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Case study

How to protect historical buildings against tunnel-induced damage: A case study in China

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ABSTRACT

This paper presents a holistic approach for safety and protection of historical buildings adjacent to tunneling excavation. A finite element model is built to simulate the impact of tunneling excavation on the distribution of structural stress of historical buildings, in order to determine stress concentration regions in materials and structures subjected to forces or loads. Some corresponding reinforcement measures are proposed according to simulative results, aiming to improve its structural integrity and rigidity of historical buildings to satisfy the load-bearing requirements prior to construction. The effectiveness of the adoption of reinforcement measures against tunnel-induced building damage is validated using a two-stage numerical simulation process, where the impact of the tunneling excavation on the deformation of surrounding soils and building foundations is simulated separately, given the reinforcement measures are implemented. A case in relating to the protection of a historical building of Roots' formal residence (RFR) adjacent to the construction of a twin tunnel, Wuhan Yangtze River Tunnel (WYRT) in China, is presented, where the tunnel in the east line passes under the foundation of RFR, and the nearest receiving shaft foundation in the west line is only 1.4 m away from the building foundation edge of RFR. Results demonstrate the feasibility of the proposed approach, as well as its application potential. The proposed approach can be used as a decision tool to provide some positive guidelines on the protection of historical buildings, and thus increase the likelihood of a successful project in tunneling environments.
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1. Introduction

Historical buildings in some way reflect the evolution of the urban expansion, as well as the historical and cultural development of a country [1]. The conservation and protection of historical buildings belonging to the cultural heritage [2], and preserving their main architectural features are becoming a very sensitive problem in China as in other countries. Many historically interesting buildings are currently used for different functions, such as residential areas, offices, and museum centers and, hence, they require a sufficient level of safety against both vertical and horizontal loads [3,4]. However, these buildings are aging and do not have complete load-bearing capability as designed, and some kinds of structural damages are likely to occur during long-term operations [5,6]. Particularly, tunnel construction has presented a powerful momentum for rapid urban development as a result of rising populations and space restrictions in the past 10 years [7]. However, the tunneling excavation is bound to produce significant disturbances to surrounding soils, which may, in turn, cause adjacent surface buildings to deform, rotate, distort, and possibly sustain unrecoverable damages [8,9], especially those founded on shallow foundations [10]. Especially for some historical buildings, the tunnel-induced ground movement may destroy these buildings unless accurate risk analyses are conducted and appropriate protection measures are implemented [11], since these historical buildings usually possess a very low deformation resistance capacity.

The reciprocal effects of tunnel-induced ground settlement and surface buildings are among the main concerns in urban underground projects. Aiming to prevent heavy casualties and property losses caused by safety violations due to tunnel-induced damages and assure the safety and serviceability of adjacent buildings in tunneling environments, it is essential that scenarios involving the potential loss of operational safety should be analyzed prior to construction [12]. Numerous studies on estimating tunnel-induced building responses have been reported in literatures. Several empirical [13] and analytical methods [14] have been employed to

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predict tunnel-induced ground movements, which pave the way for the establishment of various empirical relationships between tunnel-induced ground movements and the associated building damages. Despite its practicability, the empirical analytical methods are not able to consider the tunnel geometries or provide an estimate of lateral soil movements. Potts and Addenbrooke (1997) identified that these empirical and analytical approaches were based on greenfield scenarios (where the presence of the building was ignored) and their resulting ground settlements were overly conservative, since the stiffness and weight of surface buildings reduced the settlement trough depth [15]. Also, Burd et al. [16] indicated that the modeling of tunnel–soil–building interaction showed significant differences between settlements obtained at greenfield sites and at sites with the structure in place.

With the development and utilization of urban underground space, the number of existing buildings adjacent to the construction of metro tunnels shows an increasing growth. Systematic management and maintenance works to historical buildings are necessary for mitigating the decaying process that will lead to an unsafe condition, and have been identified as a key intervention in protecting historical buildings by prolonging a building lifespan [17]. In this research, a holistic approach for the safety assurance of historical buildings in tunneling environments is developed, where the finite element model is used to simulate the tunnel-induced impacts on adjacent historical buildings. Some corresponding reinforcement measures are proposed according to simulative results. A case relating to a historical building of Roots' formal residence (RFR) adjacent to the construction of a twin tunnel, Wuhan Yangtze River Tunnel (WYRT) in China is used to verify the applicability of the proposed approach.

2. Methodology

Tunnel–soil–building interaction is considered a complicated process, and it is very difficult to rigorously analyze the tunnel–soil–building interaction problem, due to:

- the high interaction between tunneling in soft soils and adjacent buildings;
- the three-dimensional nature of the excavation–structure interaction;
- the nonlinear behavior of geomaterials involved [18,19].

With the ability to take all relevant factors into account, such as nonlinear behavior of soils and soil–building interaction [20,21], the finite element (FE) model has proven to be effective in modeling tunnel-induced building damage subject to adjacent tunneling works through the use of finite element programs. For instance, Maleki et al. [22] studied the effect of structural characteristics of surface buildings, including stiffness, geometry and weight of the structure, on the tunnel–building interaction. They modeled building and tunneling with two separate software programs, SAP and PLAXIS, in the full three-dimensional (3D) modeling approach, and an iterative process, utilized to reach the interaction results. Liu et al. [23] conducted a parametric sensitivity analysis using a finite element model, in order to study the interaction between a surface building and the enlargement of a metro station. The results of in situ measurements were compared to simulations outcomes, and found that the simulation values were less than the monitored values. Mirhabibi and Soroush [12] presented the results of a study on field data of the Shiraz metro line1 and conduct two-dimensional numerical parametric simulations. The effects of different factors such as tunnels' depth and their center to center distance, and buildings stiffness, their weight, width and locations on the surface are assessed based on the results of the numerical simulations. Azadi et al. [24] studied the settlement of a structure adjacent to a tunnel using some finite element analyses, and used the results based on a neural network to assess the effect of proximity of the structure and their orientation in comparison with the location of the tunnel on the tunneling-induced settlement. In general, this FE-based numerical approach provides an effective solution for analyzing the tunneling construction safety, since the complex excavation–soil–structure interaction can be simulated in this approach.

In general, most of previous FE-based approaches have been devoted to the prediction of ground settlement and nearby foundation systems induced by tunneling excavations to date [15,25]. However, a universally accepted standard regarding the overall safety management and protection of existing buildings has not been reached in tunnel construction fields so far. In order to predict the tunnel-induced building responses in a systematic manner, a holistic FE-based approach to the protection of historical buildings adjacent to tunneling excavations is developed in this research, consisting of the following three main steps. A tunnel case in China is subsequently presented in accordance the guidelines of the developed approach:

- pre-reinforcement analysis. This step aims to determine stress concentration regions in materials and structures subjected to forces or loads prior to construction. The FE model should be first established as to simulate the tunnel-induced damage, and then used to investigate specific safety control standard regarding tunnel-induced deformation, as well as causes of structural failures in terms of stress analysis;
- reinforcement control. This step aims to provide guidelines on achieving reasonable reinforcement measures during the tunnel construction. Moreover, the critical checking points should be identified and highlighted with respect to those reinforcement measures;
- post-reinforcement analysis. This step aims to validate the effectiveness of the adoption of corresponding control measures. The impact of tunneling excavation on adjacent buildings should be simulated and analyzed, given the reinforcement measures are implemented.

3. Project profile

The Wuhan Yangtze River Tunnel (WYRT), known as the first road tunnel under China's longest river, the Yangtze River, is an important route connecting two large cities of Wuhan, namely, Wuchang and Hankou. It is a double-spool tunnel with a diameter of almost 12 m, a total length of almost 3600 m and a total investment of $335 million. In tunnel construction practice, the slurry tunnel boring machine (slurry TBM) is most suited for tunnels through unstable material subjected to high groundwater pressure or water inflow that must be stopped by supporting the face with a boring fluid subjected to pressure. In this tunnel project, two slurry TBMs with a cutter diameter of 11.38 m were utilized to push the tunnel from Wuchang to Hankou. Inevitably, the tunneling excavation can generate significant disturbances to surrounding environments, which may have negative effects and cause potential damages to surface buildings, especially in densely built areas. According to site investigation, there were in total 29 surface buildings adjacent to the construction of WYRT. In this central urban area, some historical buildings were also located, and cracks can be observed almost in every historical building. These buildings were almost 2–7 stories high and typically supported on shallow foundations with a buried depth of 1–4 m. Great challenges were encountered for the protection of these historical buildings in tunneling environments. One historical building, that is Roots' former residence

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