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Development of web-based system for safety risk early warning in urban metro construction

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ABSTRACT

At present, underground urban metro construction accidents in China are rising with the rapid growth of urbanization and infrastructure investment. Real-time safety and risk management during urban metro construction has become extremely important but is very difficult, time-consuming and unreliable due to the lack of information and experienced managers. This paper presents the development and application of a web-based system for safety risk early warning in urban metro construction. A hybrid data fusion model based on multisource information (monitoring measurements, calculated predictions, and visual inspections) is employed to imitate human experts to give safety risk assessment and early warnings automatically. In addition, it has significantly improved information collection, sharing and communication by establishing a collaborative platform instead of traditional manual management. The system has been successfully applied to several metro construction projects and has perfected the safety management performance in the cities of Wuhan, Shenyang, Zhengzhou and Kunming in China.

1. Introduction

China is placing high priority on construction and expansion of underground metro networks in urban areas. In its latest report, the Ministry of Housing and Urban–Rural Development in China estimated that there will be more than 30 cities with a total of 2495 km of metro lines before 2015. The investment for urban metro in China will surpass 1156 billion Yuan in the coming 5 years, which gives an impression of both the high ambition level of the Chinese government and the enormous efforts involved to implement the ambition.

However, urban metro construction projects are extremely high-risk due to unpredictable geological and hydrological conditions, complex construction equipment and methods, and third party impacts on the surrounding environment [1]. In addition, because of the short metro construction history in China, many cities don't have the technical and managerial expertise to safely develop their first metro lines. As a result, under the great pressure of project schedule and scale, accidents happened much more frequently in urban metro construction in China in recent years, which has caused unexpected casualties and economic losses.

Therefore, the safety risk of each identified failure mode in metro construction needs to be evaluated and prioritized so that appropriate corrective actions can be taken [2]. There is a growing perception that continuous monitoring of underground structure and environment provides the data necessary to facilitate safety risk identification and assessment during metro construction [3]. Moreover, measurement predictions calculated by mathematical and mechanical models [4–6], together with the visual inspections on construction sites by human beings have become an inherent part of safety risk analyses [7].

However, it will not be easy for Chinese engineers to manually and globally evaluate safety risk based on multisource information which may include monitoring measurements, calculated predictions, and visual inspections. To achieve that, it would require highly professional knowledge and experience, and would be extremely time-consuming and less reliable in practice due to the inherent difficulties in handling and communicating multisource information. Many attempts have been made to develop and implement safety risk management systems in urban metro construction in China using emerging information communication technology (ICT). In most cases, the solutions have been limited to measurement databases or video monitoring systems. Therefore, to improve safety performance in metro construction, efficient management of multisource information and its automated fusion into the safety risk early warnings is required, along with notification of proper countermeasures.

A successful alternative is a web-based safety risk automated early warning system which is also a multisource information management system. By using a data fusion model, a collaborative decision-making platform for work flows and responsibility allocations is also achieved. This paper introduces and discusses the experience of developing a web-based early warning system for safety risk in urban metro construction. Section 2 presents a literature review of techniques in this study, such as safety risk assessment, data fusion and web-based information communication. Section 3

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then offers the hybrid data fusion model for safety risk early warning in metro construction. Next, Section 4 illustrates the system design and development. Section 5 is a case study of the system in Wuhan metro construction. Finally, Section 6 presents conclusions and further research opportunities.

2. Literature review

2.1. Metro construction safety risk assessment

Since construction accidents can cause significant casualties or injuries and loss of property in an urban area, there has been considerable research attempting to identify and assess safety risk at the pre-design and preconstruction phases of a project. A risk-based safety impact assessment methodology was developed for open-cut type underground construction projects in Korea to consider "design-for-safety" in the design phase [8]. Quite a few systematic tools were applied during the construction of Beijing Olympic venues [9]. Event tree analysis to quantify the safety risk at the preliminary design stage was considered in the underwater tunnel crossing under the Han River [10].

But most of the research has focused on quantifying the safety risk during the dynamic construction phase. A general procedure for quantitative risk assessment for casualties, economic loss, and time overrun was summarized for cut-slope projects under construction [11]. An innovative simulation-based model, SimSAFE, was developed for incorporating safety management into schedule control and assessed the safety hazards and expected accident costs for each activity in a network schedule [12]. The task demand analysis (TDA) methodology used a new way to measure the safety risk of construction activities which did not estimate the safety risk in terms of probability and consequences, but quantified an activity's safety difficulty based on characteristics of the task [13]. There have also been efforts to develop and implement computerized safety risk assessment systems in construction by means of ICT. An IT-based tunneling induced risk assessment system was developed in the framework of a geographical information system (GIS) and the artificial neural network (ANN) technique [5]. From the angle of information, an integrated system was proposed by using multidimensional (nD) modeling technology for participants and decision-making support for project owners in urban transit construction [14].

Although several safety risk assessment solutions are available in the construction industry, they are limited because they don't aggregate and integrate multisource information (e.g., they often focus on the safety risk state of a single construction task, a single component, or a single monitoring measurement point). As a result, reliability and accuracy of safety risk early warning cannot be guaranteed, and the automating of global safety risk assessment is not possible. Data-driven approaches, such as data fusion technology, may prove more useful for meeting the safety risk management needs in metro construction than a point-based approach.

2.2. Data fusion in construction

Data fusion is the process of combining data and knowledge from different sources with the aim of maximizing useful information content, enhancing confidence, improving reliability and reducing ambiguity of measurements for estimating the state of entities [15]. General data fusion structure can be divided into three phases: signal-level (or data-level), feature-level, and decision-level [16]. Although each fusion algorithm has its own set of advantages and limitations, the combination of several different fusion algorithms has proved to be the most useful strategy because each algorithm approaches data fusion from a different and possibly complementary perspective [17].

Currently, some of the emerging research areas for data fusion in civil engineering include data fusion for large-scale sensor networks, data integrity and security, hybrid data fusion methods to address different aspects of data imperfection, and data fusion evaluation frameworks [18]. Combining columns' boundary and material information together was proposed for recognizing concrete columns in visual data [19]. A risk assessment methodology was developed for construction projects by combining existing large quantities of data and project-specific information through updating approaches [20]. In addition, researchers have pointed out that obtaining multi-sensor data and refining it into information for decision making are two key steps in monitoring construction performance [21]. The data fusion model as an integrated solution was used for automated identification, location estimation, and dislocation detection of construction materials [22].

In summary, civil engineering systems can benefit from data fusion by reducing ambiguity, improving detection, enhancing reliability and increasing accuracy. The area of research that is most relevant to this work concerns automating early warning for safety risk in metro construction by using data fusion technology.

2.3. Web-based information communication

In current practice, all information is commonly transferred directly between participant pairs. The participants generally keep their own files with the necessary data. This traditional communication process is often time consuming and expensive (e.g., telephones, faxes and emails) [23]. The number of participants in metro construction is much bigger than in ordinary building construction. This multiplies the complexity of relationships among them. The information communication process becomes difficult and inefficient, especially in managing and controlling construction safety risk [24,25].

This paper focuses on a web-based system to gather project information into a central database from different participants, and facilitate their acquiring and exchanging information conveniently. The information communication process among project participants with the proposed system is a sharp contrast to their traditional mode of communication. It is integrated with the site monitoring function, which allows users to engage in online meetings with the aid of real-time site status and the archives of captured images. Some major advantages of the proposed web-based system is that users are not required to install any special software packages; they only need a web browser, Internet connection and probably a few free-of-charge plug-ins. Another important benefit is that it simplifies the establishment of a collaborative environment among project team members.

3. Hybrid data fusion model for safety risk early warning in metro construction

The measurements from instruments and sensors, the predictions calculated from mathematical and mechanical models and the visual inspections from trained engineers indicate the current status and future trends of different failure modes in metro construction. Examples of different failure modes are base heave in deep excavation, instability of tunnel eye in launch shaft wall, etc. All this multisource information can be fused by experts with their knowledge and experience to assess the safety risks and give warnings of failure modes in an implicit way. In this fusion process, there are two distinct and correlated phases. The experts will give primary safety risk assessments of known and potential failure modes based on the given information source in the first phase, and then they synthesize the primary assessments from different information sources to determine the warning grade of a particular safety risk. Fig. 1 illustrates the hierarchical relationships among multisource information, primary assessments, and decision-making results.

In an initial attempt to automate assessment and early warning for safety risk, a hybrid fusion model was developed to imitate the human fusion process. In order to improve the reliability and accuracy as well as to make full use of multisource information in metro construction, this hybrid fusion model uses both artificial neural network and evidential belief reasoning techniques to develop a two-stage