https://doi.org/10.1016/j.conbuildmat.2017.06.148

This is the Pre-Published Version.

Tracing and imaging minor water seepage of concealed PVC pipe in a reinforced concrete wall by high-frequency ground penetrating radar

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Abstract

This paper studies the perturbation patterns of GPR images as a tool for tracing water seepage pathway in a plastic and concealed water pipe in a full-scale concrete wall specimen. Water seepage was triggered with a water circulation system and a pre-drilled hole (as seepage point) in a PVC pipe concealed in a concrete wall. Making use of a 2GHz antenna, different GPR perturbations patterns on the PVC pipe (as weak scatterers) and several steel bars (as strong scatterers) in concrete, were mapped. The time-lapse changes of spatial spread and degree of water seepage were monitored for 59 days to trace the water seepage path. The perturbation patterns enable the observation of the wave attenuation explained by the well-established theories of water in construction materials. Analysis in the experiment pushed the limit of GPR that the use of high-frequency GPR is potentially useful to trace and image minor degree of water seepage in concrete.

Keywords: water seepage, ground penetrating radar, water perturbation patterns.

1. Introduction

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Water seepage within building structure and fabric is a complex issue for residents. In densely populated cities in Asia like Singapore, Chew and DeSilva (2003) revealed that water seepage is the most significant building maintenance problems in high-rise buildings. It causes corrosion and eventually induces cracks and delamination in reinforced concrete structures. Severe and large scale cracks and delamination damage structural integrity which threatens safety of the residents. Water seepage causes damp environment which enhances the growth of micro-organism (Chew and W. 1998). World Health Organization (2009) stated that the growth of micro-organism such as mould, fungi, and bacteria in building elements will pollute indoor air quality which can has adverse effect on health risk. In Hong Kong, Joint Office (JO) of the Hong Kong Government received over 25,000 complaints on water seepage in building in 2010 (Hong Kong Institute of Surveyors Building, Surveying Division 2014). Therefore, it is crucial to develop a more accurate moisture mapping technique which helps to locate the source of water seepage and repair method.

Destructive method of moisture/water content determination, such as gravimetric determination, requires extraction of concrete samples. This technique measures the weight loss of hardened concrete slices and compares the result with the dry weight of the sample. However, water seepage usually involves large areas and large number of sampling is not practical. Therefore, nondestructive moisture mapping of the inspected area is recommended. Inspection can be done on large area and hence provide information for engineers to choose suitable location of detail investigation; e.g. open-up inspection, carbonation test and collection of cement powder for chloride content's chemical test.

There are several mature nondestructive testing techniques for moisture mapping on concrete structures for water seepage investigation: fluorescent dye test (FDT), rapid infrared thermography scan (RIT), electrical moisture meter (EMM), leak tracing method (LTM) and microwave. The method proposed by this paper – Ground penetrating radar (GPR) is the only one which reveals multiple layers of unseen concrete structures by producing 2D and 3D images. Though the measurement of water seepage by GPR is not novel, its wide and regular use is still very limited and subject to verification and validation amongst the seepage point, pathway and the measured signals in a well-controlled laboratory environment. In the past, application of GPR in civil engineering field is mainly on locating reinforcement in building elements or finding tendon ducts in infrastructure (Daniels 2004). However, research on applying GPR for water seepage estimation in concrete is very limited. In this project, we focus on further development of the GPR application for tracing water seepage by observation of the changes of time-lapse radargrams, slice scans at different depths of concrete.

The basic principle of applying GPR to estimate water seepage and its path is due to the specific behavior of water molecules towards incident radar wave. Apart from metallic object, water contained in porous dielectric material (e.g. concrete, soil, etc.) is the single most important effect affecting the reflected GPR wave. There are two fundamental effects of water: the first is the characteristic of attenuation and reduction of velocity as suggested in ASTM D6423-11. GPR wave is attenuated (e.g. 0.1-1mS/m in saturated sand compared to 0.0001-1mS/m in dry sand), and slowed down (e.g. 0.055 m/ns in saturated sand compared to 0.12-0.15 m/ns in dry sand) with presence of water in the material as stated in ASTM. The former (attenuation) is due to higher bulk conductivity in water-saturated media, and the latter (reduction of velocity) is due to increasing polarization of the GPR wave by water's dipole molecules. The second fundamental effect is wave dispersion at different frequency bandwidth. Water tends to absorb high frequency component of GPR wave more than the low frequency counterpart (Hugenschmidt and Loser 2008; Huisman et al. 2003; Klysz and Balayssac 2007; Lai et al. 2010; Lai et al. 2011a; Lai et al. 2011b; Lai et al. 2014). Inversion of this characteristic would allow prediction of water content in a material (Lai et al. 2006; Lai et al. 2012; Sham and Lai, 2016), and prediction of water leak in urban underground (Hunaidi et al. 2000; Stampolidis et al. 2003; Nakhkash and Mahmood-Zadeh 2004; Crocco et al. 2009; Bimpas et al. 2010; Demirci et al. 2012; Eyuboglu et al. 2013; Cataldo et al. 2014a; Cataldo et al. 2014b; Lai et al. 2016).

Most literature about studying interaction of concrete-water leak by GPR are about concrete's water content, rather than tracing or imaging water leak or seepage. Effects of moisture and chlorides in concrete on radar amplitudes were studied in Hugenschmidt and Loser (2008) using off-ground 2.5 GHz antenna, where a quotient change of reflection amplitudes was concluded for mapping blackspots of excessive water or chloride on concrete bridge decks covered with asphalt pavements. Effects of water content on the near-field direct wave's amplitude (Laurens et al. 2002; Klysz et al. 2004; Sbartaï et al. 2006a, b) and reflector's amplitude (Lai et al. 2008) were studied. Good correlation between direct wave and reflected wave attenuation were reported (Sbartaï et al. 2006a). This paper focuses on studying the first effect (i.e. attenuation) and makes use of the characteristics for tracing and imaging water path in concrete.

2. Experimental setup, instrumentation and signal processing

The water seepage scenario was simulated in a concrete wall with dimension 0.8 m (L) x 0.74 m (W) x 200 mm thick (Figure 1). A 32 mm external diameter & 25 mm internal diameter L-shape PVC pipe with a pre-drilled hole at the corner was buried in the middle of the concrete wall, with a depth of 70mm. The pipe is also sandwiched by two layers of 20 mm diameter steel reinforcement bars running in perpendicular direction. The concrete cover of the bars is 50 mm. A photo and a schematic of the setup are shown in Figure 1 and Figure 2, respectively. The inlet and outlet were connected with a hose and a sump pump that allow circulation of water within the PVC pipe. It was anticipated that water seeped slowly at the corner of the L-shape pipe through the pre-drilled hole, so that seepage can be simulated. Non-stop circulation lasted for 52 hours and stopped afterwards. GPR radargrams were collected before the circulation, at 4 hours 30 mins, 27 hour 18 mins, 52 hours 24 mins. A final measurement was made 203 days after the start of circulation where the concrete wall is expected to become dry again. Purpose of the measurement was to observe drying of concrete after seepage.

Data collections of the tests were performed in an orthogonal grid overlaid on the concrete wall (Figure 3) by using a Geophysical Survey System Inc (GSSI) SIR-4000 control unit and a 2 GHz palm GPR antenna. The grid was designed, where its center matches the position of the seepage point of the L-shape PVC pipe, such that the effects of water seepage can be recognized more easily. One-dimensional A-scan waveforms were laterally compiled to build two-dimensional B-scan radargrams for further data processing and analysis to re-construct 3D C-scan slice images. There were a total of 7 GPR traverses (X10 – X16) parallel to the x-axis and another 6 traverses parallel to the y-axis (YA to YF) of the grid. Signals were post-processed with a commercial software Reflexw for 2D signal processing and radargram display, and a commercial software GPR Slice for 3D slice image's visualization.

For 2D signal processing, the drift of waveform was adjusted by standard dewow and direct current (DC) shift, and referencing of the concrete surface position in the waveform was carried out by time zero correction at the peak position of the A-scans. A generic automatic gain control (AGC) was also applied to amplify the signals of the pipes, water seepage and steel bars.

For 3D slice image visualization (or C-scan), migration with Stolt's f-k migration and envelop in 2D distance-radar time space/B-scan radargrams were carried out to reduce the hyperbolic tail reflections/artifacts to small dots for better presentation of any round shape objects. The GPR wave propagation velocity was estimated as 0.12 m/ns. Then, slices were segmented at particular radar time/depth to generate C-scans which represent energy distribution over a surface at same depth. Energy levels at the points not covered by radar traverses were interpolated by inverse square's distance algorithm of any non-measured spaces (or simply 'gap') shown as point 'i' within the grid with an 'X' spacing (Figure 4). Purpose of such interpolation was to estimate the signal strength not covered by the traverses, according to equation [1].

$$E_i = \sum_{i=1}^{n} w_i \times z_i \;\; ; \;\; w_i = \frac{1}{{h_i}^2} \ldots\ldots [1]$$

where E_i = estimated signal strength at point 'i'; w_i = weight of measured signal at nearby grid points in the GPR traverses; z = measured signal strength at nearby grid points in the GPR traverses; h_i = distance from point 'i' and adjacent grid points in GPR traverses falling inside the search radius (i.e. 1.5 times grid spacing), as shown as the red dotted lines in Figure 4;. After signal interpolation, amplitude at every 'gap' was normalized relative to the maximum and minimum amplitude according to the amplitude distribution in the 3D cube space. As illustrated in left of Figure 5, the color scale of the amplitude histogram was defined according to the logarithmic square algorithm (Figure 5(a)) and transformed spatially in the C-scans (Figure 5(b)). This scale is able to illustrate clearly the buried objects and also the seepage points.

3. Data Analysis

During the 52-hour of water circulation process, the traverses X14 and YC are of primary interest because these two traverses coincide with the exact location of the pre-drilled hole 100 mm beneath seepage point at the L-shape PVC pipe, as indicated by the red dots in Figure 6 and 7. Time-lapse results after water circulation are further illustrated in four traverses:

- X13 (no pipe, away from the seepage point),
- X14 (partly along the pipe and coincide the seepage point),
- X15 (bisecting the pipe perpendicularly and away from the seepage point) and
- YC (partly along the pipe and coincide the seepage point).

All time-lapse radargrams collected over the perpendicular grid were used to re-generate slice scans (C-scan) exactly at the time slice (1.47-1.76 ns) at the seepage point, and time slice 2.05-2.34 ns at the vertical steel bar layer which serves as back screen. The different C-scans at different times of measurement (start, 4 hours 30 mins, 27 hour 18 mins, 52 hours 24 mins) during the circulation are illustrated in Figure 9. The following discussions describe the changes of (1) before and (2) after water seepage.

1. Before water seepage (baseline no-leak stage)

Initially before the water circulation (i.e. 0 hr), the concrete wall was dry. At traverses X14 and YC, the horizontal and vertical sections of the pipe were rendered as perfect longitudinal reflections, respectively (indicated as the red dot in 2nd and 4th column and first row of Figures 8). At traverse X15, a perfect hyperbola to the vertical section of the pipe (indicated as the yellow dot in the 3rd column and the first row of Figure 8) was clearly identified. Steel bars highlighted in blue arrows, serve as a back-screen behind the PVC pipe and seepage point, were not disturbed because the small and non-metallic PVC pipe poses little influence on its reflection. These clear reflections of PVC pipes arrive at around 1.6 ns. Combinations of the results give the slice scan in the first row of Figure 9, where the L-shape PVC is clearly identified. This case is the baseline of the experiment, where dry concrete does not polarize nor delay the incident GPR wave as much as the subsequent wetted concrete does. These strong, continuous magnitude and undisturbed shape of the PVC pipe reflection demonstrated the absence of water and the so-called no-leak state of the pipes.

2. After water seepage

At the 4.5th hour after water circulation, the pipe reflections were still clear but slightly disturbed at the seepage point in traverse X14 and YC, while the reflections in X13 and X15 (away from seepage point) remained undisturbed at all. It is because the minor water seepage only started to saturate the area close to the seepage point. Also, this very small change was not picked up by C-scans in Figure 9.

At the 27.3^{th} hour after water circulation, the pipe reflection seems to be weakened significantly, that the original spot indicated by the red dots is shifted to about 2.5 ns as shown in the 3^{rd} and subsequent row of Figure 8. In X14 and X15, the regular steel bar reflections were also affected, that the clear hyperbolas of the 3^{rd} and 2^{nd} steel bars before 4.5^{th} hour case (indicated by blue arrow in the first two rows) disappeared, respectively. In particular, the 3^{rd} steel bar in X14 seems to coincide the accumulation of water seepage posed by the water seepage point. The same appearance is also supported by the C-scans in Figure 9, where the energy at the seepage point of the L-shape pipe was significantly reduced.

At area away from the seepage point (i.e. X15), the weakening of reflection (i.e. attenuation) indicated as yellow dot is not as much as that in X14 and YC, and can therefore be still indicated in the 3^{rd} row of Figure 8. It is also worth mentioning, that in X13 which is at the bottom of X14, all radargrams are undisturbed after the entire course of water circulation. Therefore, it indicates that the direction of water seepage was going upward from X14 to X15, rather than downward from X14 to X13.

3. Stop of water circulation

After the dataset at the time 52 hour 24 mins was collected, the water circulation was stopped and so did the water seepage of the plastic pipe. At the 52 hour 24 mins, radargrams collected and C-scans created are similar with that at the 27 hour 18 mins: pipe reflection weakened and indicated steel bar reflection disappeared. Then after 203 day from the start of the water circulation, the dataset was again collected to re-construct the images of radargrams and the C-scans as shown in the last row of Figure 8 and Figure 9, respectively. These images show that the concrete wall recovered from the damage of water seepage because of the high similarity between the images in the first row (i.e. initial stage) and last row (203rd day) of Figure 8 and 9. It is obviously because of the evaporation of water contained in the seepage point after the stop of water circulation and long lapse time of the 203 day measurement.

4. Discussion and Conclusions

Concluded from data analysis of three stages after water seepage, the GPR signal of PVC pipe at the seepage point was weakened and disappear, compared with clear reflection present before water seepage stage as well as when the concrete wall recover from water seepage. This above evidence of perturbation pattern triggered by the seepage at the seepage point can be interpreted with the absorption/attenuation mechanism as discussed in Section 1. They also collectively indicate the pathway of location of water seepage. A history of water seepage is re-built and summarized as follows. Firstly, it started from the seepage point (shifted red dots in X14 and YC along with clock time). Secondly, it gradually developed towards the upward (disappeared steel bars as blue dots in X15) and direction to the right of the wall elevation (disappeared steel bars as blue arrows in X14) of the concrete wall.

Compared to a similar work by the authors Lai et al. (2016) where similar scenario of water seepage/leakage was compared but in sandy soil, it takes a lot longer time for minor water seepage to happen and detectable in concrete. It is because of the high density, small and dis-connected pores in this well-compacted concrete, which dis-connected the pathway of water seepage and amount of water seepage. This statement is supported by the small changes of time delay of the reflectors (PVC, steel bars) and small variation of GPR wave velocities compared to the big changes of water leak in sand reported in Lai et al. (2016).

Perturbation patterns due to water seepage in a concealed PVC pipe were studied and established in this paper. Signatures or fingerprints of minor water seepage were successfully traced and imaged by recognizing the time-lapse perturbation patterns in GPR B-scan radargrams and C-scans. The use of these confirmed GPR fingerprints serve as a basis to trace the pathway and extent of water seepage in water pipe in concrete buildings. Further field works are on-going and the signatures obtained in this paper will be used as a validation and proof on field studies.

Acknowledgement

The authors gratefully acknowledge the Research Grants Council of the HKSAR Government for funding support on the project entitled "Investigation of Inhomogeneous Water Distribution (IWD) in Soil and Concrete Using Ground Penetrating Radar (GPR), PolyU 5393/13E".

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