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

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ABSTRACT

The possibility of performing the inspection of an underground structure directly from the surface of the soil would be advantageous for the inspection of various type of underground utility structures present in modern cities. In part I, the behavior of elastic waves propagating in a soil profile containing a shallowly buried underground concrete utility structure was studied and it was found that it is possible to evaluate the condition of the surface of the lid of such structures based on the propagation velocity of elastic waves. The part II follows from the work that was previously performed to develop a nondestructive technique for the inspection of shallowly buried utility structures based on the propagation of elastic waves. First, the three-dimensional finite difference method implemented in the software Fast Lagrangian Analysis of Continuum was used to model an underground concrete structure to show how the presence of a manhole and of a pavement at the surface of the soil affect the propagation of elastic waves. Second, a receiver configuration typically used in three-dimensional seismic surveys is presented and its effectiveness is tested on three different existing underground structures. The signals collected during the field tests are analyzed independently in the velocity-frequency plane using an adaptive signal processing technique. The velocity-frequency representation of each signal is then used to identify the different elastic waves and to calculate their group velocities. Third, the variation of the group velocity at the surface of the three concrete structures is presented in the form of two-dimensional contour maps that enabled the detection of anomalies on the surface of two of these structures. Finally, it is shown how the collected data can be used to obtain a three-dimensional tomography representative of the condition of the surface of an underground structure.

1. Introduction

Underground utility structures are used in modern cities for several applications such as the transit of power and telecommunication cables (Fig.1). The inspection of these structures can be a challenging task due to their inaccessibility. In Tremblay et al. (2017) (part I), it was explained that although protected from most environmental hazards, the utility structures such as those shown in Fig. 1 may nevertheless experience accelerated deterioration due to a combination of phenomena detrimental to the concrete and its reinforcing steel bars (Tremblay, 2013). One of the main problems associated with their degradation is that it tends to be non-uniformly spread over the surface of the lids of these structures. The latter means that a drill core sample obtained from the concrete of the lid of a structure is not representative of the condition of the entire structure as demonstrated in part I.

This article follows the work shown in part I which presented an inspection technique based on the propagation of elastic waves which is performed directly from the surface of the soil without requiring direct access to the structure. The inspection technique is performed by placing receivers (accelerometers) on a given line along the surface of the underground structure and by recording the variation of the vertical acceleration following a mechanical impact on the surface of the soil. In part I, it was shown using the propagator matrix method, 2D numerical modelling and experimental tests how the energy and velocity of propagation of elastic waves are affected by the presence and condition of the surface of the lid of an underground structure. The comparison of the energy and velocity of propagation of waves propagating at certain frequencies over an intact and a damaged structure revealed that the wavefield recorded by the receivers located near an anomaly differs from the wavefield recorded over an intact structure. It was also shown that the variation of the velocity of the waves propagating at different frequencies (dispersion curve) is typical of the dispersion curves

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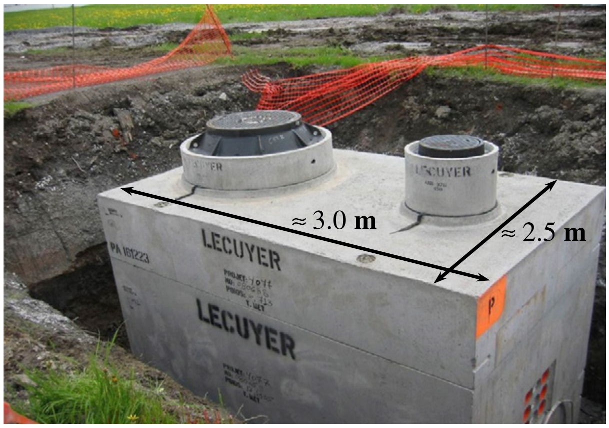

Fig. 1. Typical underground utility structure.

of Rayleigh waves propagating in a soil layer covering a layer of higher rigidity such as the concrete structure. The study of the dispersion curves therefore revealed why only certain frequencies are affected by the condition of the structure and this topic will be further discussed in Section 5.

Several techniques are available for the analysis of the propagation of Rayleigh waves. Among them, the spectral analysis of surface waves (SASW) technique has been widely used for soil and pavement testing (Nazarian and Stokoe, 1985; Stokoe and Nazarian, 1985; Roesset et al., 1990). This technique relies on the assumption that the fundamental Rayleigh propagation mode (R0) dominates the recorded waveform. However, it was explained in part I that the presence of the underground structure causes the formation of several higher Rayleigh modes sometimes carrying more energy than the R0 mode thus making the assumption invalid. In surface-wave testing, one solution used to mitigate the problems associated with the presence of higher modes in the recorded signals is to use a multichannel technique (Multichannel analysis of surface waves-MASW, Multi modal analysis of surface waves-MMASW) (Gabriels et al., 1987; Karray, 1999; Park et al., 1999; Beaty et al., 2002). Once identified, higher modes can be used in the analysis (inversion) and enable the calculation of soil profiles that can be considered optimal (Karray and Lefebvre, 2008). Nevertheless, although accurate as it will be shown in Section 5.1, the simultaneous use of several receivers in the analysis decreases the horizontal resolution of the survey and may not be suitable for the detection of relatively small discontinuities on the surface of an underground structure (Tremblay et al., 2017). Although not as accurate in terms of vertical resolution, it was shown in part I that independently analysing each signal increases the horizontal resolution of the survey. However, when analysing each signal independently, it is important to use a signal processing technique that prevents mode misidentification problems as it will be shown in Section 3. The term mode misidentification is used in this study to refer to the possibility of mistaking one wave group for another (Zhang and Chan, 2003; Gao et al., 2014). Such wave groups may for example be two different Rayleigh wave propagation modes that would either cross or overlap in the time-frequency (or velocity-frequency) plane (Karray 1999; Karray and Lefebvre, 2009).

In this study, the use of 3D numerical modelling allows to realistically reproduce the type of underground structures investigated (Section 2). The algorithms used to compute the dispersion curves are also different from the ones used in part I and are briefly presented in Section 3. The influence of the pavement and the manhole on the propagation velocity of elastic waves is investigated using FLAC3D in Section 4. A comparison of the results obtained with FLAC3D with the ones obtained experimentally and shown in part I is presented in Section 5.1. Another receiver configuration that can be used during the field tests is proposed (Section 3) and it is shown how the analysis of the signals collected using this configuration enables to better identify the location of anomalies present on the surface of real underground structures (Sections 5.1-5.2-5.3). Finally, it is shown in Section 5.4 how this receiver configuration enables to compute a 3D tomography representative of the condition of the surface of the lid of the concrete structure.

2. Cases considered

2.1. Experimental site

To verify the effectiveness of different nondestructive techniques for the inspection of the surface of the lids of their underground utility structures, Hydro-Québec constructed six underground structures on its experimental site located in Varennes, Qc, Canada. Fig. 2 shows the location of these structures which can be located based on the position of their manhole. The condition of the surface of the lid of three of these structures (A, B and C) is investigated in this study.

The experimental site (Fig. 2) is the same as the one presented in part I and the labels used for the structures and the lines are in accordance with those used in the previous study. The structures build on the experimental site are similar in dimensions and geometry to the type of utility structures found in many cities (Fig.1). The structures are all overlaid by a uniformly compacted granular soil layer of a depth varying between 0.5 and 1.0 m on top of which is a layer of asphalt (0.07 m) or concrete (0.2 m). This configuration simulates the presence of the road and sidewalk under which these structures are often located. Each structure is accessible from the surface of the soil by a manhole which appears as a dark (brown) circle in Fig. 2.

The equipment used during the field tests to record the acceleration of the soil is shown and described in part I. It consists of accelerometers linked to an acquisition system and a portable computer used to analyse the collected data. During the field tests, energy is introduced into the soil using a hammer hit on a metallic plate. As explained in part I, while the receivers may be placed directly on the pavement, the source needs to be in direct contact with the surface of the soil to introduce a sufficient amount of energy into the soil.

2.2. Numerical modelling in 3D

When it comes to model the propagation of elastic waves in complex mediums such as those considered in this study, numerical methods are preferred over analytical or semi-analytical solutions such as the thin

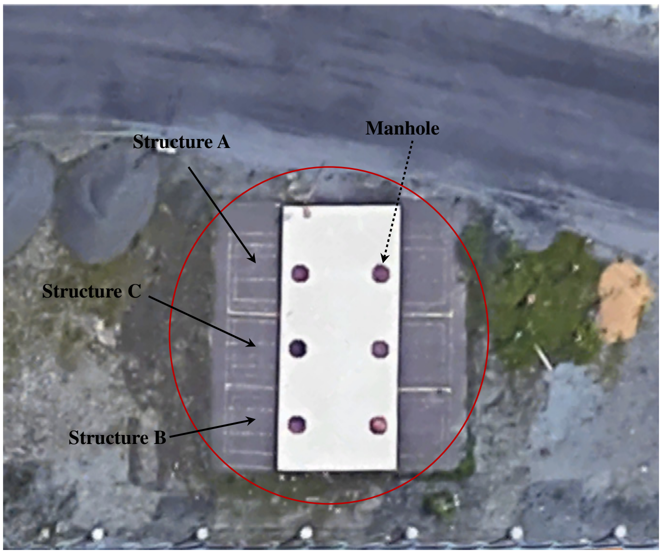

Fig. 2. Aerial view showing the experimental site where the structures are located. Each structure can be located based on the position of their manhole (dark circles).