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Research paper

Using ground penetrating radar to locate and categorise tree roots under urban pavements

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ABSTRACT

Street trees are commonly associated with pavement cracking and lifting, resulting in costly repair of the pavement and/or removal of the affected tree/s. This study used Ground Penetrating Radar (GPR) to evaluate the effectiveness of three different prototype permeable pavement designs in reducing pavement damage caused by street tree roots (*Melaleuca quinquenervia*). Initial tests conducted in a simulated test environment were then replicated in the field to examine the performance of the GPR. The initial test results were positive and indicated that this technique could be used to reliably determine tree root size and depth under pavements with minimal error. Positive root identification results were recorded for all three prototype pavements. The accuracy of the GPR results was found to vary according to soil type, depth of aggregate sub-base, and water mass contained within both the soil, and the buried objects during the calibration process. The three-dimensional nature (overlapping) of genuine tree roots also affected the detection accuracy of the GPR in the field. The study has shown that GPR may play an important role in tree root identification in future, and improve pre-emptive trip hazard reduction management. Increasing permeable pavement sub-base depths may also lead to less pavement damage by tree roots thereby preventing future trip hazards and avoiding costly repairs.

1. Introduction

Street trees are essential for a community's wellbeing. Their benefits encompass social, environmental, and economic elements (Donovan et al., 2013; Pandit et al., 2012; Donovan and Butry 2010). Street trees have been acknowledged to reduce storm water runoff, improve air quality, increase biodiversity, reduce energy consumption, increase property values, improve social interaction, and reduce crime (Kuo and Sullivan 2001; Van Dillen et al., 2012; McPherson and Peper, 1995; McPherson, 1994; Mullaney et al., 2015; Chang and Lee, 2016; Jasmani et al., 2016).

The benefits of street trees are believed to outweigh the negatives by a factor of two or more (McPherson and Peper, 1996). These negatives are primarily financial, and have been associated with the repair and replacement of pavements due to damage caused by street tree roots (Vogt, 2015). Additionally, litigation costs resulting from pedestrian trips and falls, and insurance claims made for damage to private property caused by tree root growth contribute to this financial burden (Randrup et al., 2001).

Conflict between street tree roots and pavements has been well-documented (Wagar et al., 1983; Day 1991; Francis et al., 1996; K. Coder 1998; McPherson 2000; D. ; L. Lesser 2001; Blunt 2008; Vogt et al., 2015; McWilliam et al., 2012; Morgenroth 2008). The damage is a result of growing tree roots displacing soil in their immediate vicinity, consequently causing cracking and/or lifting of pavements (Day 1991; Kopinga 1994; Barker and Peper, 1995; Blunt 2008). Despite a lack of definitive results from previous studies identifying tree roots as the main cause of pavement cracking (D'Amato et al., 2002), there remains a widely held opinion that tree roots are the primary cause of pavement failure (Sydnor et al., 2000).

Pavement cracking by tree roots is thought to occur via the process of hydrophilic roots being attracted to the condensation that gathers on the underside of pavements (Wagar and Barker 1983). The high costs associated with pavement damage by tree roots includes both pavement repair and replacement, and litigation claims (McPherson, 2000). These costs can have a major impact on government budgets which can result in localised amenity loss.

One approach to making the soil beneath pavements less conducive to street tree root growth, in addition to reducing pavement damage, is the use of permeable pavements with increased drainage layer depths (Volder et al., 2009; Morgenroth and Visser, 2011; Mullaney and Lucke, 2014; Mullaney et al., 2015; Morgenroth, 2011). Permeable pavements

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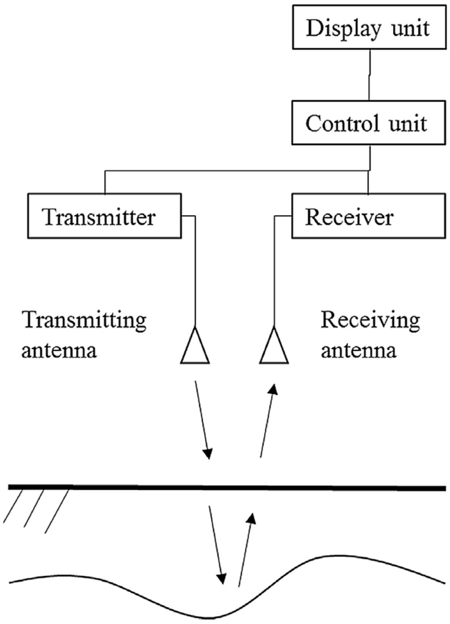

Fig. 1. Ground Penetrating Radar Components (after Takahashi et al., 2012).

increase the availability of water and oxygen in the tree root zone which can improve growing conditions. Increased drainage layer depths also encourage tree roots to grow at greater depths where moisture levels are more stable (Mullaney et al., 2015). This significantly reduces the risk of pavement damage due to tree roots (Morgenroth, 2011; Morgenroth et al., 2013).

Ground Penetrating Radar (GPR) is a geophysical detection method that uses electromagnetic waves to identify subterranean anomalies. GPR is classified as ultra-wide band (UWB) radar, operating within frequencies of 1MHZ to 1GHZ (Daniels 2004). Partial signals are reflected by a change in dielectric properties throughout the subsurface medium, and data collected in real time can be manipulated into detailed information providing the depth, orientation, and size of the subsurface feature. Adjacent scans can provide further clarification on the properties of subsurface features (Takahashi et al., 2012). Acquisition, signal processing, and 2D images are described from data retrieved (Fig. 1). GPR's are generally moved along the surface, emitting and receiving electromagnetic waves (EM).

GPR has been used for a variety of applications within the civil engineering field. For example, recent studies have successfully applied the non-destructive GPR detection method to locate buried services and pipes that might interfere with excavation and construction projects (Bassuk et al., 2011; Hruska 1999; Stokes et al., 2002), to assess the thickness of asphalt pavement layers, to evaluate the condition of concrete components, to locate and assess hazardous waste, and for general geotechnical investigations (Reynolds 1997; Reynolds 1997; Casas et al., 2000). GPR has also been successfully used to locate and identify both orientation and depth of in-situ tree roots in forests (Al-Qadi and Lahouar 2005; Willett et al., 2006; Bassuk et al., 2011; Guo et al., 2015; Butnor et al., 2016). However, few studies have used GPR to locate and characterise tree roots under urban pavements.

This project used a three-phase verification and calibration procedure to investigate the capability of GPR to determine tree root size, orientation and depth below pavements in an urban setting. The first phase of the testing was performed in a simulated environment with known sub-surface (buried) objects in an above ground tank. GPR was then used to confirm readings in the field using post-survey, non-destructive vacuum excavations. In the third phase GPR was used to evaluate the effectiveness of a purpose-built, prototype permeable pavement sub-base designs in reducing pavement damage by tree roots. This phase involved mapping the depth and size of the tree roots in relation to the different permeable pavement sub-base depth designs.

2. Methods

2.1. GPR tank study

A MALÅ ProEx® GPR was used to locate and categorize the characteristics of known, buried objects used to simulate the presence of roots in an urban environment. An above ground fiberglass tank (3 m in diameter) was filled with various layers of clean, washed river sand and gravel (20 − 25 mm in diameter), and then covered with permeable interlocking concrete pavement (PICP) bricks (Ecotrihex®, 181 × 88 × 80 mm) (Fig. 2). Sections of saturated pine dowel (19 and 30 mm in diameter, 400 mm in length), were sequentially placed at regular intervals within the layers of sand and gravel in the tank to simulate the presence of underground tree roots.

To ensure maximum possible dielectric response (Dannoura et al., 2008), each dowel was first placed into an oven at 105 °C to remove moisture. Dowels were then individually weighed before being submerged in water for 48 h to ensure complete saturation. After the saturation process was complete, the dowels were then weighed again. The effective moisture content of the dowels was then calculated using Eq. (1). The average moisture content of the dowels was found to be 21.0%. To ensure the moisture content of the dowels did not change

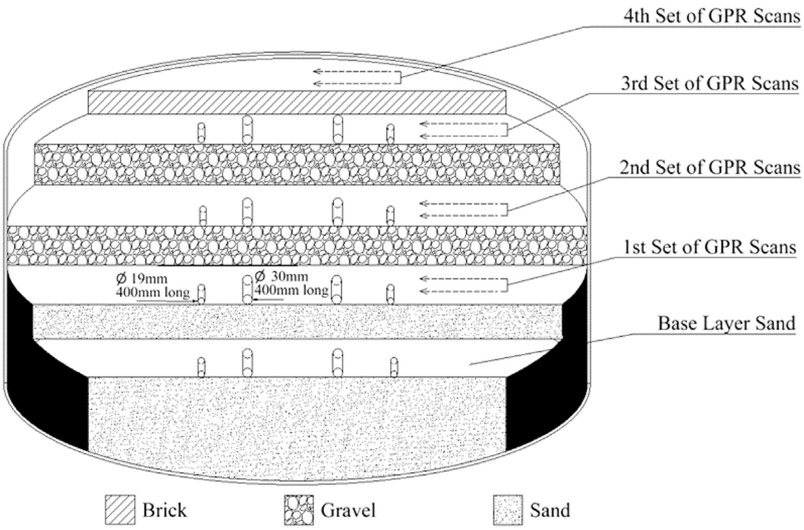

Fig. 2. Schematic of 3 m diameter fiberglass tank filled with layers of washed sand and gravel, and tiered approach to GPR scans.