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A novel model for risk assessment of adjacent buildings in tunneling environments

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ABSTRACT

This paper presents a novel model to assess the risk of adjacent buildings in tunneling environments based on Extended Cloud Model (ECM). ECM is an organic integration of Extension Theory (ET) and Cloud Model (CM), where ET is appropriately employed to flexibly expand the variable range from [0, 1] to $(-\infty, +\infty)$, and CM is used to overcome the uncertainty of fuzziness and randomness during the gradation of evaluation factors. An integrated interval recognition approach to determine the boundary of risk related intervals is presented, with both actual practices and group decisions fully considered. The risk level of a specific adjacent building is assessed by the correlation to the cloud model of each risk level. A confidence indicator θ is proposed to illustrate the rationality and reliability of evaluating results. Ten buildings adjacent to Wuhan Metro Line Two (WMLT) are randomly chosen among hundreds of adjacent buildings for a case study, and the results have proved to be consistent with the actual situation. Compared with other traditional evaluation methods, ECM has been verified to be a more competitive solution with no demands on training data. The original data can be directly entered into ECM without a normalization procedure, avoiding the potential information loss. ECM can be offered as a decision support tool for the risk assessment in urban tunneling construction and worth popularizing in other similar projects.

1. Introduction

Tunneling excavation is bound to produce significant disturbances to surrounding environments. A major concern induced by tunneling excavation is the potential damage to the adjacent buildings and structures [1,2]. On January 12, 2007, Pinheiros Station on Metro Line Four collapsed at Sao Paulo's Aquarium in Brazil, causing enormous material damages to the construction site and adjacent public infrastructures [3]. On August 23, 2012, a metro line leak caused chaos in Warsaw, Poland. Water flooded into the tunnel at the planned Powisle station, leading to considerable transportation problems in the already gridlocked city [4]. Also in China, with the rapid development of urban rail transit, adjacent buildings incur severe damages and even collapses due to the tunneling excavation. On July 1, 2003, great quantities of sand swarmed into the tunnel in Shanghai Track Traffic Line Four, resulting in a sharp inclination of an adjacent eight-story building and a collapse of its podium floors. Besides that, a 30-meter-long flood control wall was collapsed as well, causing a total direct economic loss exceeding US $700 million [5]. On January 17, 2008, a road cave-in collapse occurred above a metro tunnel under construction in Guangzhou Track Traffic Line Five. A crater of some 100 square meters large by 5 m deep had been left, causing enormous hidden dangers to the existing surface buildings [6]. In recent years, risk assessment of adjacent buildings in tunneling environments (RAABTE) has attracted broad attention due to the crowded buildings, complex environments, and its close relation with the issues of public safety [7].

Tunnel-building interaction is a highly complicated process. In recent years, numerical analyses have been widely applied to investigate the tunneling-induced impacts on surrounding environment in engineering practices [8–11]. This kind of numerical analyses provides a solution for the safety analysis of adjacent buildings in tunneling environments. However, it would be time consuming and extremely expensive, especially when a large number of adjacent buildings have to be assessed [12,13]. Meanwhile, comparatively few critical factors are chosen as input parameters in the numerical analyses, regardless of the contributions

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of other relevant factors, such as “Building intact conditions”, “Management ability of organization” and so forth. This could lead to the insufficiency for the total safety management in engineering practices [14].

A comprehensive evaluation method should have the capacity of taking all related factors into account and calculating the contribution of each factor. Current comprehensive evaluation methods can broadly be grouped into the following three categories: (1) Approach based on fuzzy mathematics theory [15], such as Fuzzy Analytic Hierarchy Process (FAHP) and Fuzzy Fault Tree Analysis (FFTA); (2) Approach based on probability and statistics theory, such as Osculating Value Method (OVM) and Bayesian Networks (BN); (3) Approach based on artificial intelligence [16], such as Neural Networks (NN), Support Vector Machines (SVM), Genetic Algorithms (GA) and Rough Sets (RS). In general, the core of a comprehensive risk evaluation method is essentially the gradation of the evaluation factors. However, due to the lack of historical statistical data and the ambiguity of the expert knowledge, great uncertainties of randomness and fuzziness exist during the evaluation factors gradation. To recognize the definite boundary of each risk related interval remains a big issue, leading to low the accuracy and reliability of evaluation results in RAABTE to some extent.

The Cloud Model (CM) provides a powerful tool in uncertain transforming between qualitative concepts and their quantitative expressions [17]. It has the capability of expressing fuzziness and randomness existing in human knowledge representation, knowledge acquirement, as well as knowledge inference. In the past ten years, CM has been widely applied in many areas, such as inexact knowledge representation, intelligence control and system evaluation data mining [18]. In the meantime, the Extension Theory (ET) is beneficial for interval parameters repression with the advantage of expanding the valid range from the fuzzy set [0,1] to the real axis $(-\infty, +\infty)$ [19]. Particularly, ET can directly use the original data without a normalization procedure, avoiding the potential information loss [20]. Combining the advantages of both CM and ET, a novel risk assessment model, namely Extended Cloud Model (ECM), is proposed for RAABTE in this paper. The approach to determine the risk related intervals is presented, with both actual practices and group decisions fully considered. The risk level of a specific adjacent building is conducted using the correlation calculation, associated with a confidence indicator. Finally, ECM is applied to the risk assessment of adjacent buildings along the route of Wuhan Metro Line Two (WMLT) in a case study. The comparisons between ECM and other three conventional evaluation methods are also discussed according to the calculated results, and the results demonstrate the feasibility of the proposed method, as well as its application potential.

2. Extended Cloud Model (ECM)

2.1. Extension Theory

Natural languages, considered as primary vehicles of human thinking, are one of the most essential and critical means of communication. However, the uncertainties associated with natural languages communications lead to a series of challenging problems, especially for the linguistic concepts [21]. In order to perform the reasonable transformation between qualitative concepts and quantitative values, there are mainly three approaches, namely the cantor set, fuzzy set and extension set. In the cantor set, an element either belongs to or does not belong to a set. Therefore, the range of the cantor set is $\{0,1\}$ which can be used to solve a two-valued problem. In contrast to the cantor set, the fuzzy set allows for describing concepts in which the boundary is not explicit. The fuzzy set with a range of [0, 1] concerns not only whether an element belongs to the set but also to what degree it belongs. The extension set, first introduced in 1983 by a Chinese scholar Cai [22], extends the fuzzy set from [0, 1] to $(-\infty, +\infty)$. Consequently, the extension set allows to define a set including any data in the domain and has the capability of solving contradictory problems which cannot be solved by the cantor set or fuzzy set [22]. Table 1 presents comparisons between the above three approaches.

Table 1
Three different sorts of mathematical sets.

Compared item	Cantor set	Fuzzy set	Extension set
Model	Mathematics model	Fuzzy mathematics model	Matter-element model
Descriptive function	Transfer function	Membership function	Correlation
Descriptive property	Precision	Ambiguity	Extension
Range of set	{0, 1}	[0, 1]	$(-\infty, +\infty)$

In the extension theory, the matter-element (R) contains three fundamental elements: matter name (N), matter characteristics (C) and values of matter characteristics (V) [23]. The matter-element can be described as $R = [N, C, V]$. Assuming a multi-dimensional matter-element $C = [c_1,c_2,\ldots,c_n]^T$ associated with a characteristic region $V = [v_1,v_2,\ldots,v_n]^T$ and a range of classical intervals $v_i = <a_{pi}, b_{pi}>$ $(i = 1,2,\ldots,n)$, a multi-dimensional matter-element is defined as Eq. (1).

$$R = [N, C, V] = \begin{bmatrix} N & c_1 & v_1 \\ & c_2 & v_2 \\ & \vdots & \vdots \\ & c_n & v_n \end{bmatrix} = \begin{bmatrix} N & c_1 & \langle a_{p1}, b_{p1} \rangle \\ & c_2 & \langle a_{p2}, b_{p2} \rangle \\ & \vdots & \vdots \\ & c_n & \langle a_{pn}, b_{pn} \rangle \end{bmatrix} \tag{1}$$

The intervals ($v_i = <a_{pi}, b_{pi}>$) are called the classical domains which stand for the defined interval values, and the region (V) is called the joint domain [24]. To calculate the evaluated level of a specific element, the element is first matched with the classical domains using the correlation function that describes the element to be positive field, negative field or zero boundary [25]. As a sequence, the recognition of the classical domains $v_i = <a_{pi}, b_{pi}>$ is significantly sensitive to the calculated results. However, great uncertainties of fuzziness and randomness are involved during the interval gradation due to lack of sufficient data. Few studies have taken this kind of fuzziness and randomness into consideration in traditional extension analysis, which would significantly affect the accuracy and effectiveness of the final evaluation results.

2.2. Cloud Model and ECM

Cloud Model (CM) is a qualitative and quantitative transformation model proposed by Deyi Li, which can use linguistic value to represent the uncertain conversion between a qualitative concept and its quantitative value [26]. Aiming to eliminate the fuzziness and randomness inherent in human cognition, CM is defined as follows [27]: Supposing U is the quantitative domain expressed by accurate numbers and C is a quality concept in U, there exists a corresponding certainty degree $\mu(x)$ to C for arbitrary $x \in U$. As shown in Eq. (2), x is a random realization of the quality concept C. $\mu(x)$ is a random number with stable tendency and called a cloud drop.

$$\mu : U \rightarrow [0,\ 1],\ \forall x \in U,\ x \rightarrow \mu(x) \tag{2}$$

A cloud model can be characterized with three digital characteristics $C = (Ex, En, He)$. The expected value “Ex” represents the