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Data based complex network modeling and analysis of shield tunneling performance in metro construction

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ABSTRACT

Shield tunneling performance depends mainly on changes in geological conditions and machine working status. Understanding its characteristics is the key to operating and controlling shield machine during the metro construction. Despite the large set of shield tunneling data in having been a big challenge in interpreting the underlying meaning, a systematical view of the shield tunneling performance has not yet been identified. In this study, a methodology for the modeling and analysis of shield tunneling performance network is proposed which aims at integrating the high dimensional data mining and the complex network approaches for shield performance evaluation. It is tested by analyzing the heterogeneous data of shield tunneling performance acquired from in the first Yangtze river crossing metro tunnel project in China. Each segment ring tunneling cycle in the construction were considered to be nodes of the network mapped while edges are determined by nodes having the similarity greater than an optimal threshold value. The construct network exhibits high clustering coefficient combined with comparatively short path lengths, which demonstrates a small world topology feature. Communities in the performance network with different size based on the complex network are detected, which provides the vital decision information for geological conditions identification and shield tunneling performance risk evaluation.

1. Introduction

With a rapid increasing urbanization rate in China, shield tunneling has become an attractive method in the development of underground spaces for transportation and utility networks [1,2]. Shield tunneling often encounters technical issues such as difficult underground conditions, malfunctions of shield machine and false decisions during tunneling [3]. These challenges can lead to the occurrence of poor shield performance and cost overrun and even catastrophic failures of the shield machine [4]. According to statistics, shield performance failures exist in almost every tunnel project, and the accident rate accounts for nearly half of all accident categories in tunnel projects in China [5]. Not only in China, some shield tunneling accidents also happened in other countries induced by poor performance. Mixed face conditions and the high abrasion of the granite resulted in the lower cutter life time and higher cost in the Kranji tunnel in Singapore [6]. In Portugal, the abnormal working status of cutter heads in the Oporto Metro project caused three collapses of excavation face and a death in a house on the ground, resulting in a delay to the project of almost 9 months [7]. Moreover, the improper shield parameters set by shield operators induced significant effects on the accelerated eccentric wearing of the shield cutter heads in the drilling process of a pipe tunnel in the Weser River in Germany [8]. It is therefore necessary to investigate and analysis the performance of shield tunneling process for the development of shield tunneling risk evaluation and control strategies.

In practice, shield operators rely heavily on the shield monitoring data to evaluate current shield performance and make necessary adjustments to the shield machine as needed [9]. Generally, such evaluations are conducted by comparing the shield monitoring data sets with design requirements or operators subjective experience, specifically referring to some advanced parameters, such as total force, torque, advanced rate and so on [10]. If the observed values of shield parameters were obviously lower or higher than the expectations, then the engineers would analysis the possible causes and take countermeasures on the problems. However, fully understanding of shield tunneling performance cannot be relied on measurement and comparative

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analysis of several advanced parameters. The main disadvantage is that this procedure will be ineffective to identify the underlying risk status of shield performance with normal or occasional anomaly in over two hundred parameters, which is a common phenomenon in many tunneling projects. Thus, single shield parameter within the performance expected value are no less risky than that out of the thresholds, and vice versa. The main reason for the misunderstanding of shield performance is that the shield tunneling is a complex system with numerous heterogeneous monitoring data affected by highly nonlinear character and uncertainty in geological and mechanical conditions [11], together with complicated human operation [2]. Nevertheless, the systematic features of the interactions, relationships, and influences in the shield monitoring data sets from each segment rings advanced in the shield tunneling are underestimated and less studied in theory and practice, which may exacerbate highly biased assessment of shield performance and lead to inaccurate decision for safety risk management [12]. Therefore, modeling and analyzing shield monitoring data sets and developing a systematic assessment approach for shield performance have a practical significance for helping engineers to evaluate and control the risks in shield tunneling.

So far, data mining in shield tunneling performance monitoring data and learning from the data attracted much attention recently [13]. In many situations, data mining approach is used to tackle this problem with the overall process performed by combining methodologies and techniques from different fields, such as statistics, databases, machine learning and data visualization [14–16]. However, the efforts to assess shield tunneling performance have been limited in the prediction of several vital shield parameters or indexes [7,17–21]. Due to the high dimensional and heterogeneous data obtained in shield tunneling process, the individual pieces of information from shield tunneling performance monitoring data are not independent and acquire a profound meaning when combined together into a whole shield tunneling system behavior, which cannot be easily modeled by data mining approach alone. A data-driven based complex science perspective [15,16,22,23] will inspire the exploration and visualization on complexity and value of shield monitoring data for performance analysis. Despite recent literatures pointing out the increasing power of computer technology does not dispense with the need to extract meaningful information out of data sets of ever growing size and complexity [14,22,23], to date a systematical view of shield tunneling performance based on shield monitoring data is still missing [24].

Recently, complex network theory has emerged as a new way to understand the behavior and performance characterizing complex systems in diverse scientific disciplines such as physics, mathematics, sociology and economics, as well as construction [25–27]. Most of them displays different network properties, such as scale-free, small-world and hierarchy, which reflect patterns of connections between their elements are neither purely regular nor purely random [27]. Undoubtedly, shield tunneling is also a complex sociotechnical system with high uncertainty and nonlinear phenomenon [1]. Thus, the shield tunneling performance measurements and interpretations could be uncovered through the lens of complex network theory. However, to date there has been no exploration in the shield tunneling with complex network theory, which could lead into shield performance prediction and optimizations in metro construction. The challenge exists in how to create an objective representation (a network graph) that can be used in successive steps of the shield tunnel performance analysis [14]. More specifically, considering each construction cycle (segment ring) in shield tunneling as a node, how to measure the performance relationships between them and how to define the optimal topological network structure? Given the similarity in the general purpose and sometimes even in procedures, it is natural to think that bridging the complex network theory and data mining approach to establish a data-based performance network from collected high dimensional heterogeneous monitoring data of shield machine. Therefore, this proposed integration of two methodologies is feasible to characterize and measure the shield performance in micro- (single nodes or links), meso- (groups of few nodes or communities) and macro-scale (the network as a whole) [14].

The objective of this paper is twofold: (1) to suggest a method or procedure based on complex network modelling and data mining to uncover the correlations and similarities in the shield tunneling monitoring data items from different advanced segments when a tunnel is constructed and (2) to analysis and verify the characteristics and communities of the reconstructed complex network could be associated with shield tunneling performance and help for further geological conditions recognition or shield tunneling risk evaluation. The paper is organized as follows. First, the motivation of data mining for shield tunneling performance was briefly discussed, together with the complex network theory and its applications. Second, the methodology for the modelling of shield tunneling performance is introduced. Third, topological analysis based on a set of performance network properties and community detection approach are proposed. Then, the results of a case study, based on the collected high dimensional and heterogeneous data in the first Yangtze river crossing metro tunnel project in China, is discussed in detail. Furthermore, the potential value in practice of the proposed approach in the geological conditions identification and risk evaluation of shield tunneling was discussed in detail on the basis of the case study. Finally, in Section 7, the research work is summarized and a prospect of further study is proposed.

2. Motivation and related works

2.1. Factors of shield tunneling performance

Performance analysis and prediction for mechanical excavation in a tunnel project are of big importance since the schedule/completion time and unit cost/profitability of the whole project is made based on the tunneling performance [20]. This is more important especially in large section tunneling projects using shield tunneling boring machine, since the shield tunneling is a complicated soil–machine interaction process and affected by many factors [20,28]. That means studying the factors that may affect the shield tunneling performance is essential prior to understanding the complexity and dynamics of the performance [29]. As reported in previous studies, the shield tunneling performance is affected by many factors, which may be classified into three major categories: geometrical characteristics, geological conditions and shield machine reliability.

Firstly, geometry parameters have a determining effect on the shield tunneling performance and excavation rate of shield-driven tunnels, such as the distance from tunnel face, depth of tunnel axis from ground level and tunnel diameter [20]. As a result, the deeper tunnel, which the ratio of depth and diameter is over 2.5, has a great effect on torque, total force and working pressure of shield machine [1]. In other words, the performance in deeper tunnel will be lower than in shallower tunnel. Due to the diameter is not change, the effect of geometry parameters will be enlarged as the excavation depth increasing in the longitudinal development of shield tunneling [7].

Secondly, geological and hydrogeological conditions must be performed prior to shield tunneling. These conditions will allow for designing the stages of the construction and avoiding unexpected events. The tunnel excavation process by shield cutters and shield excavation efficiency are related to the soil types and properties [20]. However, detailed geological investigation of the soil types and properties at each instrumentation section along the tunnel is practically impossible, making it difficult to obtain the true values of the soil types and properties [30]. Thus, many studies investigated the effect of ground conditions or soil parameters on the shield performance by numerical and inverse analysis techniques based on the shield monitoring data [31,32]. Particularly, two parameters, i.e., the shear strength and Young's modulus, were examined to find that they have great influence on the advanced ratio [12]. Moreover, difficult ground types, such as faulted zones, blocky rock masses, sticky soil, squeezing rocks, mixed