Advanced Engineering Informatics 36 (2018) 1–19

Contents lists available at ScienceDirect

Advanced Engineering Informatics

journal homepage: www.elsevier.com/locate/aei

Full length article

Topological mapping and assessment of multiple settlement time series in deep excavation: A complex network perspective

Cheng Zhou, Lieyun Ding, Ying Zhou*, Hanbin Luo

Departmant of Construction Management, School of Civil Engineering & Mechanics, Huazhong University of Science & Technology, Wuhan, Hubei, China
Hubei Engineering Research Center for Virtual, Safe and Automated Construction (ViSAC), HUST, China

ARTICLE INFO

Keywords:
Deep excavation
Settlement time series
Complex network
Similarity matrix
Topological analysis
Node influence

ABSTRACT

This study proposed a novel methodology that integrates complex network theory and multiple time series to enhance the systematic understanding of the daily settlement behavior in deep excavation. The original time series of ground surface, surrounding buildings, and structure settlement instrumentation data over an excavation time period were measured into a similarity matrix with correlation coefficients. A threshold was then determined and binarized into adjacent matrix to identify the optimal topology and structure of the complex network. The reconstructed settlement network has nodes corresponding to multiple settlement time series individually and edges regarded as nonlinear relationships between them. A deep excavation case study of the metro station project in the Wuhan Metro network, China, was applied to validate the feasibility and potential value of the proposed approach. Results of the topological analysis corroborate a small-world phenomenon with highly compacted interactions and provide the assessment of the significance among multiple settlement time series. This approach, which provides a new way to assess the safety monitoring data in underground construction, can be implemented as a tool for extracting macro- and micro-level decision information from multiple settlement time series in deep excavation from complex system perspectives.

1. Introduction

Urban underground space has shown its advantages in providing resources to solve urban problems and has been developed rapidly in China [1–3]. Various forms of underground space are developed in the metropolis: underground transportation infrastructures (metros and underground roads and car parks), underground complexes (integrated transportation, municipal, commercial, and entertainment facilities), and underground municipal facilities (public ditches, waste disposal systems, and rainwater storage systems) [1,4]. The significant challenges that exist in these underground space developments are ground movements and surface settlements induced by deep excavation, which, if uncontrolled, might cause excessive deformations and damage to existing nearby structures and utilities [5]. For the protection of adjacent buildings and environment, instruments are installed during the construction of urban excavations to monitor ground response to various construction activities by time at discrete locations [6]. Thus, fully analyzing and understanding these settlement time series in deep excavation and extracting meaningful information from the time series will attract considerable attention for safety management.

In practice, site engineers rely heavily on the observed instrumentation data to evaluate current construction conditions and make necessary adjustments to the construction activities as needed [6]. Generally, such evaluations are conducted by comparing field time series with existing national standards or design requirements, specifically referring to the thresholds of the cumulative value of settlement and deformation ratio per day [7]. If the observed settlements were over the thresholds, then the engineers would be informed by early warnings and alarms to implement countermeasures. However, the main disadvantage is that this procedure will be ineffective after most of settlements exceed the thresholds, which is a common phenomenon in many deep excavation projects. These simple comparison results are often misleading to the engineers with false warnings. Thus, some deep excavation-induced settlements exceeding the thresholds are less risky than the ones below the thresholds, and vice versa. The main reason for the false warning based on threshold is that underground construction is a complex system with highly nonlinear character and uncertainty in hydrological and geological conditions [8], together with complicated site environment [9]. The most fundamental evidence that describes the dynamic behavior and the underlying mechanism of deep excavation is embedded in the induced multiple settlement time series. Nevertheless, the character and feature of the interactions, relationships, and

* Corresponding author at: Departmant of Construction Management, School of Civil Engineering & Mechanics, Huazhong University of Science & Technology, Wuhan, Hubei, China.
E-mail address: ying_zhou@hust.edu.cn (Y. Zhou).

https://doi.org/10.1016/j.aei.2018.02.005
Received 1 August 2017; Received in revised form 31 January 2018; Accepted 19 February 2018
1474-0346/

influences among these time series are underestimated and less studied in theory and practice. In fact, the ignorance on the complicated interactions and relationships in different settlement time series may exacerbate highly biased assessment only by existing thresholds in the standards, which may lead to inaccurate warnings and wrong decision for safety risk management of excavation activity [10]. Thus, examining relationships among multiple settlement time series and developing a systematic assessment approach have a practical significance. A data-driven based complex science perspective [11–14] will inspire the macrocosmic and microcosmic scale exploration on multiple settlement time series during underground construction. Therefore, searching for a uniform language to articulate the topology remains difficult [15]. The reason is that different underground constructions can induce different interactions or generate different structures of the multiple settlement time series, which cannot be easily identified by time series analysis alone.

Over the last two decades, complex network theory has seen a remarkable development in understanding the characteristics and natures of complex systems and their components, such as scale-free, small-world, and self-organized features [16]. The network formalism is based on the notions of nodes (or vertices), which can be identified with individual structural or functional elements of a system, and edges, which represent physical interactions or other relations between the pairs of nodes [17]. A statistical physics understanding of graph theory (a considerably old branch of pure mathematics), namely, complex networks, has been used by scientists from highly different fields to describe systems ranging from power grids to social interactions and the brain [18–20]. Complex networks have two main categories in the real world: physical and influence networks [16]. Physical networks are reconstructed by mapping explicit interactions or connections into the corresponding links, as seen in the real system [17]. However, certain real-world systems lack explicit information about links, and the dynamics of each element could be considered as an effect or influence of its neighbors [16]. For the identification of the topology of reconstructed complex networks, the first step then requires quantifying these influences (hence the name influence networks). With this lens of complex perspective, many scholars have quite recently focused on how to bridge the time series analysis and complex network theory, such as original stock [20], air quality [18], mechanical vibration [21], and bioelectrical time series [22]. Nevertheless, to date, no exploration in the multiple settlement time series in deep excavation based on the complex network theory has been conducted. Therefore, this study is motivated by two questions: Given each settlement time series (settlement monitoring point at a certain location) in deep excavation as a node, how could the optimal topological network structure be defined to assess them individually in an entire system of deep excavation? Furthermore, because the influence of a settlement time series (node) could be evaluated by the topological structure of its network, what is the potential value or practical meanings of the results from the identification of vital time series (settlement monitoring point) to the risk assessment and safety management in deep excavation? Consequently, in this study, a complex network theory with time series analysis is introduced to explore the topological relationships and assessment of multiple settlement time series in deep excavation.

This paper is organized as follows. Section 2 briefly reviews the study of settlement time series, such as its distribution and factors, in deep excavation. Section 3 introduces the methodology for the modeling and analysis of multiple settlement time series. The methodology involved three main steps: correlation coefficient matrix, threshold setting for binarizing the network, and topological measurement. Section 4 provides a deep excavation case study of the metro station project in the Wuhan Metro network, China, to validate the feasibility and obtain the calculation results of the proposed approach. Furthermore, the potential value in practice of the proposed approach in the risk assessment of deep excavation was discussed in detail on the basis of the case study. Finally, Section 6 summarizes the research work and proposes a prospect of further study.

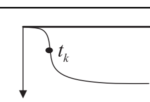
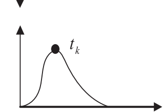
2. Time series of settlement in deep excavation

2.1. Distribution of settlement time series

Evaluating the magnitude and distribution of ground movements adjacent to an excavated foundation pit is an important part of the process when excavating in an urban environment [23,24]. Instruments are installed during the construction of urban excavations to monitor the response of nearby ground and adjacent buildings at discrete locations to various construction activities, to verify design assumptions, and to effectively reduce the safety risks during deep excavation [25,26]. However, most of the aforementioned studies focused on the maximum ground surface settlement [5]. These results do not fulfill the dynamic and real-time requirements of understanding settlement development during deep excavation [27]. Thus, profile functions, or fitting functions, have been used by various researchers to model free-field ground movements due to deep excavation [28]. One common profile function is the normal probability, or normalized Gaussian, distribution. Several researchers have employed this function to describe the profile of a settlement time series [29]. Table 1 shows a typical longitudinal settlement time series profile obtained by the instrumentation readings and the characteristics of the profile function. From time $t = 0$ to $t = t_k$, settlement value $s(t)$ and speed of the settlement development $v(t)$ are increasing with such time, whereas accelerated velocity $a(t)$ is always positive. At point $t = t_k$, $v(t)$ is up to the maximum, and $a(t)$ reaches zero. From time $t = t_k$ to $t \to \infty$, $s(t)$ is increasing to the maximum, and $v(t)$ is decreasing to zero. Meanwhile, $a(t)$ is always negative.

Although many methods for settlement time series analysis, such as empirical, analytical, numerical, and intelligent methods [15,18], are available, most of them are concentrated on the maximum values of the settlement time series, rather than regarding or studying them as a whole. Moreover, those methods have several constraints in those applications, such as limitations in ground conditions and construction techniques, underestimation or overestimation with inaccurate parameters, time consuming, and sensitiveness to boundary conditions [10]. To the extent of the intelligent methods, such as machine learning algorithms with field data mining, they are basically abductive ways to create abstract data prediction models [16]. However, the settlement time series induced by deep excavation could be measured by many instrumentations around the construction site, which are typically nonlinear and interactive behaviors of the deep excavation system. These behaviors imply that the modeling and analysis of the development of multiple settlement time series could be more challenging than that of single time series. Consequently, in many cases, existing studies only affirmed the three-dimensional effects caused by the relatively high stiffness at the corners of an excavation leading to small ground movements near the corners and large ground movements toward the middle of the excavation wall [5,29], rather than understanding and

Table 1
Features of the distribution of settlement time series in underground construction.

t	$t = 0$	$0, t_k$	t_k	t_k, ∞	$t \to \infty$	Distribution
$s(t)$	$s(t) \approx 0$	↗	$s(t) = s(t_k)$	↗	$s(t) = s_{max}$	
$v(t)$	$v(t) \approx 0$	↗	$v(t_k) = v_{max}$	↙	$v(t) = 0$	
$a(t)$	$a(t) \approx 0$	+	$a(t_k) = 0$	–	$a(t) = 0$