Tunnelling and Underground Space Technology 70 (2017) 254–261

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Identification of filler type in cavities behind tunnel linings during a subway tunnel surveys using the impulse-response method

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ARTICLE INFO

Keywords:
Tunnel
Void
Lining
Filler
NDT
FEM

ABSTRACT

A method of recognizing the filler type in cavities behind a tunnel lining based on the acoustic response to impacts is considered. This method provides a comparison between response signal spectra registered on real objects and spectra of modelled signals obtained using finite-element modelling. The model takes into account the properties of solids and fluid filling the cavity. Filler material is identified from the maximum of the correlation coefficient R between spectral components of the modelled signal and the signal obtained during an actual survey of subway tunnels. In the given example, the correlation coefficient of the spectra when the void is filled with water is $R = 0.91$, which is higher than for other filling media.

1. Introduction

One of the important goals of monitoring subway tunnels is to reveal voids behind the lining and to detect what they are filled with. Voids form for various reasons: low quality backfilling or tamping after tunnelling, transport vibrations, construction work close to tunnels, and natural or man-made objects, such as karsts, running soil, and waste landfills. The presence of voids can cause an asymmetric tension distribution, create stress concentration points near void boundaries (Kamel et al., 2012; Shi and Li, 2015), and cause impermissible deformations and lining destruction (Jifei et al., 2014; Bock, 2014) as well as promoting crack formation (Meguid and Dang, 2009; Kamel et al., 2015), waterproofing defects, rail basement and track deformation, and surface settlement (Vu et al., 2016; Camos et al., 2016; Guo et al., 2014).

Non-destructive acoustic test methods play an important part in detecting voids behind the lining. Two versions of these methods are the most common in the practical testing of concrete structures: ultrasonic surface waves (USWs) and impact-echo (IE) (Azari et al., 2014). The USW method involves the measurement of surface waves' speed in order to define the concrete strength, find cracks, evaluate the elastic moduli (Li et al., 2016), and find internal voids in structures (Azari et al., 2014). The USW task range is rather close to tasks encountered during tunnel lining surveys, but the USW method is seldom used for investigating voids behind linings. The physical base of IE is the formation of standing waves influenced by features of signal reflection at the lining–soil boundary. The bias and extent of spectral peaks (Chaudhary, 2013; Aggelis et al., 2008; Sadri, 2003; Kapustin, 2008) as well as signal form analysis, the duration of the spectral maxima existence (Aggelis et al., 2008; Song and Cho, 2009), and correlation function parameters (Feng et al., 2015) are used as informative parameters in the detection of voids and lining damage.

Impulse response (IR) is another method that is frequently used for void detection behind linings (Wimsatt et al., 2013; Davis et al., 2005; Baukov and Baukov, 2006). If IR is used, the structure's response to impact action is analysed. Compared to the IE and USW methods, the IR method uses lower frequency and higher impact force (Davis et al., 2005). The presence of a void behind the lining increases the amplitude of bend vibrations (Baukov, 2007). Both spectral and wave features of responses are informative parameters here. Problems with the detection of small voids are disadvantages of the IR method (Wimsatt et al., 2013). Measuring simplicity and the high speed of the survey as well as noise resistance may be deemed as its advantages. The list of methods can be continued (Mazzeo et al., 2012; Suda et al., 2004; Gao et al., 2014; De La Haza et al., 2013; Yu et al., 2016), but other approaches have a number of problems such as expensive equipment, low resistance to acoustic noise, laboriousness, and so on. At the same time, the IR method has a number of advantages. The low frequency range corresponds to big wavelengths and a larger experimental impact area. This makes it possible to increase the speed of the tunnel survey, which is important in surveys of operational tunnels where train traffic is stopped for a short period only. The IR method will be considered hereinafter as the basic one.

The practical value of information on the condition of the space behind the lining is that it makes it possible to plan tamping, to evaluate the lining stress by modelling (Jifei et al., 2014; Leung and Meguid,

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http://dx.doi.org/10.1016/j.tust.2017.07.010
Received 24 September 2015; Received in revised form 21 January 2017; Accepted 17 July 2017
0886-7798/

2011), and to evaluate the impact of seismic waves on the tunnel (Sedarat et al., 2009). Answering the question “What fills the void – gas or water?” is a special challenge. A literature review has shown that this problem is rather poorly investigated. Publications (Azari et al., 2014) contain studies describing the sensitivity of non-destructive methods to void-filling media but these studies are related to voids inside concrete structures only. Definition of the filler type is important because tamping is performed via special service holes. When these holes are opened, ground water under pressure can rush into a tunnel, and preparations for this need to be made in advance.

Thus, we can notice that the detection of void positions behind the lining is a frequent problem. At the same time, the challenge of defining what these voids are filled with is rather poorly investigated despite the fact that in practice it is often necessary to solve it. The aim of the investigations described in this publication is to develop a method to detect void-filling media (water, air, water–soil mixture) based on real surveys and to interpret the results using numerical simulation.

2. Investigation method and problem formulation

2.1. Surveys in real subway tunnels

Tunnel surveys were performed under real conditions of operational subway tunnels. Surveys were performed at night time when trains do not circulate on tracks (the so-called “night window”). A two-channel seismic station IDS-1 (Logicheskie sistemy – IDS-1, 2016) with electrodynamic sensors was used. The registration parameters were a data recording system bandwidth of 7 Hz to 8 kHz, a sampling frequency of 96 kHz, and a realization length of 21.3 ms. The transducer was pressed down onto the lining during the survey. A series of 5–10 strokes were made on the lining 10–30 cm away from the transducer. The recording process was started in case the threshold was exceeded, and then the signal prehistory was also recorded. The obtained signals were averaged. Fig. 1 shows an example of the waveforms for various void fillers behind the lining.

If no void exists (Fig. 1a), waveforms feature low amplitude and fast signal fading. Soil behind the lining acts as a damper. If a void exists, the waveforms feature a greater amplitude and slow fading (Fig. 1b). In this case, the lining acts as a membrane and the damping action of the media behind the lining is much less than that for soil. Low-frequency spectrum components also appear in some cases if a void exists (Fig. 1c). It is convenient to evaluate the described signal features using the energy parameter:

$$E_p = \int_0^{t_{\max}} A^2(t)dt, \tag{1}$$

where $t_{\max}$ is the duration of signal recording; E_p is an energy parameter value for the time range between $t = 0$ and $t = t_{max}$; and $A(t)$ are the signal values. For digital signal processing, Eq. (1) looks as follows:

$$E_D = \sum_{i=0}^{n_{\max}} A_i^2 \cdot \Delta t, \tag{2}$$

where $n_{\max}$ is the number of the samples corresponding to $t_{\max}$; A_i is the i-th signal value; E_D is the energy parameter at an acquisition interval with count numbers $n = 1 \ldots n_{max}$; and Δt is the sampling interval. It should be noted that this is not about the physical meaning of signal energy but about an informational energy parameter. If this parameter exceeds a certain threshold, it means that a void exists behind the lining.

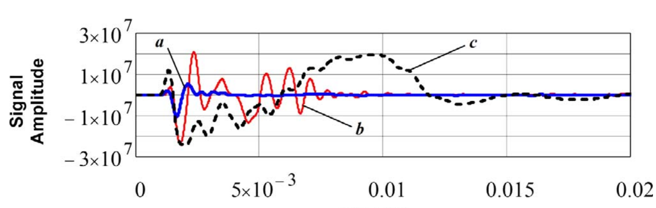

Fig. 1. Example of waveforms for various void fillers: a – no void behind lining, b – void exists behind lining, c – void exists behind lining, an instance with prominent low-frequency signal components.

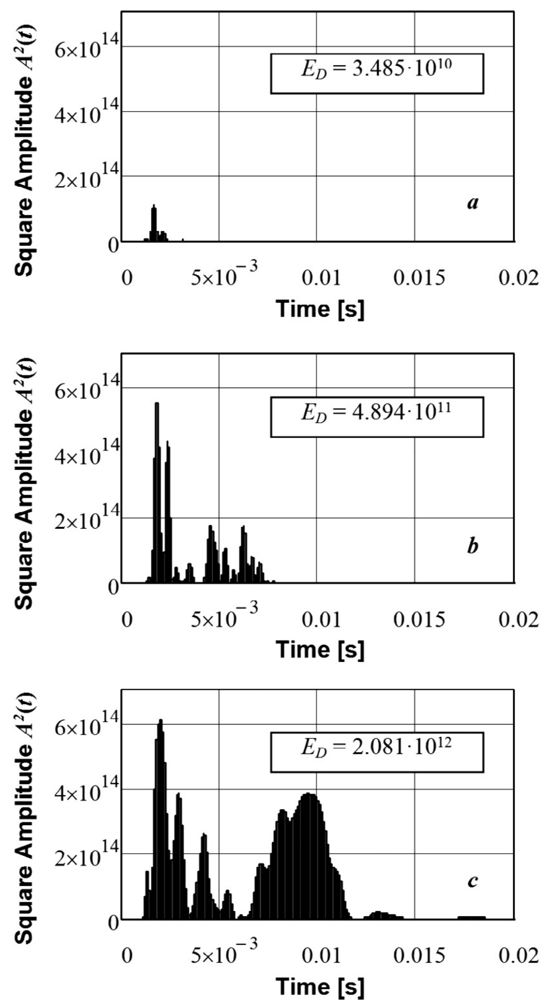

Fig. 2. Examples of functions $A^2(t)$ and estimates E_D corresponding to instances with and without a void behind the lining. Plots a, b, and c correspond to waveforms a, b, and c in Fig. 1 (a – no void; b, c – void exists).

Longer signals with higher amplitude have higher energy, which indicates the existence of a void behind the lining. This is illustrated by the examples shown in Fig. 2, where plots of the $A^2(t)$ function for the signals shown in Fig. 1 are displayed. It can be seen that the area beneath the plots of the $A^2(t)$ function is proportional to E_D; it is larger if a void exists behind the lining (Fig. 2b and c). This can also be seen from the calculated E_D values, which are orders of magnitude larger for an existing void than for an absent one. The threshold E_D level, which, if exceeded, indicates the presence of a void, is established based on a survey of reference sections with known void positions.

The frequency of the spectrum peak $F(A_{max})$ for the registered signal was also used as an informative parameter. Low $F(A_{max})$ values indicate the presence of a void since they appear due to flexural oscillations of lining that is not pressed by soil and may also be related to standing waves that form in water-filled voids. Fig. 1c shows an example of a waveform containing low-frequency components. This component changes the signal spectrum significantly and also increases E_D (Fig. 2c).

The values E_D and $F(A_{max})$ between points were interpolated using the Kriging method and plotted in the form of maps during the processing of survey results. An example of these maps for cast iron lining