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Monitoring for close proximity tunneling effects on an existing tunnel using principal component analysis technique with limited sensor data

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ABSTRACT

A realistic field monitoring application to evaluate close proximity tunneling effects of a new tunnel on an existing tunnel is presented. A Principal Component Analysis (PCA)-based monitoring framework was developed using sensor data collected from the existing tunnel while the new tunnel was excavated. The developed monitoring framework is particularly useful to analyze underdetermined systems due to insufficient sensor data for explicit relations between force and deformation as the system input and output, respectively. The analysis results show that the eigen-parameters obtained from the correlation matrix of raw sensor data can be used as excellent indicators to assess the tunnel structural behaviors during the excavation with powerful visualization capability of tunnel lining deformation. Since the presented methodology is data-driven and not limited to a specific sensor type, it can be employed in various proximity excavation monitoring applications.

1. Introduction

Sensor-based continuous monitoring techniques are employed to ensure structural safety during construction. In geotechnical engineering, the monitoring techniques often used is the Observational Method after Peck (1969) to collect necessary geotechnical instrumentation measurements to assess the behavior of the structure during construction; the original design, usually based on most unfavorable assumptions, can be modified for most probable conditions based on the actual measurements for maximum economy and assurance of safety. Structural Health Monitoring (SHM) is another major application of the sensor-based continuous monitoring techniques to detect damage and characterize structural conditions for a wide range of structures in civil, mechanical and aerospace engineering (Doebling et al., 1996; Sohn and Laboratory, 2004; Farrar and Worden, 2007).

Sensor-based monitoring techniques have been applied to various tunnel applications, and some examples are as follows: Carvalho and Kovári (1977) studied displacement measurements as means for safe and economical tunnel design using distometers; Forth and Thorley (1995) reported a monitoring study of the ground and buildings affected by the tunnel construction of the Mass Transit Railway in Hong Kong using ground settlement measurements; Inaudi et al. (1998, 1999) evaluated fiber optic sensors for different tunnel types, including a dam tunnel, a cut and cover tunnel, and a Tunnel Boring Machine (TBM) tunnel. Multi-point optical extensometers were applied to measure vault curvature of tunnel linings for short and long-term monitoring applications; Carnevale et al. (2000) monitored TBM-induced ground vibration using geophones with a sampling frequency at 300 Hz. They measured change in steady state particle velocity at different distances from the TBM; Tsakiri et al. (2006) used a terrestrial laser scanner for deformation monitoring; James (2006) developed an automatic tunnel measuring system to guide boring machines underground based on displacement data; Zeidler and Schwind (2007) compared Finite Element Analysis (FEA) results with monitoring results using surface settlement and in-tunnel deformation sensors for 15 m wide vehicular tunnel under shallow ground cover that was constructed with the New Austrian Tunneling Method (NATM) in Singapore; Vardakos (2007) studied the back-analysis methods for optimal design for supported and unsupported tunnels, including simplified parametric identification, parametric identification using a local

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optimization method, simulated annealing method, and differential evolution technique; Kosnik et al. (2009) applied continuous monitoring technology in an in-service utility tunnel application using LVDTs and crack gauges at 14 construction joints combined with a web-based, data-driven decision making system; Colombo et al. (2012) monitored tunnel inflow in permeable rocks nearby a river; Mohamad et al. (2012) monitored twin tunnel interaction using Brillouin optical time-domain reflectometry (BOTDR). The data were analyzed using three parametric approaches: the symmetrical ovaling of tunnel lining, symmetrical ovaling of tunnel lining, and integration of actual strains to displacements.

The premise of these sensor-based continuous monitoring techniques is that a signature of structural hazard or failure can be observed from sensor datasets to ensure structural safety at different stages of construction and operation. With the recent advances in sensing and data acquisition technologies, the collection of instrumentation data can be done relatively easily. However, one can still come across many technical challenges in interpreting complicated raw sensor measurements: the *data* should be processed to extract meaningful *information*. A comprehensive literature survey on parametric and non-parametric inverse analysis and system identification techniques for geotechnical structures can be found in Yun and Reddi (2011).

Under realistic field conditions, one can encounter the following technical challenges in monitoring:

- Tunnel failure mechanism can vary depending on construction phases that affects structural capacity and load combination. In addition, since tunnel collapse mechanisms commonly involve brittle failures, it is critical to detect a "small" signature prior to tunnel collapse, which is related to structural failure from sensor datasets. Moreover, tunnel collapse is usually initiated from localized structural defects. Therefore, *spatio-temporal* identification of a potential structural failure is critical in tunnel safety monitoring.
- Field sensor data are usually influenced with various environmental factors (e.g., ambient temperature and humidity variations) represented as "large" daily, seasonal and yearly trends in sensor time-history data, which obscure the important "small" signature of structural failure. Therefore, to improve the detectability of structural failure, efficient data processing techniques are necessary to separate the structural failure factors from the environmental factors.
- Complex structural behavior of tunnel systems can be expressed using coupled thermo-hydro-mechanical (THM) models: their system input (or force) and system output (or deformation) relations are defined with numerous system parameters associated with a set of interrelated differential equations. In forward analysis, THM models are efficient to estimate structural response for given system parameters and structural excitation conditions. In inverse analysis, however, a large number of sensors should be employed to obtain all necessary system input–output data in the parameter identification, which results in increasing data acquisition costs. Consequently alternative modeling approaches are desirable in monitoring applications, which do not require explicit relations between the system input and the system output.

To address the above technical challenges, a Principal Component Analysis (PCA)-based monitoring methodology is presented. Since the methodology is data-driven using response-only sensor data and therefore is not limited to a specific sensor type, it can be used in various tunnel monitoring applications when sensor data are insufficient to determine explicit relations between the input forces and the output responses of tunnel structures. Here, the response-only data are defined as the sensor data measuring the output response or tunnel deformation (e.g., strain, slope, displacement, acceleration, pore water pressures), and the input forces (e.g., service loads, excavation-induced loads, thermal loads) are not used during data processing procedures. Therefore, the monitoring framework presented in this study is particularly designed for the case that one needs to monitor civil engineering structures during construction to evaluate important structural behaviors at different construction phases when the structures are *underdetermined* due to insufficient sensor data. In order to demonstrate the feasibility of the monitoring methodology, a field experimental study of a close proximity tunnel excavation site is presented.

This paper is outlined as follows: the proximity tunnel construction site is described in Section 2; Sensor installation on the tunnel is described in Section 3; The data-driven signal processing techniques used in this study are described in Section 4; and the analysis results are discussed in Sections 4 and 5.

2. Site description

To demonstrate how the aforementioned monitoring methodology can be applied, a realistic railway tunnel construction site was selected: a new tunnel (NT) was excavated adjacent to an old single-track tunnel (OT) in parallel with the ground pillar width of about 10 m (Fig. 1). A sensor network was installed in a cross-section of OT in its lining direction to observe the NT excavation effects on the OT to monitor structural safety in different phases of the construction.

The OT was constructed in 1981 as a single-track railway tunnel using the American Steel Support Method (ASSM) between the Ajoong and Sinri Stations on the Jeolla Line owned and operated by the Korail in Korea (Lee et al., 2006). The tunnel dimensions are 5 m in width, 6.2 m in height, and 1,231 m in length, located between 30.285 km and 31.516 km from the Ajoong Station (Sta. 30k 285 $\sim$ Sta. 31k 516). In 2008 as a part of the Jeolla Line double-tracking project, the NT was constructed using the New Austrian Tunneling Method (NATM) in parallel to OT. The NT dimensions are 11 m in width, 9 m in height, and 1245 m in length, located between 29.880 km and 31.125 km from the Ajoong Station (Sta. 29k 880 $\sim$ Sta. 31k 125). The tunnel cross sections are illustrated in Fig. 1. Since the ground pillar width between OT and NT was designed for only about 10 m which is smaller than the width of the NT cross section, it is critical to ensure that the NT excavation should not structurally weaken the OT during its construction.

Fig. 2 shows the plan and longitudinal views with geological profile of the tunnel site. Since, the geological conditions near the start point were considered weaker than those near the ending point according to a geological survey conducted in 2007 (Park, 2008), monitoring for OT near the starting point was conducted during NT construction.

The NT was constructed in 2008 using the top-heading and bench method. The advance of NT excavation was recorded during construction, and the locations of top-heading and bench excavation fronts are shown in Table 1. To measure the effects of NT excavation on OT, an array of sensors was installed at the location of Sta. 30k 475 (190 m from the starting point tunnel at Sta. 30k 285). The values in the parenthesis in Table 1 are the distance between the top-heading front and the sensor location (d_t), and the distance between the bench front and the sensor location (d_b). The negative value indicates that the excavation front locates *before* the sensing location in the direction of excavation, and the positive value indicates that the excavation front locates *after* the sensing location. The details of the sensor array and instrumentation will be described in Section 3.

The NT excavation began on May 27, 2008. The top-heading front passed the sensor location on October 2, and the bench front followed the top-heading front on October 30, 2008.