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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 2 GHz 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 validation 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.

1. Introduction

Water seepage within building structure and fabric is a complex issue for residents. In densely populated cities in Asia like Singapore, Chew and DeSilva [5] 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 [6]. World Health Organization [31] 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 [11]). 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 [8]. However, research on applying GPR for water seepage estimation in concrete is very limited. In this paper, 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.

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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 [1]. GPR wave is attenuated e.g. 0.1–1 mS/m in saturated sand compared to 0.0001–1 mS/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 [12,13,15,20,21,22,19]. Inversion of this characteristic would allow prediction of water content in a material [24,23,29], and prediction of water leak in urban underground [14,30,26,7,2,9,10,3,4,17].

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 [12] using off-ground 2.5 GHz antenna, where a quotient change of reflection amplitudes was concluded for mapping black-spots 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 [25,16,27,28] and reflector's amplitude [18] were studied. Good correlation between direct wave and reflected wave attenuation were reported [27]. 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) × 0.74 m (W) × 200 mm thick (Fig. 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 70 mm. 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 Figs. 1 and 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 h and stopped afterwards. GPR radargrams were collected before the circulation, at 4 h 30 min, 27 h 18 min, 52 h 24 min. 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 (Fig. 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

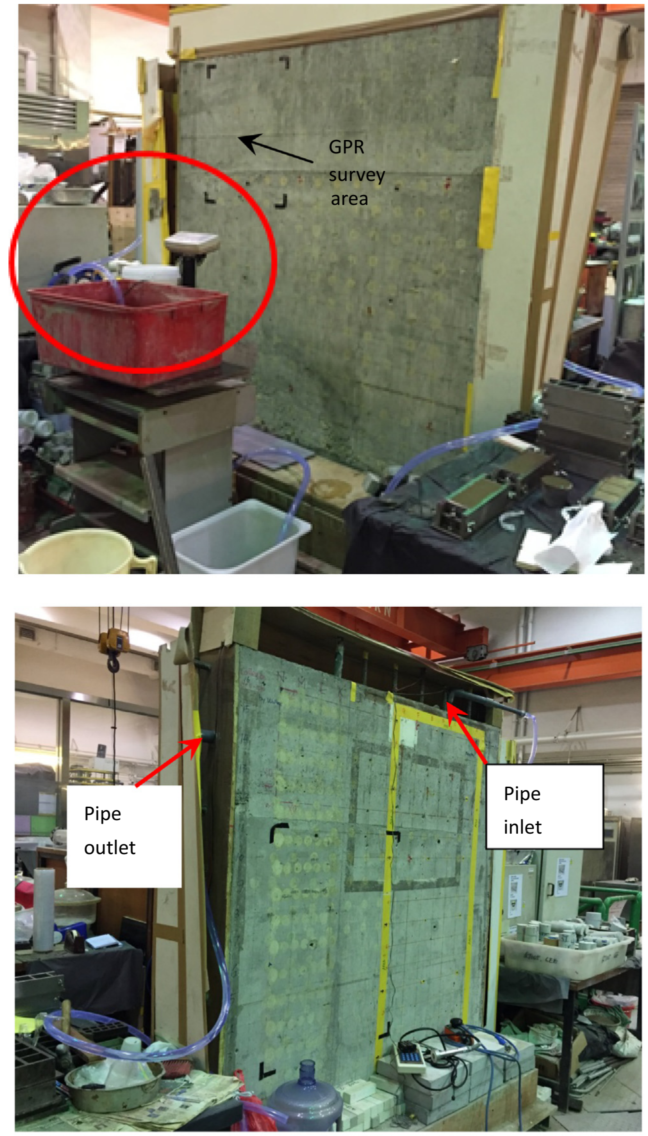

Fig. 1. The concrete wall with the circulation water tank at the front (top) and at the back (bottom). Remark: the red rectangle is the GPR survey area.

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