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Fragility analysis of gray iron pipelines subjected to tunneling induced ground settlement

Pengpeng Ni[a,b], Sujith Mangalathu[c,*]

[a] School of Civil and Environmental Engineering, Nanyang Technological University, Singapore 639798, Singapore
[b] MOE Key Laboratory of High-speed Railway Engineering, Southwest Jiaotong University, Chengdu 610031, China
[c] Department of Civil and Environmental Engineering, University of California, Los Angeles, CA 90095, USA

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ABSTRACT

Tunnel excavations can cause ground surface settlement which in turn affects the structural integrity of adjacent pipelines. This paper explores the probabilistic risk assessment of gray iron pipes subjected to tunneling. In the beam-on-spring analysis, a modified Gaussian distribution profile was incorporated as displacement-controlled boundary conditions on spring elements. The modeling strategy was evaluated by comparing calculated pipe strains with field and centrifuge experimental measurements, as well as empirical solutions. The calibrated numerical model was then used to perform parametric fragility analyses using a machine learning technique called Lasso Regression to demonstrate the relative importance of various parameters. It has been found that existing pipelines with a smaller pipe diameter and a larger pipe wall thickness buried at a shallower depth in loosely compacted soils with a smaller soil friction angle are less prone to failure due to tunneling induced ground settlement.

1. Introduction

Pipelines form a network to transport essential products for human society to wide geographic areas. Except for offshore pipelines or pipelines in permafrost regions (e.g., Trans-Alaska Pipeline System), most pipe installations are buried underground to avoid disturbance by human activities. However, the integrity of pipeline network can still be influenced by different sources of differential ground movement. Unfavorable ground conditions can be induced either by natural disasters or human activities. Over several decades, the detrimental effect of ground discontinuity due to natural hazards has been recognized incrementally from the development of analytical solutions (Trifonov and Cherniy, 2010; Karamitros et al., 2011; Wang et al., 2011a; Kouretzis et al., 2015), reduced-scale experiments at elevated gravity (Saiyar et al., 2016), prototype-scale laboratory tests (Erami et al. 2015; Ni et al., 2018a), and numerical simulations (Balkaya et al., 2012; Wols and van Thienen, 2014; Ni et al., 2018b).

The tunnel-pipeline interaction problem is inherently complex due to the difficulty in estimating the ground settlement and its effect on pipelines. The profile of ground settlement trough needs to be determined carefully for various geological conditions, tunnel diameters, cover depths, and excavation methods. Mair and Taylor (1997) presented an excellent review of the problems encountered while evaluating the settlement trough due to tunneling. Recently, different techniques have been used to facilitate a better understanding of the ground surface settlement during tunneling. Field responses of tunneling induced settlement were observed using distributed optical fiber sensing systems (Mohamad et al., 2010; Mohamad et al., 2012; Hauswirth et al., 2014; Klar et al., 2014). Although the field data are important to calibrate calculation models for settlement trough, field testing is an expensive approach and the measured data often contain huge variations that hide trends of the mechanism. Alternatively, controlled laboratory tests were performed to model the tunnel excavation process in the centrifuge environment (Chapman et al., 2007; Marshall et al., 2012; Ma et al., 2017). Marshall et al. (2012) indicated that the settlement trough arising from tunneling could be influenced by the backfill material, and different calculation models should be used for clays and sands considering the difference in volumetric behavior on shearing. Advanced numerical approaches were employed to investigate the soil displacement profiles due to tunneling (Vlachopoulos and Diederichs, 2009; Zheng et al., 2015; Ma et al., 2017). However, the application of numerical methods requires calibration of constitutive models and professional expertise. The simplest form of estimating the settlement trough is to develop either empirical formulas or analytical solutions. Some empirical correlations, such as Gaussian distributions, have been proposed based on field measurements of

* Corresponding author.
E-mail addresses: pengpeng.ni@ntu.edu.sg (P. Ni), sujithmangalath@ucla.edu (S. Mangalathu).

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surface settlement profiles above tunnel (O'Reilly and New, 1982; Attewell et al., 1986; Mair et al., 1993; Marshall et al., 2012). Analytical models have also been developed for tunneling induced ground movement in an elastic half-plane (Verruijt and Booker, 1996; Park, 2004, 2005).

Another issue that requires extensive understanding is the mechanism by which pipelines are affected by tunneling induced settlement trough. The response of adjacent buried pipelines has been monitored during tunnel excavations in the field (Takagi et al., 1984). In the laboratory, reduced-scale model tests have been performed at increased gravity to provide experimental data of pipe strains subjected to tunneling (Marshall et al., 2010; Shi et al., 2016b). All these available data can be used to calibrate their numerical or analytical models. Zhang and Huang (2012) studied the interaction between pipe and tunnel using a boundary element model. A boundary integral method has been developed to estimate pipe strains under the influence of tunnels, and the approach can provide elastic (Vorster et al., 2005; Klar et al., 2008) and elastoplastic solutions (Klar et al., 2007). Klar and Marshall (2008) compared two modeling strategies for pipelines using shell and beam representations in finite difference analysis. They found that the elastic beam theory could produce comparable results to the shell element theory as long as the relative pipe-soil stiffness was greater than 1500. However, the complexity of continuum based analyses hinders their use in fragility analysis since a large database needs to be generated. Alternative numerical method of beam-on-spring analysis is advantageous to reproduce the effect of tunneling on pipelines in a much shorter time span when the pipe has a high flexural rigidity. The pipe is modeled as a beam type structure surrounding by a series of independent elastic-perfectly plastic Winkler springs acting along the pipe. The application of Winkler analysis on pipelines crossing tunneling induced settlement trough can be found in the literature for both continuous (Klar et al., 2005; Wang et al., 2011b) and segmented pipes (Shi et al., 2016a; Wham et al., 2016).

The detrimental effect of tunnel excavations on pipelines has been previously identified, but there are limited studies on the fragility analysis of the tunnel-pipeline interaction problem in order to calculate the risk of pipe failure due to excavations of a nearby tunnel. A fragility curve represents a conditional probability to indicate the likelihood that a pipeline will meet or exceed a predefined limit state for a given intensity measure (IM) of settlement trough. Fragility analyses have been conducted on pipelines crossing other types of differential ground motion, such as unstable slopes (Zhou, 2012), and climate change induced soil settling (Wols and van Thienen, 2014). The impact of differential ground movement on pipelines could also vary significantly depending on the pipe material. A successful tunneling project can limit the volume loss to 1–2% during excavation (Mair and Taylor, 1997; Marshall et al., 2010), such that the magnitude of the ground settlement could be minimized. Normally, most pipes, such as steel, ductile iron, and thermoplastic polymer (polyvinyl chloride and polyethylene) pipes, can withstand a certain level of soil displacement. However, gray iron pipes were found to be prone to damage due to limited ground discontinuity (Seica and Packer, 2004; Balkaya et al., 2012; Rajani and Abdel-Akher, 2012; Chan et al., 2015; Erami et al., 2015). Therefore, fragility analysis on gray iron pipes subjected to tunneling needs to be investigated in detail. Note that the generation of fragility curves for all possible pipe configurations is beyond the scope of the current research, and the methodology is illustrated with a specific case study. Dukes (2013) explored the application of fragility curves in design offices by providing a probabilistic information on the structural performance than the traditional deterministic one. Understanding the likelihood of damage levels that the functionality and restoration of service is important these days and fragility curves generated in this study can be used to estimate the probability of pipeline failure for a set of input parameters.

In this paper, a finite element model was calibrated for continuous gray iron pipelines using beam-on-spring analysis technique. The tunneling induced settlement trough was characterized using a Gaussian distribution model, which was input as boundary conditions for soil elements in numerical simulations. The efficacy of numerical models was assessed by comparing calculated pipe strains with those measured in the field (Takagi et al., 1984) and in the laboratory (Shi et al., 2016b), as well as numerical data of other researchers (Wang et al., 2011b). Upon the successful calibration of numerical models, fragility analysis was performed using a machine learning technique called Lasso Regression. The procedure of the fragility framework is outlined in Section 3. Parametric fragility analyses were also performed to characterize the uncertainties of all influencing parameters, including soil (e.g., internal friction angle, and unit weight), pipe (e.g., pipe diameter, wall thickness, Young's modulus, and Poisson's ratio) and tunnel parameters (e.g., tunnel diameter, maximum settlement, and length scale of settlement trough) and burial configurations (e.g., pipe burial depth, tunnel cover depth, and tunnel-pipeline crossing angle).

2. Behavior of pipelines and numerical modeling

2.1. Settlement trough

The tunnel-pipeline interaction problem needs to be analyzed in two steps: (a) determination of ground settlement trough induced by tunneling, and (b) modeling the interaction between soil and pipe by setting the settlement trough as boundary conditions in numerical analysis.

A schematic illustration of three-dimensional ground settlement profiles induced by tunnel excavation is presented in Fig. 1a. A Gaussian distribution (Attewell et al., 1986) can be used to represent the ground settlement trough S (x, y) as follows:

$$S(x,y)=\frac{S_{\max}}{2}\exp\left(-\frac{y^2}{2i^2}\right)\left[\operatorname{erf}\left(\frac{x-X_f}{i\sqrt{2}}\right)-\operatorname{erf}\left(\frac{x-X_s}{i\sqrt{2}}\right)\right] \tag{1}$$

where the tunnel centerline is positioned along the x-axis; $S_{\max}$ denotes the maximum settlement that occurs right above the tunnel face, and the settlement reduces with increase in the distance along the direction of the tunnel advancement; i is the distance measured from the tunnel centerline to the inflection point of the settlement trough; the Gauss error function erf(x) has a sigmoid shape and it turns to be 1 or -1 when x approaches positive infinity ($+\infty$) or negative infinity ($-\infty$), respectively; X_s and X_f are the entry and exit locations of tunnel excavation. Generally, this Gaussian distribution can be simplified to S (y) by assuming that the tunnel-pipeline crossing location of concern is far away from the starting and final locations of the tunnel face.

$$S(y)=S_{\max}\exp\left(-\frac{y^2}{2i^2}\right) \tag{2}$$

The effectiveness of the general Gaussian distribution to approximate the ground settlement profile has been demonstrated through field measurements (O'Reilly and New, 1982; Mair et al., 1993) and reduced-scale laboratory tests in the centrifuge environment (Chapman et al., 2007; Shi et al., 2016b; Ma et al., 2017). Although different forms of modification to the Gaussian representation of the settlement trough have been proposed for various backfill conditions (Vorster et al., 2005; Marshall et al., 2012), the general Gaussian distribution is adopted in this investigation due to its simplicity. Saiyar et al., (2016) and Ni et al. (2018a) indicated that the accuracy of beam-on-spring analysis could be improved by using correct soil stiffnesses rather than by imposing a more realistic ground displacement profile.

O'Reilly and New (1982) suggested that the i value could be correlated with the cover depth, Z (measured from the ground surface to the tunnel centerline), of the tunnel as follows:

$$i=K\times Z \tag{3}$$

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