Testbed Hardware Design to Collect Data for Underground PVC Water Pipe Crack Detection: Challenges and Solutions

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ABSTRACT

A premature crack is a significant indicator for early failure detection for underground polyvinyl chloride (PVC) water pipes. Using an array of strain gauges mounted on a pipe surface to monitor the strain of adjacent areas of a premature crack is a novel technology that has not been explored. To reduce the risks and up-front investments, we need a testbed to investigate, verify, and validate the innovative technology. However, establishing such a pipe monitoring testbed that covers completely realistic underground situations is challenging. The main reason lies in three main challenges: (i) mimicking the natural changes of water flowing in pipes; (ii) identifying the proper placement of strain gauges and detectable crack sizes; (iii) simulating the crucial underground conditions such as temperature and external stress. To this end, in this paper, we present a testbed to get more insights into the effects of different crack types on the pressure-strain characteristic in realistic conditions. In particular, we use pressure meters and water pumps to control the water flow (for challenge (i)); deploy various strain gauges types and induce cracks with different sizes (for challenge (ii)); fill the pipe with water at various temperatures and underground-like external stress (for challenge (iii)); Analyzing experimental results reveals useful hints for designing a realistic testbed, including but not limited to, the required distance among strain gauges, the influence of temperature and pipe axial stress. The dataset and analytic results of this work would provide more insights into how to design a realistic testbed for underground PVC water pipe crack detection.

CCS CONCEPTS

• **Hardware** → *Sensors and actuators*; *Sensor applications and deployments.*

KEYWORDS

Pipe crack, testbed , strain gauge, pressure strain characteristic

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1 INTRODUCTION

Cracking is one of the main failure types of PVC water pipes. It makes up for more than 60% failures at a pipe wall [1]. Not only do cracks pose a serious threat to the operation of the pipeline, they also introduce repair costs. Therefore, it is necessary to detect a premature crack, a crack in its developing state. This premature crack is shallower than the pipe wall thickness, and has not become a leak yet. Commonly initiated by material impurities or an excessive external point load, the premature crack gradually elongates in the axial direction before suddenly propagating at sound speed to become a long break [5]. The premature crack is one of the critical factors to PVC pipe health [11]. For that the pipe with premature cracks should be replaced as soon as possible to prevent a large break that might lead to severe consequences such as damage to infrastructures, traffic jams, and water losses.

Premature crack detection for water pipes is conducted in [6, 12]. In [6], PZT bonded on a PVC pipe wall induced acoustic waves to detect a circumferential crack. Another approach used an optical fiber to detect a crack as in [12]. The cable must be wrapped around the pipe to measure change in the hoop strain to internal pressure. To the best of our knowledge, strain gauges have not been used to detect cracks in the PVC pipelines.

To this end, we propose a smart sensing system which can detect a premature crack using strain gauges. Figure 1 illustrates an overview of our proposed smart sensing system, which comprises these blocks: sensing, data processing, communication and power supply. Inspired by work described in [7, 12], we replace the optical fiber with strain gauges (SGs) integrated directly on the PVC pipe surface. These SGs connect to a data acquisition and processing

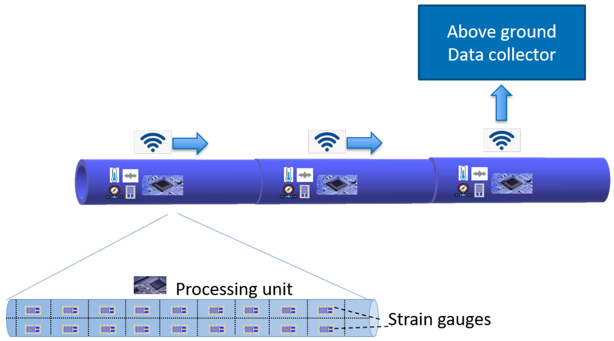


Figure 1: A system of smart-pipes using strain gauges.

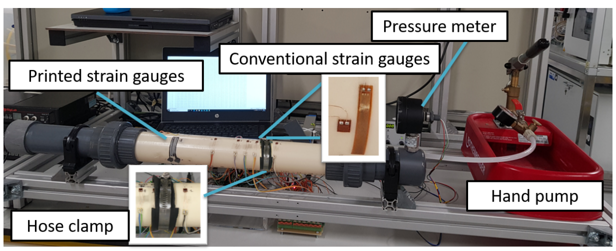


Figure 2: The experimental setup overview

unit to identify the crack's existence. Each pipe operates independently with a battery supply or energy harvesting unit. In addition, wireless communication modules will be integrated with the pipes to transfer the processed information to an above-ground data centre. Finally, the sensors and electronic devices are envisioned to be protected by a cover layer in manufacturing so that the pipes can be installed with a similar process as conventional pipes.

While other components such as data processing, communication, and power supply are also essential to study, this paper focuses on obtaining reliable measurements of the SGs. Because conducting crack detection research on real buried pipes is time-consuming and complicated to control, a test-bed mimics the pipe defects and underground conditions can minimise such problems. However, building a testbed covering all underground conditions is unrealistic.

Therefore, this paper identifies the challenges and proposes solutions for a feasible testbed. First, we determine the signal required for the crack detection - the pressure-strain characteristic (PSC). Then, we identify the challenges in collecting the signal as well as additional influencing factors to that signal in practice. To address the challenges, we first theoretically analyze the contribution of each factor to the signals. Then, we set up experiments to investigate the contributions of the factors that existing theoretical results can not address. Finally, we discard the elements that have minimal effect on the PSC. The final result reveals useful hints for designing a realistic testbed, including the required sensors and their quantity, and the effect of significant factors that need to be mimicked.

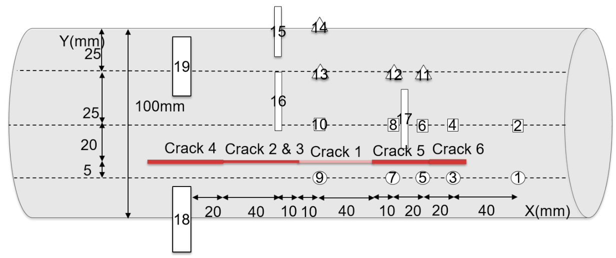


Figure 3: Schematics of strain gauges and cracks

2 CHALLENGES AND SOLUTIONS

This section introduces the challenges and solutions in establishing a testbed that uses SGs to detect a premature crack on PVC water pipes. As in [12], the crack changes the local hoop strain induced by internal water pressure. As a result, these changes affect the PSC, which is the linear correlation between the strain and the internal pressure in the normal operating pressure range of a water pipeline system. Therefore, the testbed challenges are around reliably acquiring the change of PSC caused by a crack and mimicking the other factors that most affect the PSC.

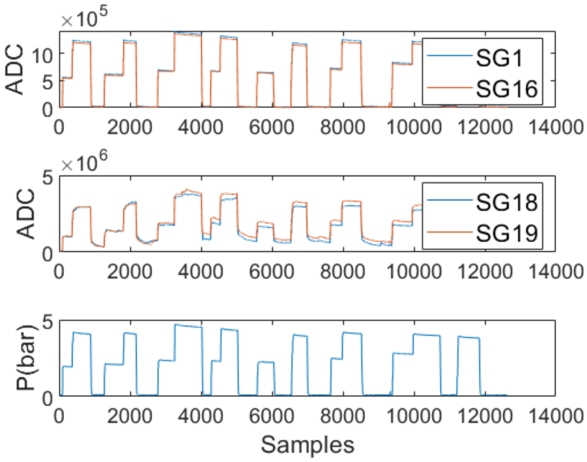
Constructing the PSC requires a variable water pressure source. Therefore, the first challenge is mimicking the practical pressure variation influenced by the water flow and pressure source. Because a typical pipe length of a horizontal pipe section is 10m, pressure differences due to water flow on this length are negligible. Furthermore, the daily pressure slowly varies from 1 to 5 bars [10]. Therefore, we can consider the pressure is homogeneous in space and constant for a short duration. As a result, the testbed requires only controllable static pressures in the practical pressure range. A pump connected to a sealed pipe through a check valve can simulate the pressure regime.

The second challenge is determining the desired crack size and setup SGs for sensing it. From an internal failure report of a water utility where the premature crack length is less than 280mm, we focused on the crack less than 200mm in length with different depths. Then, we conducted experiments in Section 3 to investigate the influence of a crack on its adjacent area.From the result in Section 4, we propose a proper SG setting to detect each crack type.

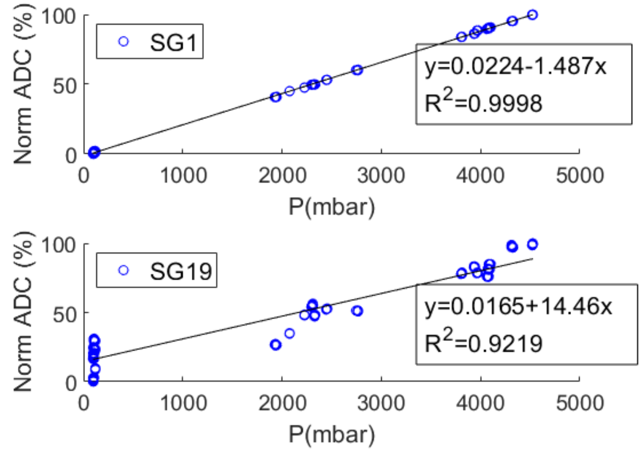
The underground medium has an effect, by the soil load and temperature, which can influence the crack detection result. Temperature affects strain gauge sensitivity and the pipe strain[9]. Soil load induces extra stress on the pipe wall. Particularly, a 30-ton live load or a 30-day rain can exert extra stress of 300 kPa on a buried pipe wall [2, 3] while the soil subsidence itself can exert a few MPa stress [4]. To study the effect of these elements on the PSC, we conduct experiments of Section 3. Then, we compare their impact with the crack to determine the crucial elements to be simulated.

3 EXPERIMENT

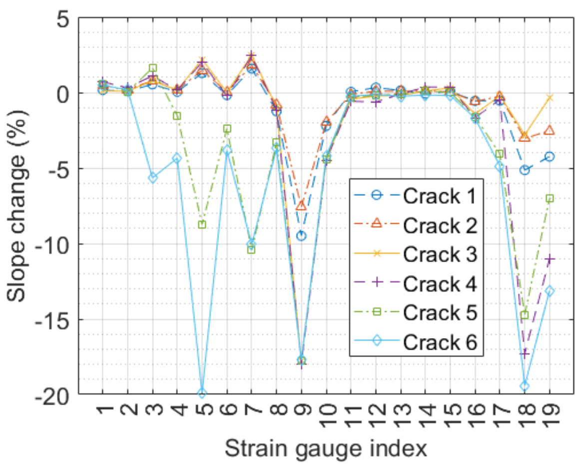
We conducted experiments to investigate the effect of a crack, temperature and external stress on the PSC on a 63mm diameter, 2.3mm thickness PVC water pipe as shown in Figure 2. The pipe temperature was controlled by filling it with water at 23^{o}C, 30^{o}C and 15^{o}C. A hand pump controlled the internal pressure at three levels:



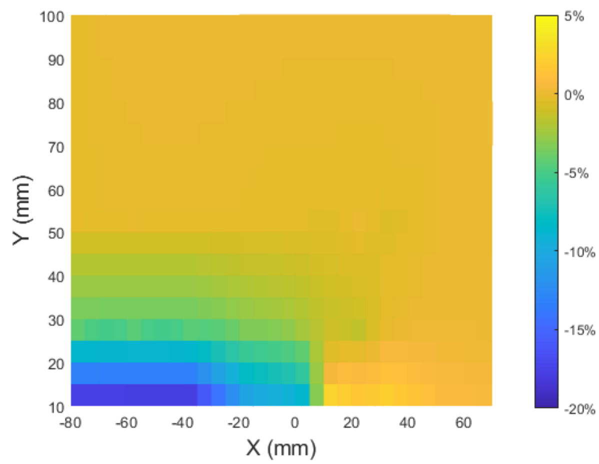
(a) Raw ADC readings



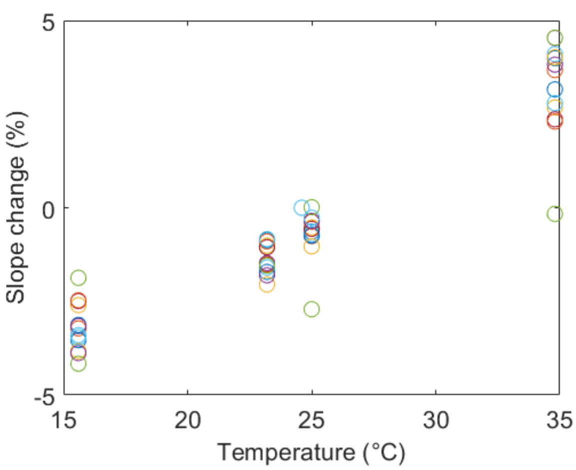
(b) Pressure strain characteristics



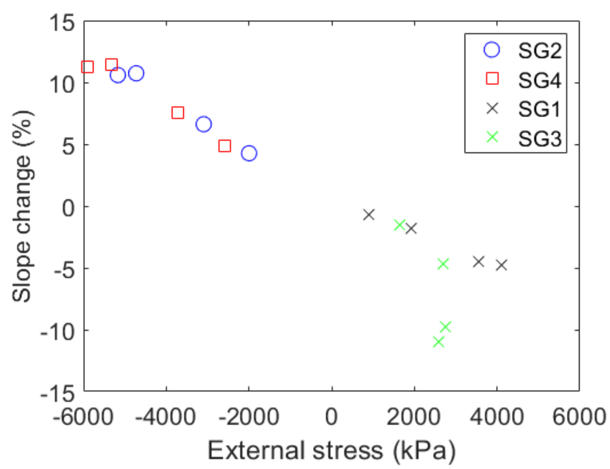
(c) PSC slopes changed by the cracks



(d) Influence area of a deep crack



(e) PSC slope changed by temperature



(f) PSC slope changed by external stress

Figure 4: The experimental results. In Figure (d), X and Y are the distances to the crack in axial and circumferential direction. The negative X is the locations enclosed by the crack tips, whereas positive X is outside of the crack

0 bar, 2 to 3 bars, and 4 to 5 bars. They were measured by a digital pressure meter. For the external stress, it was controlled by a hose clamp with four stress levels by adjusting the screw.

On the pipe, the small conventional SGs (4x3mm) were the main ones for investigating the crack influence. They were installed at locations from 1 to 14 in Figure 3 organized in 4 rows with more density at the close area to the crack. The row containing SG 1 is next to the crack, while the SGs 2, 11 and 14 are at one-eighth, one-quarter and one-half pipe perimeter away from the crack in the circumferential direction. In addition to the small SG type, we also tested the long type (4x32mm) and on-pipe printed ones (16x35mm). The former, marked as 15, 16 and 17, was to figure out whether a point or area of strain can sense better. The latter, marked as 18 and 19, were to test for an opportunity of printing SGs directly on the pipe wall in manufacturing. Each SG was connected to a Wheatstone bridge. Then, an HX711 chip amplified the voltage of the Wheatstone bridge by 128 (for the conventional SGs) or 64 (for the printed ones) times, and converted to 24-bit digital data at a 10 Hz rate. An Arduino MEGA 2560 read all analogue to digital (ADC) outputs concurrently from nineteen HX711 chips and sends it to a computer.

Six cracks with size increasing gradually from short to long, shallow to deep were created as the order in Figure 3. First, shallow crack 1 with 50mm length and one-third wall thickness in depth was created. Then, it advanced 50mm to the left as crack 2 to test the impact of the shallow crack's length. Then the crack was deeper to crack 3 to test the influence of crack depth. Next, the deep crack was elongated to the left as crack 4 to test the printed SGs and the effect of the deep crack's length. Finally, the deep crack was elongated to the right as cracks 5 and 6 to get more information about points enclosed by the crack tips in the axial direction.

4 RESULTS AND DISCUSSION

First, we can see that the conventional types have the same response to water pressure in Figure 4a. Their PSCs, which was reconstructed from 2390 samples at twelve stable pressure values, is linear with a small variation in Figure 4b. The linear result match with theory in [8]. As cracks were introduced, the slopes of these lines changed, as illustrated in Figure 4c. A slope decrease of more than 2% can be seen at the SGs 9 and 10. Based on the small SG data, we constructed the crack influencing area illustrated in Figure 4d. In that, the crack-sensitive area, where the slope changes more than 2%, is enclosed inside the crack tips and one-eighth pipe perimeter, respectively, in X and Y directions. Therefore, the distance between SGs should equal the desired crack length in the X direction and a quarter of the pipe perimeter in the Y direction.

Regarding the crack size, its length does not influence the slope as there is no change of all conventional SGs between cracks 1 and 2 or between cracks 3 and 4 in Figure 4c . However, the crack depth significant changes the adjacent slopes, as in SGs 9 and 10 when crack 2 is deeper to crack 3. Therefore, for a testbed, we can pre-define a desired crack length from 50-200mm before setting the strain gauges.

Regarding the size, the small SGs are more sensitive to the cracks than the longer ones when we compare the outcomes SGs 16 with 13, and 15 with 8 in Figure 4c. It is because the change of a long SG are the average changes of small locations in the Y direction. For the printed ones, though they also respond to the pressure change as in Figure 4a, they possess long transient and highly drifting offsets when returning from high pressure, which might come from the material brittleness and makes them become unstable. The drifting offsets result in the high variation of their PSCs slope in Figure 4b and 4bc. However, they are still able to sense the crack with higher sensitivity than the conventional longer ones when comparing SG 18 and 19 to SG 16 and 17 at crack 4 because the printed ones have the same length but are wider 4 to 5 times than the conventional long ones.

The maximum temperature effect to the PSC slope is about 0.4 %/1^{o}C as shown in Figure 4e. Therefore, a typical temperature sensor with a precision of 1^{o}C can be used to compensate for the temperature influence on the PSC.

The change of slope corresponding to external hoop stress is illustrated in Figure 4f. Refer to [3] and [2], the shear stress varied by the moister from dry to saturate and a load of typical bed fill are less than 300kPa. Applying this value to Figure 4f results in the change of slope being less than 1%, which is negligible. However, the axial deformation due to soil subsidence can cause the stress to change up a few MPa, leading to a significant change of PSC slopes. Therefore, we need to monitor the axial shape to complement its influence on the PSC slope. The shape monitor can follow the result from [2], where the strain change can be the offset of PSC.

5 CONCLUSION

The paper is preliminary research investigating a testbed for detecting a crack on an underground PVC pipe. Its purpose is to explore the crucial factors of underground and pipe conditions that need to be mimicked and controlled. We have reduced the complication of an underground PVC pipe's crack detection testbed by analyzing the impacts of these factors on the PSC. First, the desired crack length should be defined and fixed from 50 to 200mm, whereas different crack depths should be considered. Then, small strain gauges are bonded on the pipe wall with spaces equal to the crack length in the axial direction and a quarter of the pipe perimeter in the circumferential direction. This setting allows the strain gauges can sense at least 2% changing in PSC caused by a shallow crack. In addition to the SGs, varied water pressure from 1 to 5 bar and a pressure meter with a resolution of 0.01 bar resolution are also required for the PSC. Regarding the underground environment, only temperature and axial pipe deformation are required. The temperature can be controlled by filling the pipe with water at desired temperatures and can be measured with a temperature sensor of 1^{o}C precision. The axial deformation can be mimicked and controlled by bending the pipe, and its deformation can be estimated based on the bending angle.

Last but not least, the on-pipe printed SGs show that they can sense the impact of the crack though there still exist limitations in durability. It can be improved by using other ductile materials and can be conducted in future research.

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REFERENCES

[1] Yasuhiro Arai, Akira Koizumi, Toyono Inakazu, Haruhiko Watanabe, and Masahiro Fujiwara. 2010. Study on failure rate analysis for water distribution pipelines. *Journal of Water Supply: Research and Technology—AQUA* 59, 6-7 (2010), 429–435.

[2] Selçuk Bildik and Mustafa Laman. 2019. Experimental investigation of soil—structure—pipe interaction. *KSCE Journal of Civil Engineering* 23, 9 (2019), 3753–3763.

[3] Mohammed Bouatia, Rafik Demagh, and Zohra Derriche. 2020. Structural behavior of pipelines buried in expansive soils under rainfall infiltration (Part I: transverse behavior). *Civil Engineering Journal* 6, 9 (2020), 1822–1838.

[4] Yahong Ding, Heng Yang, Ping Xu, Minxia Zhang, and Zhenguo Hou. 2021. Coupling Interaction of Surrounding Soil-Buried Pipeline and Additional Stress in Subsidence Soil. *Geofluids* 2021 (2021), 16.

[5] Tarek M. A. A. EL-Bagory and Maher Y. A. Younan. 2016. Crack Growth Behavior of Pipes Made From Polyvinyl Chloride Pipe Material1. *Journal of Pressure Vessel Technology* 139, 1 (08 2016).

[6] Xiaobin Hong, Xiaohui Lin, Bo Yang, and Maodong Li. 2017. Crack detection in plastic pipe using piezoelectric transducers based on nonlinear ultrasonic modulation. *Smart Materials and Structures* 26, 10 (2017), 104012.

[7] Kenneth Lim, Leslie Wong, Wing Kong Chiu, and Jayantha Kodikara. 2016. Distributed fiber optic sensors for monitoring pressure and stiffness changes in out-of-round pipes. *Structural Control and Health Monitoring* 23, 2 (2016), 303–314.

[8] F Povolo, G Schwartz, and Élida B Hermida. 1996. Stress relaxation of PVC below the yield point. *Journal of Polymer Science Part B: Polymer Physics* 34, 7 (1996), 1257–1267.

[9] T Pulngern, T Chitsamran, S Chucheepsakul, V Rosarpitak, S Patcharaphun, and N Sombatsompop. 2016. Effect of temperature on mechanical properties and creep responses for wood/PVC composites. *Construction and Building Materials* 111 (2016), 191–198.

[10] Hossein Rezaei, Bernadette Ryan, and Ivan Stoianov. 2015. Pipe failure analysis and impact of dynamic hydraulic conditions in water supply networks. *Procedia Engineering* 119 (2015), 253–262.

[11] Vinh Q. C. Tran, Duc V. Le, Doekle R. Yntema, and Paul J. M. Havinga. 2022. A Review of Inspection Methods for Continuously Monitoring PVC Drinking Water Mains. *IEEE Internet of Things Journal* 9, 16 (2022), 14336–14354.

[12] L. Wong, S. Rathnayaka, W. K. Chiu, and J. Kodikara. 2017. Fatigue Damage Monitoring of a Cast Iron Pipeline Using Distributed Optical Fibre Sensors. *Procedia Engineering* 188 (1 2017), 293–300.