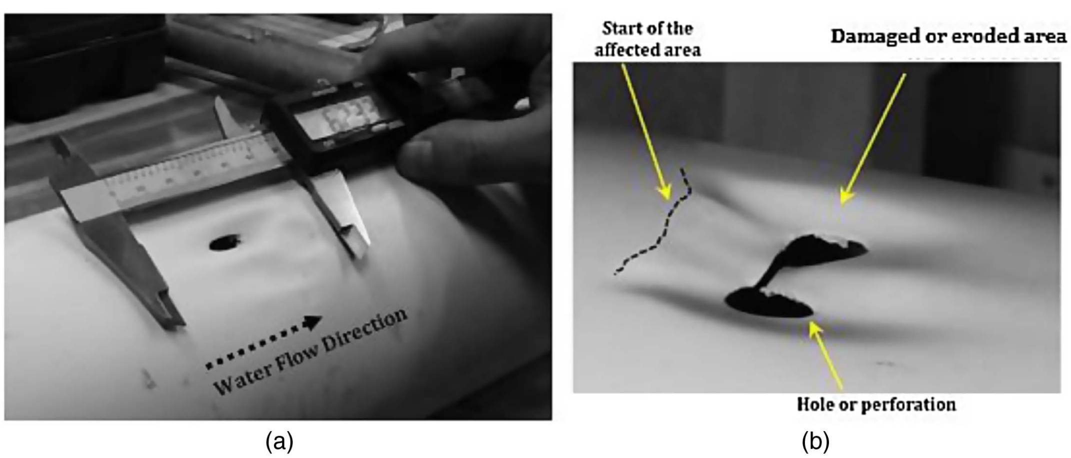

Fig. 7. (a) Failure measurements of PVC tested pipe; and (b) characteristics of scour damage seen.

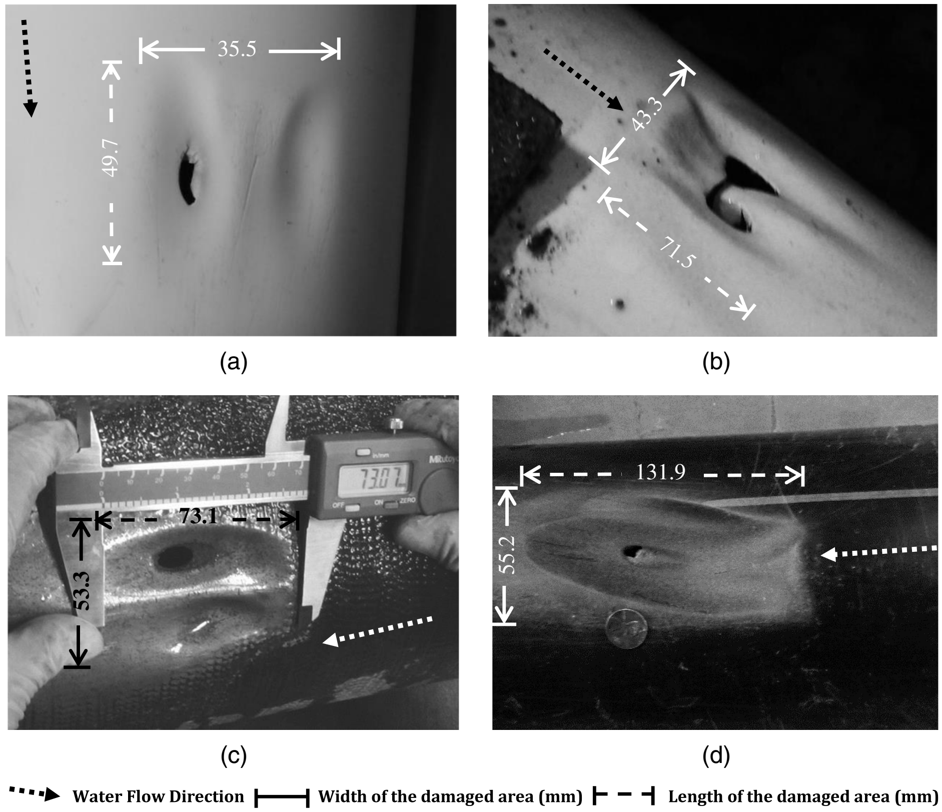

Fig. 8. Worn areas of different tested pipes.

by the water pressure coming out of the flute at a constant abrasion rate. In general, the behavior of the failures was very similar among tests, while there were differences in the size and location of the perforations.

Usually damage began close to the outlet of the flute and developed several centimeters downstream. The affected areas showed well-defined elongated shapes that tended to be oval and extended mainly in the direction in which the water jet was ejected. As seen before, some pipe tests (Tests 2, 4, 5, and 7) showed two valleys with a crest in the middle that had greater wall thickness, while in the other tests a single valley was formed. This damaged shape followed no detectable trend. For example, comparing results in Fig. 8, it can be seen that perforations did not always appear when two valleys were formed, and holes that would go through both valleys occurred even less frequently. There were two tests (Tests 3 and 8) where no perforations occurred, so they were repeated using the same input conditions, and on the second attempt the perforation indeed appeared.

Furthermore, it is noteworthy that, in the case of ductile iron pipes, not only abrasion problems were recorded but also corrosion. This happened because the movement of the particles removed the protective coating of the pipes; therefore, water could come into contact with the metal wall and oxidation occurred.

Likewise, from the results obtained for the 13 tests, it is important to highlight the correlation between input and output variables. For example, the pipe resistance is clearly affected by the relation between the initial parameters of pipe size and wall thickness. If only failure time is analyzed, it can be seen in Fig. 9 that Test 10 lasted 2 h more than Test 5 and almost 4 h more than the second test because of the larger diameter and thickness.

On the other hand, the pipe material also presented some differences in the results, as seen in Table 2, as ductile iron and polyethylene had a performance far superior to that of PVC. Whenever the latter was tested, the results were always worse than with the other materials, even at lower pressures. Knowing that test pressure is a major factor in determining the duration of a test, and considering that it is an inversely proportional relationship, the time differences ranged between 40 and 150 h under equal input conditions. Another correlation can be noted in the time from pipe failure and the end of the test; this time is proportional to the size of the holes and, to a lesser extent, to the damaged area. In this table, width refers to the dimension perpendicular to the flow (across the pipe) and the length corresponds to that dimension parallel to the flow (along the pipe). This notation also applies to soil subsidence; however, in subsidence there is another dimension, depth, which is measured vertically.

It can be also noticed that pressure affects considerably the sizes of the perforations, damaged area, and soil subsidence. As shown in the following table, for all test pipes of the same size, the dimensions of the perforations and damaged areas were larger as the pressure increased. On the other hand, for PVC pipes at the same water pressure, the dimensions of the perforations and damaged areas are smaller for larger pipe diameters evidencing a higher resistance of the material. In all cases, the dimensions of the soil subsidence depended mostly on the water pressure (at higher pressure, bigger dimensions) and the test duration. At lower pressures the tests were longer, which means more time for the water jet to impact the soil and increase the damage dimensions.

The uncertainty in the results is not negligible since there is significant variability in the data between tests, and some exceptions were noticed. This means that results might have errors that must be taken into account in the analysis and conclusions about the test. The main factors inducing this phenomenon could be related to randomness in the process of soil compaction or in the exact

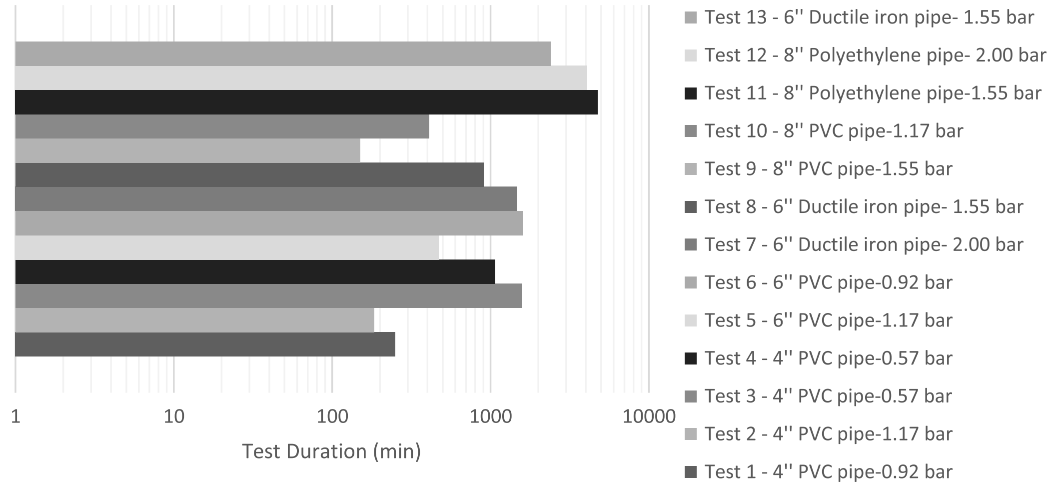

Fig. 9. Test duration for every test made.

Table 2. Overall results of tests

Test No.	Material	Diameter (mm)	Test pressure [kPa (bar)]	Test duration	Dimensions of perforation: Width (mm)	Dimensions of perforation: Length (mm)	Dimensions of damaged area: Width (mm)	Dimensions of damaged area: Length (mm)	Dimensions of soil subsidence: Width (cm)	Dimensions of soil subsidence: Length (cm)	Depth (cm)	Time since pipe failed until test is stopped	Weight of soil material inside pipe (g)
1	PVC	101.6	92 (0.92)	4 h 10 min	5.26	12.79	38.74	62.33	N/A	N/A	N/A	N/A	N/A
2	PVC	101.6	117 (1.17)	3 h 4 min	7.40	20.90	45.80	66.29	53	70	11	11 min	9,200
3	PVC	101.6	57 (0.57)	26 h 22 min	N/A	N/A	42.08	49.20	34	47	4	N/A	N/A
4	PVC	101.6	57 (0.57)	17 h 44 min	4.66	10.03	35.51	49.73	32	34	2	1 h 9 min	N/A
5	PVC	152.4	117 (1.17)	7 h 51 min	9.3 7.9	14.5 15.9	43.37	71.5	61	83	14	1 h 49 min	20,981
6	PVC	152.4	92 (0.92)	26 h 38 min	3.34	8.48	44.11	62.42	43	62	9	4 min	N/A
7	Ductile iron	152.4	200 (2.00)	24 h 32 min	7.87	13.89	53.29	73.07	70	92	20	13 min	17,340
8	Ductile iron	152.4	155 (1.55)	150 h	N/A	N/A	57.2	92.75	70	96	19	N/A	N/A
9	PVC	203.2	155 (1.55)	2 h 30 min	4.33	22.87	23.11	95.11	50	94	10	30 min	7,035
10	PVC	203.2	117 (1.17)	6 h 50 min	4.71	14.65	43.49	86.86	54	85	9	5 min	N/A
11	Polyethylene	203.2	155 (1.55)	79 h 5 min	5.79	8.93	55.22	131.87	65	95	34	20 min	7,980
12	Polyethylene	203.2	200 (2.00)	69 h 40 min	6.82	7.04	41.2 53.2	153.11	70	143	20	34 min	N/A
13	Ductile iron	152.4	155 (1.55)	39 h 48 min	10.07	21.47	33.33	107.44	70	122	23	29 min	4,689

position of the flute. Despite these factors, from a global perspective, the results of this research are precise in showing how external abrasion occurs in drinking water pipes.

Another aspect to discuss is soil fluidization, which affects the soil arrangement and destabilizes the surrounding environment (Fig. 10). At first, an assumption was made that the bore in the soil surface was formed because the tank was not completely filled. However, after several trials it was observed that the water jet affected the structure of the granular material owing to soil fluidization.

A significant amount of studies have been carried out on this topic, but the most relevant one for this research is the one by van Zyl et al. (2013). This research aimed to understand the effects of leaks (through orifices) in a water distribution pipe in the surrounding soil throughout several tests (van Zyl et al. 2013). During this process, the finest particles were washed out, and as time passed only material of larger particle size was found near the nozzle area. Granulometric analysis was conducted on the soil material that entered the test pipes through holes, assuming that it corresponded to the same type of sample as the one in the tank that remained near the nozzle of the flute. Indeed, Fig. 11 shows that the samples collected from each test had particles with sizes (on average) larger than in the original mixture.

The results presented in this research offer information that can be used as a guide on how pipeline failures are generated due to

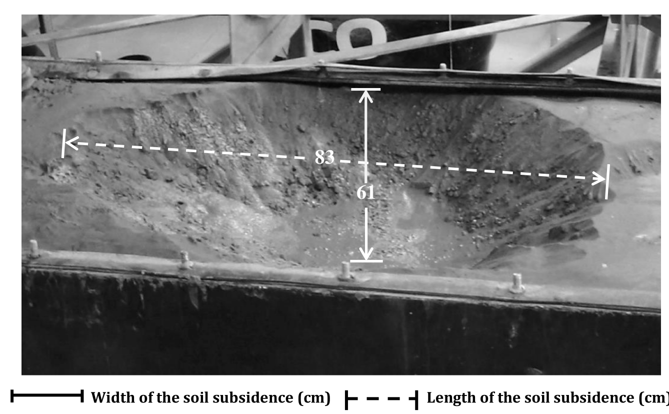

Fig. 10. View of land subsidence in Test 5.

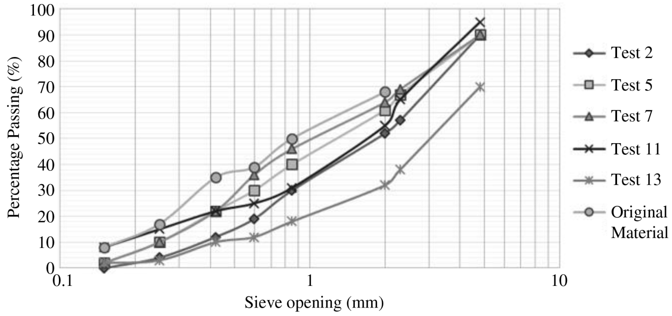

Fig. 11. Granulometric curves of material found in inner part of pipe at end of test and original mixture.

Fig. 12. External abrasion real case.

external abrasion in the laboratory. Nonetheless, it is essential to take into account the differences between the conditions used in this research and what happens in a real-life scenario. In the latter, the breakdown of pipes could be principally caused by the internal pressure of the water flow rather than the wear-off of the surface as leaks appear. This is a consequence of reducing the thickness of the pipe wall, which eventually will not be able to withstand the forces generated by water and will fail in a rather dramatic way.

Finally, a real external abrasion case is shown in Fig. 12 that exhibits erosion characteristics very similar to what was found in laboratory tests. In this case, the pipeline was a GRP Pipe 2200 that was 272 mm in diameter with a wall thickness of 29 mm. The external abrasion was caused by Movement 273 of the O-ring seal under a pressure of 20 bar.

Conclusions

Owing to the deterioration and failure of pipes in WDNs and sewage systems, rehabilitation and maintenance activities are becoming a very important concern for water utilities. The study and analysis of the causes and effects of certain damage to water pipes must be taken into account in the definition of technical specifications that influence the design and operation of water systems. Abrasion is a widely studied phenomenon, since both the inner and outer walls of pipes can undergo continual damage by external factors until leaks or breakages occur.

This research aimed to analyze the impact of external abrasion when leaks appear in the joints of water pipes and interact with the surrounding soil. A laboratory model was built to simulate the conditions of an underground pipe with a leaky joint. A total of 13 tests were carried out in the laboratory using a setup where pipes made of different materials and having different diameters were installed under a soil sample that was selected according to local characteristics. Realistic soil compaction techniques were applied manually, and both flow and pressure conditions were controlled for each test. Pipe failures occurred after a range of 20–100 h depending on the tested pipe.

The results indicated that all pipes in a WDN are vulnerable to the effects of external abrasion. Leaks in joints or domestic connections can produce scouring damage in the outer walls of a pipe due to the combination of the force of water jets coming out of the pressurized pipe and the swirls of particles of the surrounding soil. The thin water jets wash the finest particles away, leaving the larger ones to scour the surface. Once leakage appears, the damaged area will start to grow, and it is just a matter of time before not only the pipe fails but also soil fluidization begins to interfere. It was noticed that as the tests proceeded, a bore appeared in the surrounding soil caused by the impact of the water jets in the soil arrangement and some soil particles going were lost through leaks. In real situations, soil fluidization could affect the pavement structure of a street above the WDN and cause damage to other urban infrastructures. Metal surfaces suffer not only external abrasion but also oxidation, which can accelerate damage in pipes; in addition, the oxidation may exacerbate sanitation and environmental issues with water quality.

Since the model configuration presented in this research was established for understanding the external abrasion phenomenon in pipes of WDNs, the results obtained are tied to the input parameters and experimental approach of creating an additional accessory for simulating the jet of a leaky joint. Therefore, it must not be assumed that the performance of the pipe failures shown here are the same as in reality. While the limited conditions in the laboratory can only reproduce progressive failures, in real cases the walls of pipes cannot resist the high internal pressure of flow trying to be ejected through a small orifice, and quick interventions must be implemented. If more accurate real-world leakage performance needs to be represented in a future study on external abrasion, it is highly recommended to improve the approach of the experimental setup. This could be done by including other variables, such as water flow through a pipe under pressurized conditions, or adding defective connections to create real leaks of various sizes.

Water utilities may use these results as a guide to improve the techniques and quality of connections of pipe fittings, rather than criteria for selecting the piping material during the design of water networks. This research showed how leakages have a significant influence on the condition of water pipelines, as the phenomenon of external abrasion can wear the walls of pipes until failure. This is an important issue that should be tracked and addressed by water utilities considering that most leakages of this type are usually hidden underground until serious impacts emerge. Water service can be affected and then an immediate and more complex rehabilitation process will be required. Therefore, this analysis might help prevent situations related to breakages in pipes that would require costly rehabilitation activities before the end of their operational life.

Finally, it is important to carry out tests using different pipe materials of varying thickness, diameter, pressure, and, perhaps, soil gradations and compactions. This could lead practitioners to choose pipe junction systems and seals that perform best in those different scenarios.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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