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Inspection of the lids of shallowly buried concrete structures based on the propagation of surface waves

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ABSTRACT

The inspection of underground concrete utility structures can be a challenging task due to their inaccessibility. This article presents a nondestructive inspection technique for the lids of such structures based on the propagation of elastic waves where the variation in soil vertical acceleration following an impact is recorded along a given line at the surface of the soil. The structures investigated are made of reinforced concrete and are located below a shallow homogeneous soil layer which is covered by a pavement. It is shown through finite difference numerical modeling that elastic waves are affected by the state of degradation of the underground concrete structure. It is also shown that the difference in dynamic properties between the soil and the concrete structure causes the latter to act as a waveguide that affects the variation of the vertical acceleration measured at the surface of the model. The propagation of elastic waves within different underground profiles is studied in terms of the variation of their energy and of their group and phase velocity. Theoretical models, computed using the propagator matrix technique, are presented in the appendix to demonstrate the importance of the waveguide effects, caused by the presence of the concrete structure, on the group and phase velocity dispersion curves of Rayleigh waves. Finally, some of the results obtained from the inspection of two different real underground structures are also presented. These results show that the proposed inspection technique, developed based on 1D and 2D numerical testing, is also effective for real structures.

1. Introduction

Modern cities have an important part of their infrastructure buried underground. Although the structures are protected from a number of environmental hazards, they may be subject to other problems. One of these is inaccessibility, which may hamper inspection and maintenance. The type of underground structures investigated in this study is similar to the access chambers (vaults) found in many cities for the transit of electricity and other utilities (Fig. 1a). These reinforced concrete vaults are typically located beneath roads or pavements under a well-compacted granular soil layer. Although the depth of the granular soil layer may be up to 1.0 m, the vaults are often located at a shallower depth. Their size will vary depending on their application but they typically have dimensions similar to the ones shown in Fig. 1a. Just as is the case for any aging structure, the maintenance of underground structures must be carefully planned in order to ensure public safety. Fig. 1b, which was taken from the interior of the vault, shows the advanced state of degradation of the roof of the vault which, due to its condition, will have to be replaced. In most cases however, the damages are not as severe as what is shown in Fig. 1b and are not visible from the inside of the structure. Even if the exact causes of the degradation will vary from one structure to another, a conjunction of phenomena such as freezing and thawing, chemical attacks, carbonation and chloride attacks of the steel reinforcing bars are the main factors contributing to the degradation of the vaults (Tremblay, 2013).

The maintenance planning for these structures is often based on the results obtained from inspections requiring the use of various destructive techniques such as excavation or drilling. Fig. 2 shows the results of an inspection carried on an existing vault. The drill core samples shown in Fig. 2 were collected from the interior of the vault and the damaged portion of the samples is always the one that was in direct contact with the soil. Based on the condition of the core samples collected, it appears that the damages present on the surface of the vault are unevenly distributed, meaning that a drill core sample obtained from one location is not necessarily representative of the overall condition of the vault. Therefore, several core samples are required in order to get an overall estimate of the condition of the vaults. Excavation of the

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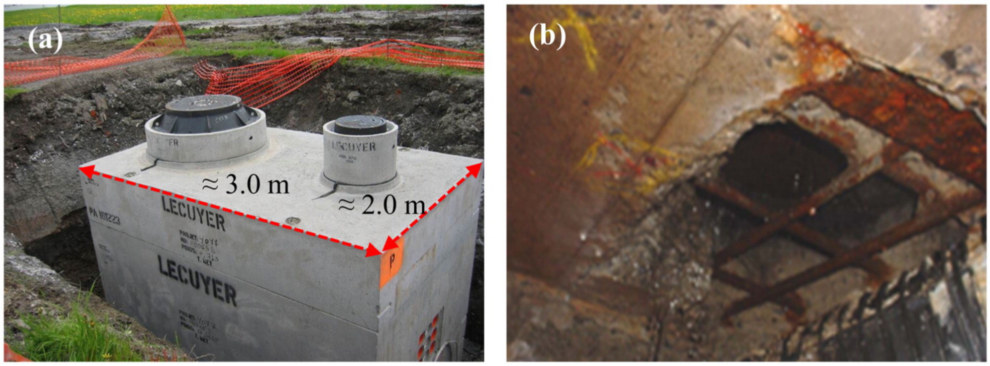

Fig. 1. a: Picture showing a typical underground concrete structure. b: Picture of the concrete slab forming the roof of the structure. The picture was taken from the interior of the structure.

soil covering a vault is also not a viable alternative due to its costs and the inconvenience caused to the population. Moreover, both techniques require direct access to the structure as well as the use of heavy machinery, which can be problematic in many cases. Indeed, direct access to underground structures similar to those shown in Fig. 1a raises several safety concerns for the workers having to get into them. Safety concerns are mainly due to the presence of electrical equipment and water in a confined spaced with limited access (Hydro-Québec, 2008). The use of a non-destructive technique to evaluate the state of degradation of an underground structure directly from the surface of the soil would therefore offer several advantages over the techniques currently used. Although several non-destructive techniques are available for locating underground structures, none are able to estimate the state of degradation. Techniques having received the most attention include ground penetrating radar (GPR) (Haven et al., 2001; Costello et al., 2007; Gurbuz et al., 2010), infrared thermography (Wirahadikusumah et al., 1998; Costello et al., 2007) and magnetic/electric techniques (Metje et al., 2007).

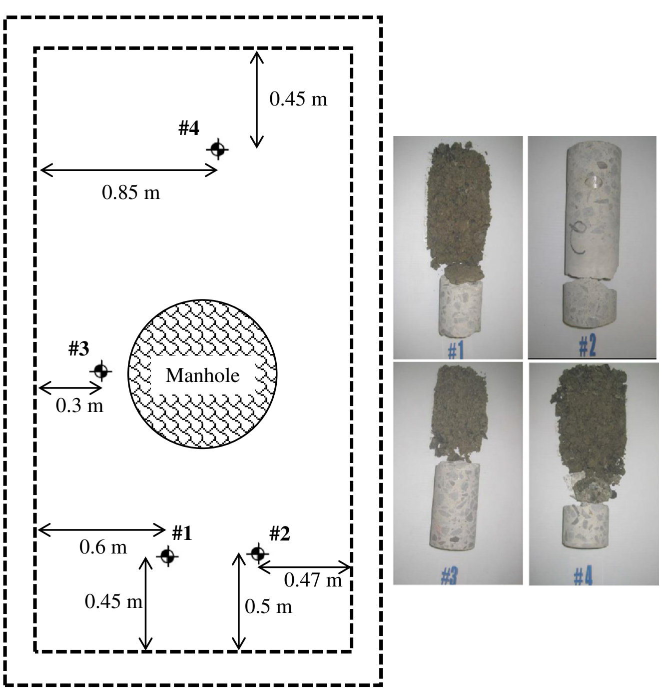

Fig. 2. Left: Top view showing the location of the drill core samples shown on the right. The dashed lines indicate the location of the inner and outer walls of the structure. The coring was performed from the interior of the structure.

The objective of this work is to present the development and the potential of an inspection technique based on the study of elastic wave propagation through the subsurface. The proposed technique is aimed at identifying which structures are potentially damaged and would require further investigation. The inspection technique presented in this study may therefore be seen as a complement to those currently used, allowing more targeted and limited use of destructive techniques.

1.1. Elastic waves in non-destructive testing

The effectiveness of the study of the propagation of elastic waves, through the use of several receivers (either geophones or accelerometers) placed at the surface of a given profile to detect shallow underground heterogeneities, either cavities or lateral changes into the soil profile, has been shown in several studies (Grandjean and Leparoux, 2004; Nasseri-Moghaddam et al., 2005; Strobbia and Foti, 2006; Lin and Lin, 2007; Xia et al., 2007; Tallavó et al., 2009; Boiero and Socco, 2010; Orfanos and Apostolopoulos, 2012). The presence of a pavement at the surface of the soil was also shown not to significantly impair the quality of the recorded signals provided that the seismic source is in direct contact with the soil (Miller et al., 1999; Karray and Lefebvre, 2009). For instance, Karray and Lefebvre (2009) demonstrated that cavities located within a soil layer overlaid by a paved road can be accurately located using surface wave techniques.

As elastic waves travel through a vertically non-homogeneous profile, the elastic properties of each successive layer of material will influence their propagation. A particular case arises when these waves travel through a soil layer that is bounded at a certain depth by a layer of far greater density and rigidity such as the bedrock. Appendix A demonstrates why the concept of Airy phase, first described by Pekeris (1948), is important in this study by examining the theoretical dispersion curves of several underground profiles containing a concrete layer at shallow depth.

2. Part I: numerical modeling

2.1. Model creation

In this study, numerical modeling was used to determine, on a preliminary basis, the accuracy and limitations of an inspection technique based on elastic wave propagation. Numerical modeling was performed with the software FLAC (Fast Lagrangian Analysis of Continua). FLAC is an explicit finite difference program designed to solve engineering problems. In all models created with FLAC, the underground profile is divided into different square elements of 0.025×0.025 m. As a guideline to avoid numerical distortions of the waves propagating through the discrete grid, the following criteria is suggested (Kuhlemeyer and