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Non-Destructive *In-Situ* Condition Assessment of Plastic Pipe Using Ultrasound

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Abstract

Pipelines in potable water distribution system are a vital part of modern infrastructure, providing one of the most important services for society. This vital, complex infrastructure is endemic to our urban environments but is ageing, with current average age of around 70 years and with current replacement rates an inferred serviceable asset life of hundreds of years. Hence it is important that we develop technology that will enable pipeline condition assessment without service interruption. Due to environmental and operational stresses acting upon these pipelines, the common structural health problems include stress corrosion, thermal degradation, cracks or even leaks [1]. In particular, it has been suggested that void formation external to buried pipe wall is a crucial factor in pipe breakages due to lack of structural support [1, 2]. This paper presents the development and laboratory testing of ultrasonic non-destructive inspection technology for the condition assessment of plastic pipes, provide a measure of the structural integrity of the pipe, as well as ‘looking’ through the pipe wall to assess void formation and critical loss of support. Ultrasonic detection results are presented for grooves and cracks with two common plastic pipe materials, HDPE (High-density polyethylene) and PVC (Polyvinyl chloride) in order to simulate material loss in pipe wall. In addition, four voids in the ground external to plastics with varying shapes and dimensions were detected. Tested soils include two particle sized sands and two particle sized gravels. The study demonstrates the feasibility of developing a new technique for condition and health assessing for buried water plastic pipes

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1. Introduction

Pipeline systems buried underground are serving precious resource to our community, but is invisible from the ground surface. It was reported that pipe breakage was occurring under both environmental and operational stresses in the process of gradually losing structural integrity (circumferential breaks, longitudinal breaks, and split bell [4, 5]). Moreover, a figure of 35%-65% of the supplied water volume was wasted caused by pipe breaks [3]. Any type of pipeline failures can be extremely costly, including repair costs, disruption and associated damage [2]. Therefore the condition assessment of them cannot be a more important topic for both civil engineers and the society. It has also been widely recognized that proactive techniques are both technical and economically beneficial than reactive strategies [6]. It is advantage to assess and monitor the condition of the buried infrastructure routinely, so that proactive warning of impending failure can be achieved and thus the probability of the serious consequences of accidents of the utility network can be effectively reduced.

In the past 40 years, a new generation of low cost and high resistant polymeric pipelines, such as polyethylene pipe, has been extensively used in pressurized water distribution systems. Early surveys were usually carried out by an inspector walking or crawling through the pipe and providing visual and non-destructive defects information, i.e. CCTV for inner surface defects detection. However, when the pipelines are too small for manual inspection, i.e. potable water distribution pipelines, limited information can be obtained for engineers and water society. Therefore the working condition assessment can only be carried out by theoretical analysis or pipe sampling and destructive lab testing.

For *in situ* pipe inspection sensing technologies, camera, laser and ultrasound have been reported in application. Moraleda et al. [8] and Choi & Ryew [9] addressed the adoption of camera for inpipe inspection for water and gas pipelines individually. By producing the interior surface of the pipe wall, this inspection method was mainly and applied to sewers, storm water pipes or gas pipelines. Poor quality of the acquired images due to difficult lighting conditions was considered to be an inherent disadvantage. As a more accurate detecting method, laser scan has been developed for pipe inspection [10,11]. This profiling technique was only used in de-watered pipes. There is no document reporting the application of laser profiling on underwater application even though it produces more accurate internal image of pipe wall. Skjelvareid et al. presented a lab experiment using ultrasonic technique for internal surface imaging for a section of cast iron pipe [7]. The potential inspecting capability by this method for pipe surface imaging was investigated as well as the sensitivity of ultrasonic transducer position within the pipeline. Beller and Barbian addressed the use of a combined ultrasound technique for simultaneously metal loss quantification and cracks detecton while an array of sensors were traveling through a metal pipe by a carrier [12]. This technique was designed for gas and oil pipelines only rather than water pipes. Clearly, what has been done to date is only for gas/oil/water non-plastic pipelines. Recently, Liu and Kleiner [13], Dingus et al. [14], Makar and Chagnon [15] reviewed pipe condition assessment technologies applicable to different pipe materials. Again these techniques are not suitable for small sized plastic pipelines. Particularly, these pipe assessing techniques only focused on surface cracks and material loss detection, but nothing that looked beyond the pipe wall for surrounding condition, i.e. voids in the bedding soil. It has been suggested that the presence of voids could result in a lack of structural support and therefore break by stresses [16, 17]

Nowadays, a new research area has arisen which concerns the influence of ground conditions surrounding pipes, including the interaction of the pipe material, soil and fluids, and particularly the formation of voids in the bedding medium. Rajani et al. found that unsupported length and temperature differential are the most important considerations for small-diameter pipes [18-20]. In other words, small-diameter pipes are sensitive to the extent of loss of bedding support due to voids. It is therefore important to detect the existence of voids, which would facilitate targeted maintenance or replacement of pipes prior to breakages.

In this work, three experiments were conducted using the focused ultrasonic transducer with a central frequency of 10MHz for two common plastic pipe materials, Polyvinyl Chloride (PVC) and high density polyethylene (HDPE), and for varying particle sized soils. The first experiment was conducted for detecting the material loss on HDPE plate. Three linear grooves with varying depths and two through slots were machined for simulating the material loss on pipe wall. Ultrasonic scanning was performed to detect the location of those 'defects'. The second test was carried out for detecting the crack in the material. In this experiment, a crack was produced through a PVC

plate for ultrasonic detection. The last experiment was to determine the location and size of hand-made voids external to plastic pipe wall by applying ultrasonic scanning. Reflected ultrasound pulse amplitude and time of flight were analyzed and presented.

2. Experimental method

2.1. Samples preparation

In the first experiment (material loss experiment), a 100×100mm HDPE plate with a thickness of 6 mm was considered. In order to represent different sizes of material loss on water pipe wall, three grooves and two slots with varying sizes were machined on the plate, as shown in Figure 1 (a). The widths of those linear grooves and slots were assumed to be 1 mm or 2 mm. Due to the size limitation of drilling tool, the grooves with width of 2 mm were cut by drilling tool while the ones with width of 1 mm were cut by slitting saw. The depths of the grooves cutting by slitting saw varied along the length, which was lowest in the middle and shallowing towards the end.

In the second experiment (crack experiment), a 135×100 mm PVC plate with thickness of 6 mm was considered. In order to simulate the cracks in the material, the plate was struck by an impact rig. Several cracks were produced, of which one was selected for ultrasonic scanning, as shown in Figure 1(b).

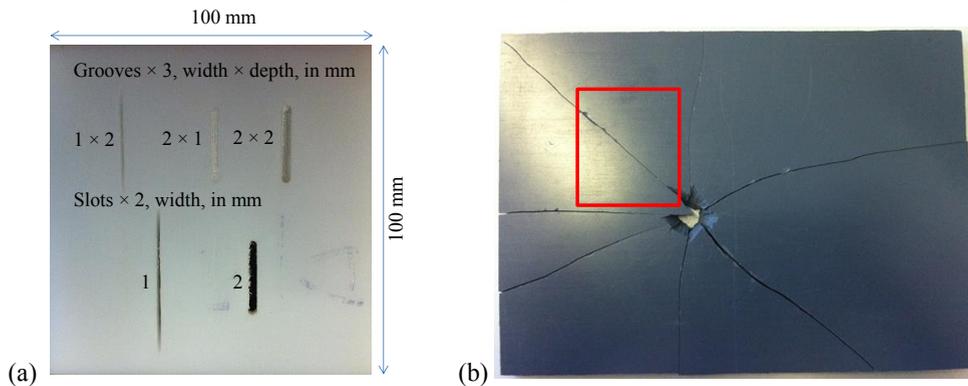


Fig. 1. (a) Size of grooves and slots machined on HDPE plate for experiment 1; (b) photo of cracked PVC plate with ultrasonic scanned area highlighted for experiment 2.

In the third experiment (voids detection experiment), four soils with a range of particle size up to 10mm were chosen for testing, including Replacement density (RD) sand, David Ball Fraction C (DB) sand, gravel with particle size of 5-6.35mm (finer particle size) and with size of 8-9.5mm (coarse particle size). The properties of these soils are shown in Table 1. The reason of choosing the nominal particle size up to 10 mm for the soils was that in practice the soils with such sizes are usually used for the flexible plastic pipes with nominal bore up to 100 mm [21].

A former was made for creating varying voids in soil bed, as shown in Figure 2. In order to cover different sizes and shapes of voids external to real buried pipes, formers were made from narrow half pencil to sharp outer edge hexagonal star with cross section areas varying from 2000mm² to 6400mm². The details of sizes for the shapes are given in Table 2.

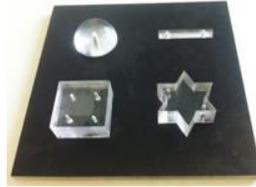


Fig. 2. Former for voids making.

Table 1. Tested soil properties.

	Replacement density (RD) sand	David Ball Fraction C (DB) sand	Gravel 1	Gravel 2
Particle size	100% passing 600 μm , 100% retained 63 μm	600-300 μm , max. 10% larger than 600 μm , max. 10% finer than 300 μm	5-6.35mm, non-rounded	8-9.5mm, non-rounded

Table 2. Former shapes and dimensions.

	Half cylinder	Hexagonal star	Half sphere	Cube
Dimension, mm	20 \times 100 (diameter \times length)	100 (diagonal points distance) 40 (thickness)	80 (diameter)	80 \times 80 \times 40 (length \times width \times thickness)
Max. section area, mm ²	2000	4330	5026	6400

A soil bed with a thickness of around 200 mm was prepared in a plastic box. The soil surface was levelled manually after filling tap water to a level of 80mm above the upper soil surface. The former was manually pushed against the soil bed until four Perspex shapes were fully immersed into the soil bulk. It was then gently lifted up before sitting the plastic plate onto the soil surface. Therefore four vary shapes and sizes voids were made and ready for ultrasonic scanning.

2.2. Ultrasonic measurement

A water-coupled focused ultrasound transducer with central excitation frequency of 10 MHz and a focal distance of 75 mm was used for ultrasonic testing. Figure 3 (a) shows the sketch of the testing configuration. The high frequency sound waves are excited and sent out, targeting on the test plastic plate. On the interface where an acoustic discontinuity existing, i.e. the first interface composed of couplant water and plastic material, some of the sound waves are reflected back while others continue to travel through the medium. The ultrasonic transducer should be aligned vertically to the plate surface in order to have high reflected energy transmission, otherwise, the signal will be scattered away without returning to the transducer. Figure 3 (b) presents an example of ultrasound signal where reflections from varying interfaces are marked. When an ultrasonic pulse reaches the plastic wall, the energy of the pulse is divided, with one part being reflected (the first echo) and the other part being transmitted into the material of the wall (ignore energy loss from scattering). When the transmitted pulse reaches the second interface of the wall, it is reflected back against the first interface. Reflected time series ultrasound signal is acquired through LabVIEW during scanning and the transducer location at each ultrasonic pulse is recorded. Information of time of flight (TOF) and signal amplitude for ultrasound signal is extracted from those peaks, which is further used for reconstructing plastic plate, material loss, cracks and void surfaces. The distances from transducer to individual boundaries are worked out when sound speed in each medium is measured. It should be noted that all three reflection signals presented on one figure is only the case for void detection test. In assessing of grooves or cracks, only the first two pulses appear.

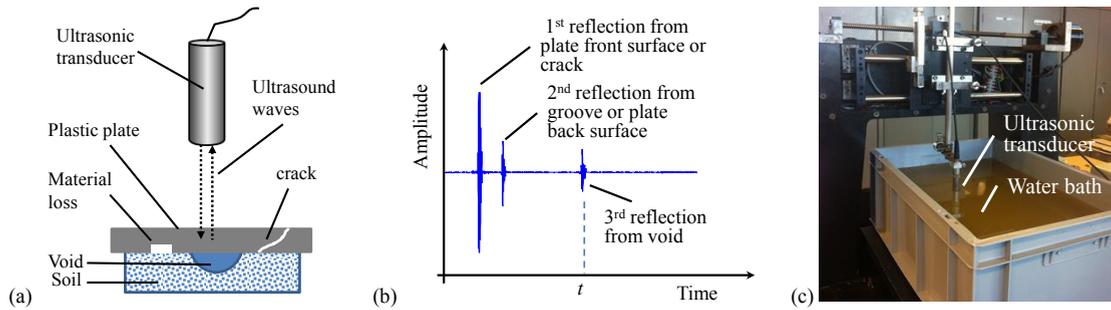


Fig. 3. (a) sketch of ultrasonic measurement; (b) photo of Ultrasonic scanning setting up; (c) .example of ultrasound signal.

Figure 3 (c) shows the ultrasonic scanning facility. The transducer is mounted to the gantry driven by a stepper motor, performing reciprocating sliding movement while the gantry table is driven by another stepper motor with a pre-set feed speed. Interfaces between the water, upper and bottom plate, groove and crack surfaces, and/or supporting substrate soil form three boundaries which will result in respective ultrasound energy reflection. Movement of transducer and the gantry table in two axes accommodate a 2D scanning. For voids detection test, location information of the table and transducer during scanning is recorded, which will be analysed for coordinate of voids (X and Y). Together with calculated depth (Z) from TOF of ultrasound for each scanned point, a 3D reconstruction of voids could be obtained.

2.3. Void test validation

An area covering four voids in the soil bed beyond PVC or HDPE is ultrasonically scanned. Potentially, a few factors might contribute to the void shapes change, such as the feed motion of the gantry, lifting and putting plastic plate. In order to make sure ‘the same’ voids are scanned each time, validation tests are conducted for the replacement density sand and the gravel with particle size of 5-6.35mm.

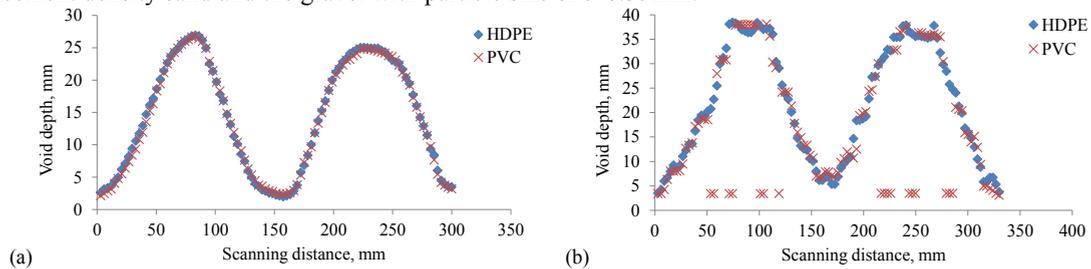


Fig. 4. Change of void shapes for (a) replacement density sand (voids profile of hexagonal star left and cube right); and (b) gravel with particle size of 5-6.35mm (voids profile of hexagonal star left and cube right).

Figure 4 (a) compares the detected void cross section profile with placing two plastic plates, HDPE and PVC for RD sand. It can be clearly seen that same void profile was detected for both plates. There is no change for the void shapes and the dimensions during two separate ultrasonic scanning. Figure 4 (b) presents the same result for gravel. Even though noise signal was captured for PVC case, both materials show good repeatability for void cross section shapes and depths. Therefore, it can be concluded that no disturbance from applying and lifting plastic plate has been introduced during the test. The ultrasonic method for void detection is valid for both fine and coarse particle soils.

3. Experimental results

3.1. Grooves and slots detection

Figure 5 (a) highlights tested grooves while (b) indicates the groove detecting principle. The focused sound waves are sent out by water-coupled transducer (not shown on the figure for simplification), reflected from water-plate interface and recorded. The amplitude of reflected signal shown as 2nd peak shown on Figure 3 (b) is of interest in this test. Due to sound wave energy attenuation in material bulk, reflection sound amplitude from grooves is expected to be greater due to thinner material thickness. Figure 5 (c) presents detection result for three grooves with varying depth from 1 to 2 mm and width from 1 to 2 mm. Deeper grooves produce higher ultrasonic reflection shown as red due to shorter sound travelling distance. It should be noted that along the boundaries of these grooves, much lower ultrasonic reflection has been found. This indicates the sound energy loss due to scattering while travelling along those boundaries.

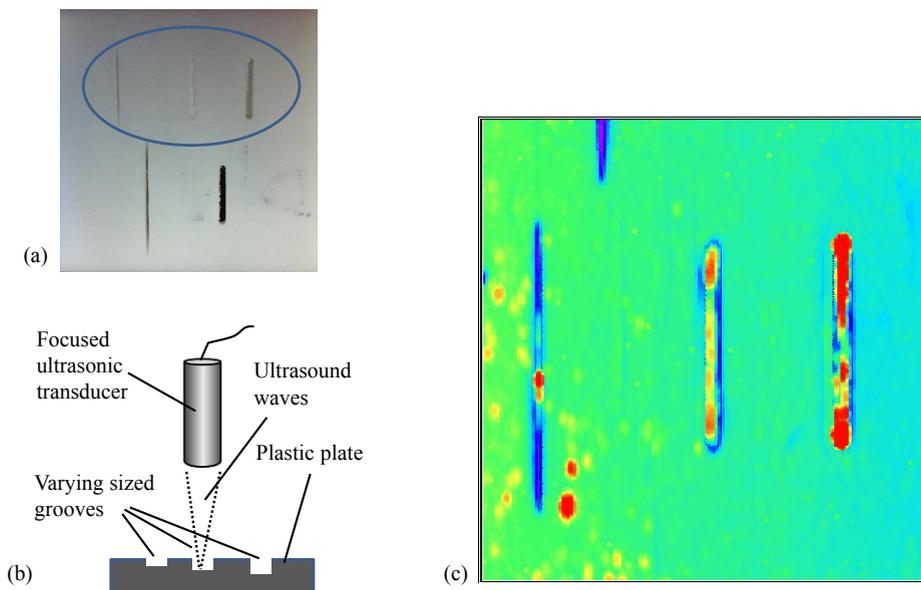


Fig. 5. Grooves detection test, (a) tested grooves highlighted; (b) ultrasonic testing sketch; and (c) detection result.

Figure 6 shows two slots detection results. An area of 50×70 mm covering two slots is scanned by the ultrasonic transducer. The 1st reflection signal on Figure 3 (b) is selected for analysis in this test. While the sound waves are arriving on the top surface of the plate, greater reflection is received by the transducer due to acoustic mismatch between water and plastic material, shown as a background colour. On the position of slots, the ultrasound waves travel through without being reflected. Therefore recorded reflection signal amplitude approaches zero, especially in the middle of the slot, shown in Figure 6 (b). The reflection signal over the slot is gradually dropping down from the boundary to the middle, making a wedge shape.

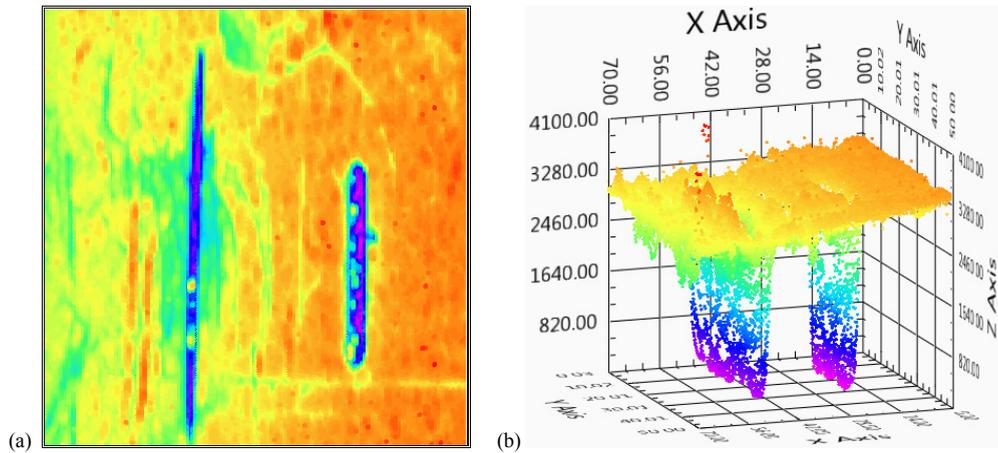


Fig. 6. Slots detection test, (a) top view of detected slots; (b) 3D of slots detection.

3.2. Crack detection

Figure 7 shows tested crack on PVC plate. The testing setting up is the same as groove detection test as the plate is water immersed. The amplitude of the first reflection in Figure 3 (b) is analyzed to distinguish the one reflected from crack. Detection result is shown by Figure 7 (b), from which the location of the crack can be clearly observed. However, along two boundaries of the crack, the reflected signal amplitude is found to be higher on one side but lower on the other side. There are two contributions to this phenomenon. On one hand, on the edge of the crack, ultrasound signals are scattered, which lead to lower reflection amplitude. On the other hand, it has been noticed that the crack along the material bulk is not vertical to the plate surfaces. Therefore the signals travelling through the crack gap may be multi-reflected from fracture surfaces which will result in amplitude superposition.

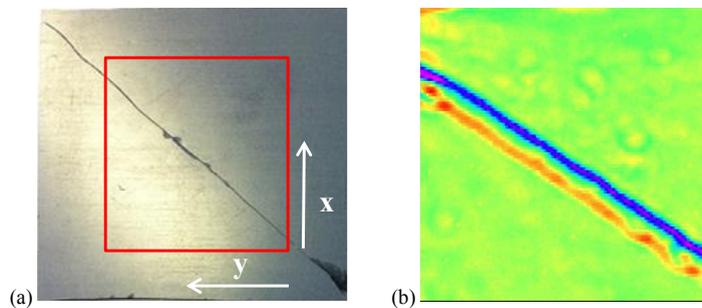


Fig. 7. Crack detection test, (a) photo of crack; (b) top view of detected crack.

3.3. Void detection

Figure 8 shows 3D reconstruction of four voids based on the measurement from the RD sand, DB sand and two gravels, with HDPE and PVC pipe materials. Figure 8 (a), (c), (e), and (g) presents voids detection results for HDPE while (b), (d), (f), and (h) for PVC. The sketch of ultrasonic detection for voids beyond plastic materials is shown in Figure 3(a). Ultrasound waves are excited and sent out, travelling through plastic material until arriving on void surfaces in the soil. Part of those waves are reflected and travelling back to the transducer, which are recorded and used for extracting information of voids. The recorded reflection signal is shown on Figure 3 (b), while the first two reflections correspond to the top and bottom surface of the plate and the third one is from void

surface. The recorded TOF for ultrasound signal is used to calculate the distance from the plastic plate bottom surface to soil surface by multiplying ultrasound wave fling time with sound wave speed in water, which is taken as 1480m/s in this study.

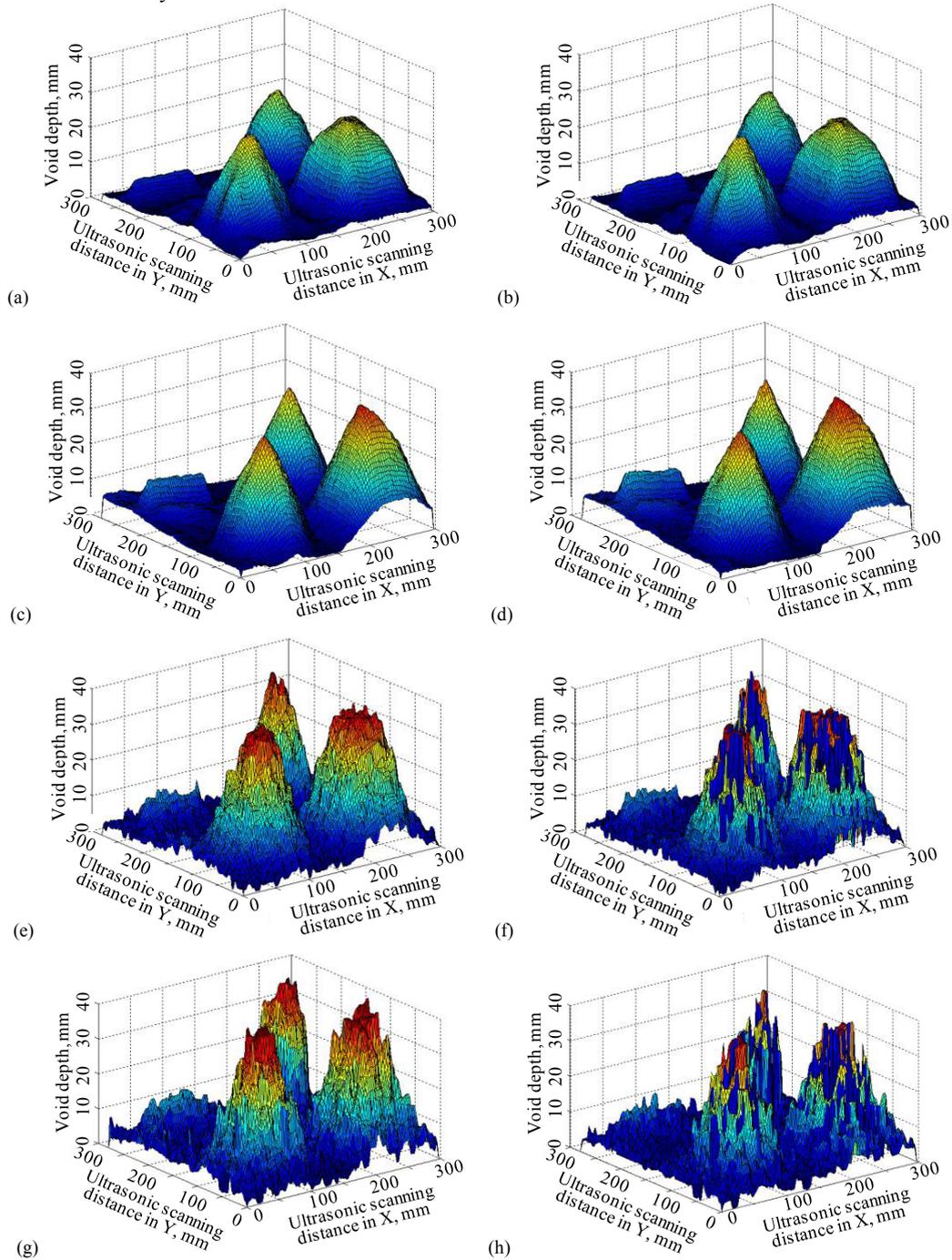


Fig. 8. Voids 3D reconstruction for HDPE and PVC, (a) and (b) for replacement density sand; (c) and (d) for David Ball Fraction C sand; (e) and (f) for gravel 5-6.35mm; (g) and (h) for gravel 8-9.5mm.

The depth of voids in mm is indicated by Z axis in figure 8, where a value of zero represents the soil surface contacting with plastic bottom surface. Four voids with varying shapes and dimensions are clearly detected and presented by ultrasound method, especially for finer soils. During testing, it has been noticed that sharp edges and flat bottom are difficult to be maintained due to collapse of fully saturated sand when the former was pulling out. Sand collapse also decreases voids depth. In contrast, gravel voids tend to be easily maintained. For replacement density sand, the maximum depth of cube was found to be 26 mm for HDPE and 25 mm for PVC while the former has a maximum depth of 40mm. For gravel with size of 8-9.5 mm, the corresponding depths are 43 mm and 39 mm respectively, which are more close to the former's size. The void depth greater than 40mm was deemed to indicate the depth of the gap between adjacent gravel particles.

From Figure 8 it can also be found that, for RD and DB sands, the distribution and shapes for four voids are distinctly reproduced. However, with increasing particle size, void boundaries become blurred and indistinct. The most extremely case is gravel with size of 8-9.5mm, detected void zones have been found to be discontinuous for either HDPE or PVC. This is because coarse particles produce an un-evenly surface which scatters ultrasonic pulses. Less reflection signal is recorded for void reconstruction. For the same soil, it is found that HDPE produces better detection results than PVC, especially for coarse soils. This is due to the fact that more ultrasound energy is lost during travelling though PVC bulk material due to the higher sound attenuation of PVC than HDPE. In spite of this, voids with varying shapes and dimensions could be successfully detected by the ultrasonic method regardless of the soil mediums and plastic materials.

4. Conclusion

The assessment of structural integrity of plastic pipe has been studied using ultrasonic method. The material loss, bulk crack and voids beyond plastic material were investigated in order to validate the ultrasound technique in assessing the health of buried plastic pipelines.

Varied sized grooves and slots on PVC plate are precisely detected and located by analyzing recorded ultrasound reflection amplitude. Reflected sound amplitude is greater in the groove area but lower for slots compared to that in the plate surface. In addition, it has been found that there is significant scattering of ultrasonic energy along the edges of grooves and slots.

Experiments have been conducted on two common plastic materials of pipeline to verify the detection capability of ultrasound method for soil condition external to buried pipes. The location and dimension of premade voids have been successfully detected for varying soils, covering a wide range of soil particle sizes. This finding verified the feasibility of the ultrasound technique to 'find' soil condition beyond the pipe materials, HDPE and PVC.

Results in this study have shown that the use of the ultrasound provides a comprehensive diagnostic tool for plastic pipe inspection.

Acknowledgements

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