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A probabilistic design approach for load of metro tunnel induced by surrounding development
Part A: Determination of development intensity

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ABSTRACT

Adjacent development causes metro tunnel problems in soft-soil areas. A mathematical framework based on conventional integration and probabilistic method is purposed to include development-induced external loads into a metro tunnel design. In this framework, the development-induced load on the tunnel is a convolution of development intensity on the load-transfer functions over the adjacent area of the metro line. The development intensity is related to the urban development pattern, which is gathered by using categorized statistics. The load transfer functions adopt analytical solutions and empirical equations describing construction impacts on surrounding soil or structures. Monte Carlo simulations are used to generate the development impact, i.e., the load and displacement, on the basis of which the design value under a certain reliability index can be obtained. Therefore, determination of the development-induced load is divided into two stages. Part A of the paper introduces a statistical description of the development intensity of a location. Street blocks and metro stations are qualitatively cataloged with respect to development trends, periods, and frequencies. Maps, satellite photos, and street views are used to collect data in three Chinese cities: Shanghai, Guangzhou, and Nanjing. For each city, samples include the central station in the new district, and the central station, grouping station, and intermediate station in the built-up areas. In addition, residential districts inside and outside the inner ring in Shanghai are analyzed. The distribution of the building heights and stories with distance, the proportion of urban renewal with time, and the areas/depths/shapes of the excavations are obtained. The development patterns of blocks surrounding the metro line and the residential areas are analyzed. These data become input descriptions of development intensities in Monte Carlo simulations. Part B of the paper introduces the load transfer functions and the generation of loads on the tunnel.

1. Introduction

Metro tunnels in soft-soil areas are vulnerable to excessive settlement and secondary cracks with leakage during operation. Current research projects mainly concentrate on deformation mechanisms, settlement control, and structural repair methods. Existing literature considering deformation mechanisms shows that the geological conditions of the underlying stratum, construction quality, cyclic trainload, groundwater infiltration, water level changes, and regional subsidence are major contributors to structural changes during the operation period. Adjacent development is responsible for the long-term settlement of a tunnel; in some cases, nearby construction is the dominating factor in tunnel deformation (Ng et al., 2013; Shen et al., 2013, 2014; Di et al., 2016). An observation of the Nanjing Metro line (Di et al., 2015, 2016) noted formed settlement troughs in the densely constructed area, and their maximum cumulative settlements reached 122 mm after only four years of operation. Zhou et al. (2016) investigated cracks in these shield tunnels and proved the impact of adjacent construction activities. The separation of ballastless track beds and linings was also reported in Zhou et al. (2016) and Di et al. (2016). A useful method of reducing tunnel settlement is to set up a railway protection zone. Construction projects in this area are strictly designed and extensively monitored, as reported in Hu et al. (2003), Tan et al. (2015), and Liu et al. (2016). Another routine shown in Richards (1998) and Chang et al. (2001a, 2001b) is to improve the tunnel and soil with foundation treatments, secondary grouting, nearby unloading and lining reinforcement

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measures, and to repair segment cracks after large deformations or displacements occur. All of these measures will increase the maintenance cost of a metro tunnel during the operation period, or increase the costs outside of the metro system.

Nearby construction changes the loading states of existing structures. At present, the design code for metro tunnels regulates the load caused by environmental variance; however, the determining method for magnitude is not given. The International Tunneling Association (2000), Chinese code GB50157 (2013), considers only the ground surcharge. The surcharge is considered vertically at 20 kPa in Chinese GB50157 (2013). The Japanese design guideline (2010) takes account of parallel tunnel influence and adjacent construction activities. In addition to evaluating loads precisely, the guideline confirms the necessity of considering load variance with time (for both load history and lining) and distinguishes between temporary and permanent loads. However, this calculation is based on the complete information of a nearby construction scheme, and the specific process is absent.

Urban rail transit has been determined to promote surrounding area development. With modern urban planning concepts, the city adopts transit-oriented development (TOD Standard, 2017) to fully develop an area and optimize the land utilization. In this case, regions surrounding the metro line will form highly mixed, densified, and compacted communities to match the transit capacity. Even without TOD, research from Cervero et al. (2009), Sung et al. (2014), and Chorus and Bertolini (2016) showed that business opportunities brought by the human flow of rail transit improves the convenience of the surrounding area and will attract high-density buildings under market circumstances. In large cities, the intensified utilization of land and underground space create further disturbances to the geologic strata. Such environmental variance will increasingly affect the structural serviceability of metro tunnels.

During the entire operation period of a metro tunnel, the number of load variances caused by surrounding development is small, but the magnitude cannot be neglected. Therefore, to improve the serviceability and durability of the tunnel structure and to achieve the optimum cost benefit, the tunnel design should consider the inevitable changes in the load state caused by surrounding development during metro operation. This paper provides a preliminary investigation of development-induced load on a tunnel with respect to the usage characteristics of shield tunnels for urban rail transit in China, in order to provide a better understanding of load effects and load combinations during the design stage.

2. Quantification method for surrounding development-induced tunnel loads

The design method of geotechnical engineering has transformed from the allowable stress method to the limit state design based on reliability theory. The stochastic process of surrounding development after tunnel operation even enhances the necessity of reliability-based design. With regard to reliability theory, a complete analysis of the quantitative response of a tunnel structure to its surrounding development contains the following five steps:

1. Establish the distribution of development activities: Several statistical indexes of development activities are chosen as basic random variables, and statistical descriptions of these indexes are researched and analyzed.
2. Define the load transfer mechanism of the surrounding development: By obtaining the load effect for the surrounding development of the tunnel, load-transfer functions are defined to describe the relationship of the load effects to the statistical indexes of development.
3. Analyze the tunnel response: A calculation method is necessary for the tunnel response under the surrounding development. Under certain design objectives, even utilizing functions of certain structural measures against development-induced loads may be established.
4. Conduct a random characteristic analysis of the load effect by the surrounding development: In this step, load combinations are used to describe superimposing possibilities of every single effect of the comprehensive development activities, and its relationship function with the basic random variables is obtained.
5. Limit state design of tunnel lining: According to different design objectives, the reasonable structural limit state, design condition, target reliability index, and corresponding load combinations and partial factors are determined.

To summarize, the quantification of the complete environmental variation process and its effect on existing structures requires significant systematic work. Under the existing design framework, this paper concentrates on common building development activities and their impact on a cross section of the tunnel structure, and puts forward a quantification approach for the first and second steps above.

Obviously, the additional effect caused by the surrounding building development is a variable effect that is suitably described by a random process. The key to development-induced loads is to obtain a stochastic process model of the additional load on the structure. Three features of this stochastic process include the amplitude of the loads, the average number of times of variation, and the duration of each variation. The amplitude of the variation range is the most important among the three. To determine this, the distribution form of the additional load is used as a premise.

The parameters used are defined below:

x, i is a point in 3D space that is expressed as $x, i \in \Omega = \{(x_1, x_2, x_3) | x_1, x_2, x_3 \in R\}$.

$P(x)$ is the development intensity at position x. $P$is a random variable, and its probability density function is $p(x)$.

$t(x)$ is the load-transfer function, which describes the transfer of a load by the development activity intensity at position x, to the origin point (0,0,0). $\Omega_1 \subset \Omega$ is defined as a development influenced zone. If $x \in \Omega_1$, then $t(x) \neq 0$.

F_x is the load effect in space caused by development activity at position x. F_x is a random variable, and its probability density function is f_x. Therefore, an additional load at position $i$induced by development at position $x$can be expressed as $f_x = p(x) \cdot t(x-i)$.

F is the total external load effect for some position in space. It is a random variable, and its probability density function is f. For the load effect at position i, we have $F = \iiint_{\Omega_1} p(x) \cdot t(x-i) dx$, i.e., the total external load effect for position $i$equals the convolution of the development intensity at any position in the influence zone to the load-transfer function in 3D space.

If we assume that the development intensity is independent at each point, the influence of the surrounding building development on the existing metro tunnel can be calculated by quantifying the development intensity of the different locations in the surrounding space of the existing metro tunnel, and by quantifying the influence zone and load-transfer function of the development.

However, the explicit multi-dimensional convolution calculation would strictly restrict distribution function of development intensity, as well as load-transfer functions; and comprehensively expressing the development intensity is nearly impossible under such restrictions. Therefore, this paper adopts the Monte Carlo simulation method.

As is shown in Fig. 1, the solution process for the external load is divided into two parts: A. determination of the statistical description of the development intensity, and B. the calculation of the load-effect on the tunnel. The distribution of the development intensity is described as the input parameters of the Monte Carlo method, which processes the input data using load-transfer functions to obtain the statistical indexes

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