A SAFETY RISK MANAGEMENT DATABASE FOR METRO CONSTRUCTION PROJECT

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ABSTRACT

This research focuses on the build of a new kind of database, named metro safety risk database(MSRD), which integrates the accident case library and engineering information library to provide more practical and valuable safety information for the project participants, so that we can take effective measures to prevent the tragic accident from happening again. The use of modern database technology with powerful project data processing capability has aroused the attention of the builders, but there are still many things have to be done to improve the database. Therefore, it is extremely important to analyses the database composition, the data acquisition process and the database functional design. In this research, an effective tool to improve on-site safety performance has been developed from historical data and project engineering information.

Keywords: metro construction, database, safety performance, accident analysis

1. INTRODUCTION

City managers around the world consider railway transit to be an effective policy for both economic development and environmental improvement. Advantages include movement of large volumes of people quickly, safely, generation of good jobs, and reduction of traffic congestion. According to the world subway database statistics, about 187 cities around the world have subway lines, with a total run length of 11,860km. In China, 14 cities have subway lines with a total run length of 1899 km, accounting for 16% of the worldwide running mileage.

Due to its intrinsic nature, construction is one of the most hazardous industries(Laitinen et al. 2010). For example, in 2010, the American construction industry experienced 571 deaths of total industrial deaths of 4547(United States Labor Department, CFOI 2010), compared with 2,634 deaths of 75,572 total industrial deaths in China (State Administrator of Work Safety, Safety Production Control Index 2011). Although detailed and complete official data is lacking, it is known that metro construction is of higher risk than the general construction industry(Patterson et al. 2002).

Metro projects are very risky because of the inherent uncertainties in ground and groundwater conditions(You 2010) and complex construction methods and equipment. There are three reasons that these risks are even more severe in China: 1) The short metro construction history where many engineers are working on their very first project. They do not have the technical and managerial experience required to safely design and construct these technically complex projects; 2) The engineers and sometimes workers must manually process excessive and multisource information, including monitoring measurements, calculated predictions, and visual inspections; 3) Safety risk analysis needs to provide relatively accurate probability and consequence of loss projections. Both the direct and the indirect analyses should be based on objective calculations rather than subjective judgments.

Many attempts have been made to implement safety risk management systems into urban metro construction projects in China, using emerging information and communications technology (ICT). The goal of this research is to build a new kind of database which integrates the historical case library and the engineering library in order to provide more practical and valuable safety information for project participants. Section 1 introduces the background of the paper. Section 2 is a literature review, which provides an introduction of major achievements in safety research and points out the importance of the database in safety management. Section 3 provides the logical structure of the database, the composition of the database, and the data collection workflow. Section 4 discusses how the database management system achieves the goals of summarizing and analyzing the data, providing early warning of potential danger, and measuring the cumulative probability of occurrence. Section 5 provides conclusions and some proposals for further developmental studies.

2. LITERATURE REVIEW

As seen in Section 1, the safety problem in the construction industry has never been solved. Therefore, experts and scholars are committed to developing construction practices which will prevent and eliminate safety incidents. Many achievements have been made in various management domains.

2.1 Safety achievements

Accident causation models such as the Domino model(Heinrich et al. 1950), the Disorder Model(Johnson et al. 2004)，and the Hazard Barrier Target Model (Schupp et al. 2004) can explore the causes of actual accidents and lay a foundation for preventing them. One research study identified, by the questionnaire survey method, factors influencing safety on construction sites including historical, economic, psychological, technical, procedural, organizational and environmental issues(Tam et al. 2004, Haslam et al. 2005, Cheng et al. 2010). Crash accidents that occurred between 1995 and 2002 (Hinze et al. 2005) identified several important factors: the time of crash occurrence, the age distribution of people in crash accidents, materials and equipment involved in the crash, and the frequency distribution of the number of casualties in the accident. The research provided suggestions for improvement of PPE（Personal Protective Equipment）and workers training. Considering that 60% of fatal construction accidents are caused by decision-making and design aspects upstream of the construction site, scholars (Behm 2005, Gambatese et al. 2008) believe that construction site safety will be improved if safety of construction worker is considered at the design stage.

Research has made considerable progress in identifying safety risks and developing solutions to reduce safety incidents. However, the goal is zero casualties and minimization of injury and cost. Therefore, expansion of existing management methods and adoption of new techniques and management methods are required.

2.2 Database research

By establishing an accidents case library, project participants are able to conduct cause analysis, scene exploration, and safety training. An example is the European Union mandatory accidents reporting system which is used to extract data to conduct research. In the construction engineering industry, the OSHA database is mentioned most often. Some researchers (Koehn et al. 1995, Arboleda et al. 2004, Hinze et al. 2005, Zhou et al. 2008) analyzed accidents from the OSHA database and determined that this analysis is an effective tool to increase the level of construction safety management.

Moreover, there are many project specific databases created for particular research. Accident data from technical literature, newspapers and correspondence was collected with experts in the specific area of tunneling. Versatile databases for safety management of metro construction were developed (Suwansawat 2004, Decker et al. 2006, Zhou et al. 2008). Although great achievements have been made, it is very difficult to implement quantitative risk assessment (QRA) for safety management in subway construction because of the shortage of sufficient information about accidents happening in subway construction. To enhance the possibility of QRA and further the safety management in subway construction, a versatile subway construction incident database was developed, named Metro Safety Risk Database (MSRD), which integrates the case accident library and the engineering information library to provide more practical and valuable safety information for the project participants. The former library expands knowledge of safety management through providing accident causes, accident occurrence times, and possible preventive measures. By combining measurement data, geological data, design data, users can identify sources of risk and make quantitative risk assessments. Another important benefit of the MSRD is that it simplifies data processing and provides the parameters for design optimization. Utilizing the visual display on the browser/server (B/S) model, all project participants can manage on-site safety in accordance with their role on the project team from any location.

3. DATABASE STRUCTURE AND DATA COLLECTION

The MSRD is developed by the Institute of Engineering Management, Huazhong University of Science and Technology. The system design is based on the traditional concept of a central database and the implementation of the database uses Oracle 10i. The database is supported by an IBM System x3850 server, which is a high-performance server containing two Intel Xeon 7420 processors with 8 GB RAM, and four 146GB hard disks. There is also a backup server, an IBM System X3650 to prevent data loss.

3.1 Logic structure

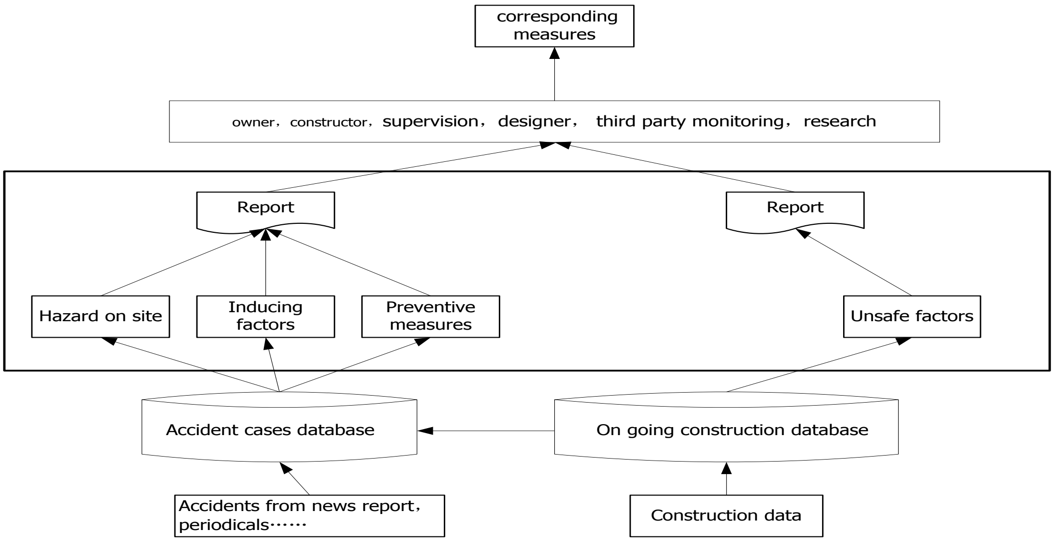

Figure 1: The three- level architecture of MSRD

3.1.1 Basic structure

MSRD is used by the owner, contractor, designer, supervisor, third party monitoring consulting company and the domain expert. In order to maintain data consistency, the MSRD act as a central database. Because users are in different locations, it is necessary to build a data collection application for all stakeholders (users) which is web based and uses a visual display to collect the information stored in the central database. The foundation of the MSRD is three-level architecture as shown in Fig. 1: user layer, information layer and data storage layer.

3.1.2 Task of every layer

In this system, the function of the data storage layer is to collect and store data. Data sources are both external and internal. The external data is the accident information coming from newspapers, technical literature, and knowledge from experts in metro construction. The internal data is the construction site data accumulating as a project progresses. Therefore, MSRD includes two logically separated but actually unified databases. One is the accident case database; the other is the actual project construction database which accumulates as construction continues. The information layer automates safety risk calculation with specialized statistical and calculation functions. The user layer allows input and retrieval of vital and crucial information by means of a web based, visual user interface. Easy access to such vital information makes it possible and feasible to identify sources of risk and to take necessary measures to eliminate them.

3.2 Composition of the database

3.2.1 Accidents database

The main table of the accident case database is the accident information table. The accident information table consists of two parts: the easily obtainable accident information table and the project information tables. Accident information includes accident number, project name, time of the accident, accident location, accident type, environment where the accident occurred, duration, results, evolution process, cause analysis, measures taken and their effectiveness, losses caused by the accident, and on-site video information(Landrin et al. 2006). The project information tables contain the unit owners, design units, contractors, supervision unit, and monitoring unit, the start date of construction, the tunnel parameters, geological information, groundwater, shield selection and other technical factors. A typical metro accident table template is shown in Table.1.

3.2.2 Projects database

The projects database includes about 40 tables. The primary tables are the project name table, station/section table, monitoring information table, design table, geological table, shield information table, surrounding environment information table and the patrol table. The relationship of tables in the project information database is shown in Fig.2. In addition, there are the user table, role table, short mobile message table, and other supporting information tables for database and project management. In fact, these tables can be divided into dynamic tables and static tables. One of the most important tables is the engineering monitoring information table which contains the initial observation point, warning standards, daily measurement information, safety warning standard and specification codes.

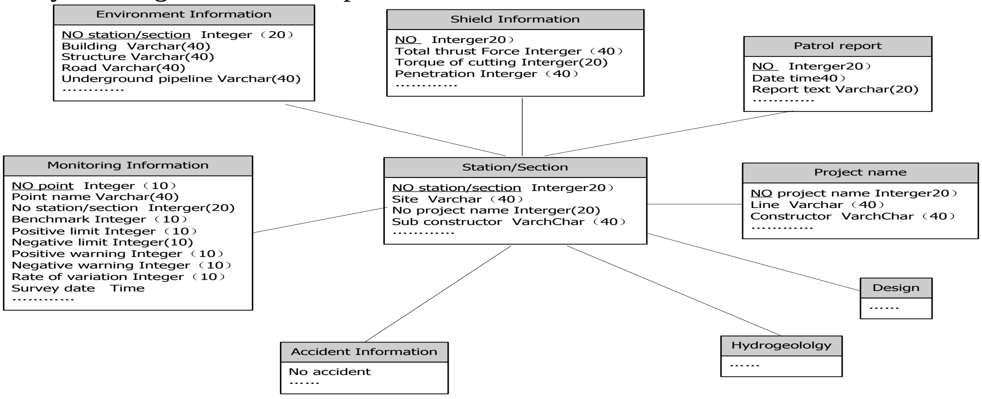

Figure 2: The relation of tables in on-going construction database

3.3 Data collection

3.3.1 Accident data collection

The continuous process of construction data collection is drawn from multiple sources of engineering safety information. Generally, the designer is responsible for the drawings and clarification of the safety control points and the safety control standards of the monitoring measurements; the contractors and the supervisors are responsible for the daily progress of the project, obtaining the monitoring data, and the safety inspection records; the third-party monitoring consulting company is responsible to provide independent safety monitoring data and the safety warning unit is responsible for providing data entry interface and data mining work. The MSRD system maintains data integrity by requiring intraday recording of monitoring data and by barring any data modification after 48 hours. Divisions of labor and work flow are shown in Fig.3.

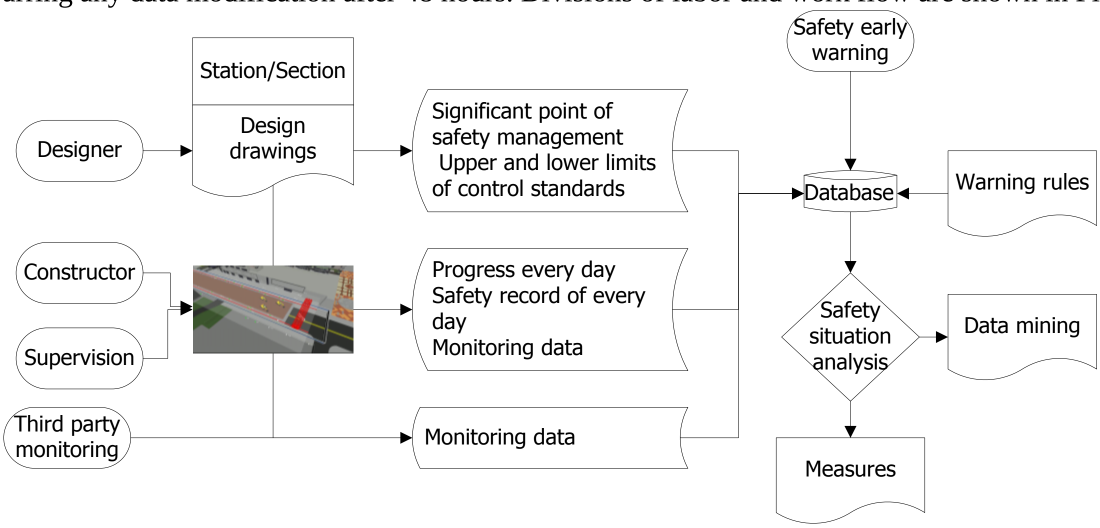

Figure 3: The

flowchart of continuous construction data collection

3.3.2 Information storage

The information can be divided into structured information and unstructured information. Structured information can show the original meaning of the information objectively and vividly. As seen in the Table.1, it is much easier to grasp and understand the information after being structured.

Table 1: A typical metro accident sheet

Accident ID		City	Beijing
Data	2010-07-14	Time	16:30
Site	M15, Shunyi Station	Construction methods	Open cut
Direct Causes	Steel support fall off	Geology	
Consequence	2 Fatalities, 8 Injures	Economic Loss	￥145940.00
Accident type	Falling object		
Punishment	8 people has been arrested, constructor and supervisor are fined 30 percent of its revenue, that is about 150000yuan respectively		
Reason direct	Illegal construction, operation at risk, steel brace supporting system construction seriously flawed		
Accident process	The Shunyi Station started to construct in March 2010, the accident was happened on July 14. During excavation, because of large number of earthworks in the north part of the foundation pit and long-term parking of heavy vehicles above its surface, the ground can’t stand it and start to appear irregular depression on July 11, leave a 3-meter-by-10-meter sink area. Without taking effective measures, the situation become worse, it sunk at the rate of 62.15mm per day, accumulated as deep as 295.35mm. On 16:42, 14th July, the steel support of the northeast corner of the foundation pit dropped and some workers has been hit by the falling things, 8 of them injured and 2 died.		
Pictures:	 		

At present, all of the cases in MSRD were obtained from reliable channel, the construction companies of which have been cooperating with us for a long time, such as Shenyang Metro Corporation and Wuhan Metro Corporation, the others are collected in other way after being proved reliable.

We have collected millions of data in the MSRD, as we can see in figure 4, the database already has a large scale, 2335186 cases have been stored in it, and much more cases will be added into it.

Figure 4: Implemented MSRD for Wuhan metro project

4. MSRD APPLICATIONS

As the MSRD was developed in electronic format, it can be easily changed to incorporate the requirements of each particular project through adding or removing forms and changing the fields within the forms themselves. From June 2009 to June 2011, this system is applied to Zhengzhou Metro Line 1 safety risk management. After two years of operation, the accident database collected a total 67 public accidents and 24 near miss accidents of Zhengzhou metro. In the project database, a station averagely collected 423 third-party monitoring records and 1492 contractor monitoring records and there are 20 stations and 19 intervals in Zhengzhou metro line 1. As such, the MSRD is not designed to be static. It is a flexible system which can be varied to suit the needs of the project in which it is being implemented. Hence, the benefits which should be gained are through the easy accessibility, maintainability and usability of the MSRD. The main applications of the MSRD are as follows.

4.1 Improve the ability of risk identification

The main function of the accident database is statistical learning, defined by three sub-functions: to deduce the cause of the incident, to understand the characteristic parameters of the accident, to identify the best after-accident emergency treatment. Project participants learn the importance of risk sources before the project start date and are continuously learning lessons from accidents. The database becomes an increasing important management tool and accidents are recorded in more accurate detail over time.

As shown in Fig. 5, collapse accidents (46%) account for the largest number of accidents(Zhou et al. 2011). Fire and exploration, fall from height, and struck by a falling object, are the other three categories of high frequency accidents at 8%, 8% and 7%, respectively. These results show that the key to safety management on subway construction sites is the prevention of collapse accidents. In addition to adherence to strict engineering safety management systems and procedures, the contractor must special attention to grouting reinforcement, monitoring data analysis, identifying abnormal cracks in structure or land soil, the envelope pile and sealing curtain, the quality of continuous underground wall molding, and emergency materials management in case of collapse.

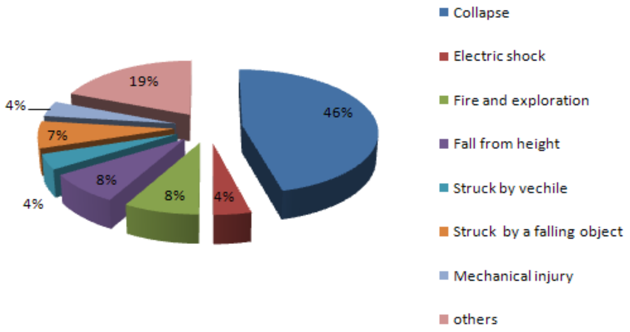

Figure 5: Statistics of subway construction accidents by types

4.2 Prevention of accidents

Even though construction failures are totally undesirable, a failure does, at least, greatly improve knowledge and information in the MSRD, which helps prevent future accidents. For example, after the Beijing Shunyi Station steel support incident, the city's subway construction project team organized a comprehensive steel support checking/monitoring system for all future projects.

The database contains all relevant steel support standard practices and safety requirements which are easily retrievable. Deviations from the standards and requirements will be reported so that corrective action can occur in a timely manner. Fig.6 illustrates an example of faulty steel support practices. Standard practice requires double steel talons when less than 10cm long, fixed wire rope greater than 16mm in diameter, infill closely behind the steel purlin, and steel support flange ends. In this case, the MSRD system issued a notification of an incident in time to take corrective action and prevent an accident in the future. Even events, not causing serious consequences, do contain information important to the prevention of future accidents. For example, in the excavation process of a metro station, the pit accumulated water because the entrances to an abandoned sewage line were not sealed. This event should be recorded into MSRD. The event/code might read: Leaving ports of migration pipeline open in the excavating pit. Close open ports of migration pipelines in inspection wells to prevent seepage during rainy season.

Figure 6: The noncompliant steel support (partial)

4.3 Real-time risk monitoring

The risk analysis and forecasting functions are accomplished in the MSRD system through real-time analysis of a large amount of monitoring data collected from monitoring sites. This analysis produces a prediction of the risk evolution trend. The analysis includes 3 categories: a single-point analysis, coincidence analysis and comprehensive analysis. Monitoring data typically includes the following categories: surface subsidence, top settlement of the pile (wall), pile (wall) displacement, groundwater level, steel support shaft force, reinforced stress, pit bottom uplift, and settlement observation points set in buildings and pipelines.

The single-point analysis is the most common safety state analysis, usually including two evaluation methods, threshold interval alarm and a rate interval alarm. Assuming the limit value is A, a measurement result in the lower 80% of A is considered a safe state, more than 80% less than 100% is considered early warning state; over 100% is a dangerous state. Based on monitoring data provided by the participants, the MSRD generated the historical monitoring data curve, observing the trends in order to perceive the structure steady state. If the value is within the warning or dangerous interval, the MSRD sends a warning signal to full-time safety management personnel.

Table 2: The security status of the threshold value range and rate interval

Threshold interval	[，A]	[A，A*80%]	[A*80%,B*80%]	[B*80%,B]	[B,]
	dangerous	warning	safety	warning	dangerous
Speed range	[C,]	[80%C,C]	[0,80%C]		

A:the low limited value, B:the up limited value, C:the absolute value of developing speed every day

Multi-point analysis analyzes the connections between different monitoring data on the same location, including connections between the inclination of the pile, the value of steel support axial force and the rise height of the bottom of pit. We can deduce the possible danger from the variation trend of the combined monitoring data and take preventive measures. As is shown in figure.7, if the pile of the envelope structure moves to pit inside, the bottom of the pit descends and the steel support axial force grows rapidly at the same time. Therefore, it is likely that the foundation pit will seriously deform so preventive actions should be performed. The MSRD provides such information so that we can reduce the probability of risk events by take effective measure in advance.

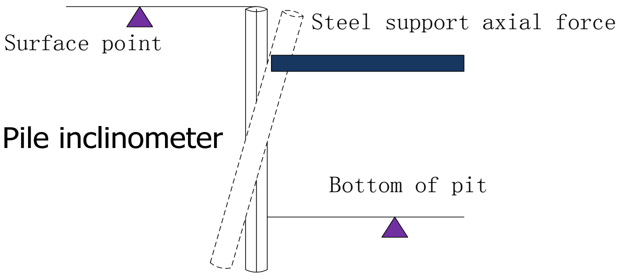

Figure 7: A group of multi-point analysis diagram

Comprehensive analysis means that we should take hazardous situations that may occur during construction into consideration and not solely rely on the monitoring data. For example, water or sand springing up in the bottom of the pit, cracks in the envelope structure, fatigue of steel support and large scale soil subsidence surrounding the pit may all lead to danger. These potential hazards cannot be recorded in numerically or in diagrams, but the database can record them with pictures so that the risk can be analyzed with the picture.

4.4 Shield trigger Settlement Regularity summarize and forecast

Because the shield tunneling machine must pass beneath city roads, rivers and buildings, construction companies need to ensure that no large-scale settlement occurs in these areas(Suwansawat 2004). The MSRD system can continuously check if settlement triggered by the shield machine is within the allowable deviation from the appropriate standard such as the Peck formula. For instance, is the settlement curve in a cross section compliant with the Peck formula? Does the settlement distribution before and after the shield machine comply with the longitudinal distribution function? Also, is the settlement appropriate with the particular geological conditions? One shield line of Zhengzhou City subway passed through a reinforcement area, farmland, green belt, and urban roads. Different regions of the surface settlement caused by the shield machine are shown in Fig.8: The denser the land, the smaller the settlement; the reinforcement measurements are acceptable; the settlement is proportional to the distance from the top of the shield tunnel (the farther into the tunnel, the smaller the settlement).

A settlement time series can establish a model of the surface deformation process, which can forecast the shield triggered by the maximum deformation combined with engineering geology and main shield parameters in real-time .

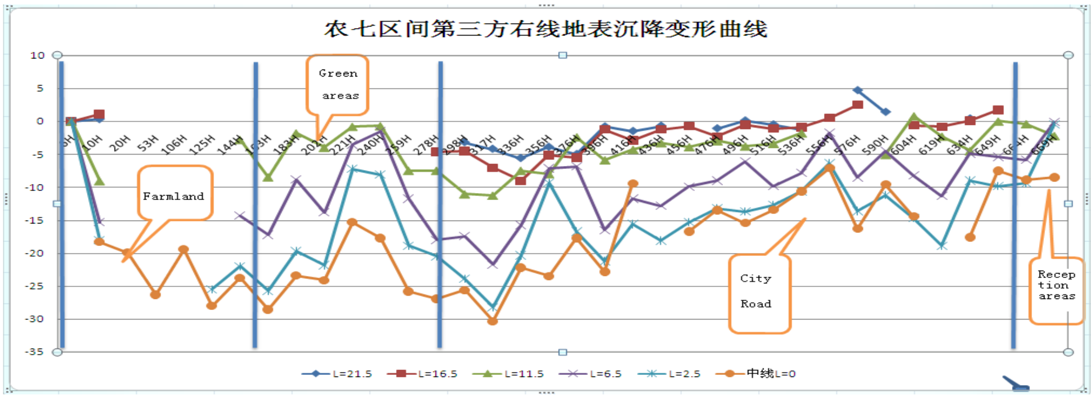

Figure 8: Different regions of the surface settlement caused by the Shield

4.5 Monitoring work assessing

An engineer once said(Johnson et al. 2004), safety monitoring is the eyes of subway construction. By using engineering standards in the MSRD and a maximum deviation for monitoring tests, continuous and effective quality testing in subway construction becomes feasible and orderly. Two steps are involved: 1) the contractor and the third party monitoring consulting company must define and follow a monitoring frequency (i.e., 2 times / day or 1/1/2 times / day). In 2004, the Singapore Nicoll accident was caused by a lack of monitoring. When the frequency is determined, the MSRD system warns the owner if monitoring data is missing. 2) The MSRD system must validate data accuracy through analysis of existing data. In addition, accuracy should be maintained by comparing monitoring results between the construction unit and the third party monitoring consulting company. Although the absolute values might be different due to differences in initial values and instrument accuracy, the relative change in trend should be the same. This test also ensures good communication between the construction company and the third party consulting company.

4.6 Accumulation of risk probability

The probability of risk events has been determined in the past by industry experts. Over time, this subjective analysis inevitably loses accuracy due to the expert's limited knowledge and experience, psychological factors, and emotional impact of larger accidents. The probability of risk events is such an important measurement that to be reliable and effective, it must rely on objective information from an engineering database to determine the relationship between the construction accident and engineering data(Jacobsson et al. 2010).

The contents of the MSRD are the result of the important work of defining common risk events and the statistical probability of an accident being caused by them. The definition of some common risk events in the MSRD are: foundation pit structural failure, originating or receiving failure, geological prediction accuracy of the tunnel face instability, facing an unknown body during tunneling, and shield tail seal failure. For example, under the Yangtze River bottom, the shield machine facing an unknown body was generally believed to be a small probability event as it was estimated that the probability of occurrence was ten to the power of minus six. In fact, the risk was much higher. In this segment of the river tunnel in Wuhan, facing an unknown body during tunneling caused a delay twice in 4 months. Therefore, the risk probability of occurrence was amended to ten to the power of minus two, which is a relatively high risk event. This is also a good example in the growth of knowledge over time when sufficient data is recorded into the MSRD system.

5. CONCLUSION

This paper aims to build a metro safety risk database (MSRD) for risk identification. Two critical problems can be solved by the database. First, it can store complete information about engineering accident data, project profiles, design information, measurement data and progress data for risk identification. Because this enables all stakeholders to grasp the complex characteristics of accidents occurring in the subway construction industry and to control safety risk points during a project with objective expert support. Second, this database can improve people's risk identification ability; all participants have access to this important information so that everyone can improve their own performance, take preventive and corrective actions, and effectively communicate with others.

The database needs to be improved constantly, because the MSRD system is just a management tool and not intended to replace human beings in safety management. It allows users to have objective data, and it, therefore, improves their efficiency and precision in calculating risk. The safety knowledge and control ability of engineers and the safety management mechanisms of the project team are also important factors to safety performance(Schupp et al. 2004). However, it is equally clear that further research is needed in the following areas:

1) Accident database only records incidents that have actually occurred. It is necessary to increase the library, with a near-miss accident sub-library to strengthen accident precursor management;
2) Combined with finite element analysis software of monitoring data on soil conditions, the construction process and progress, the MSRD would provide a reliable prediction of deformation and settlement in successive construction stages;
3) Because of the analysis danger signals in MSRD is not real time, there may be a lag in the evolution of danger trend function on the construction site. Automating the communication of danger to specific project participants can be accomplished by embedding a communications platform which would enable real time decision making;
4) Manual measurement data is inevitably flawed. Therefore, automatic monitoring instruments and the use of three-dimensional scanning instrument data can improve the accuracy. Further research is needed MSRD into various types of automated data input on the construction site.

In addition, the MSRD accident database part should be developed by the State Administrative Department of Construction and Development into a commercial database, so that it can become the most authoritative and comprehensive accident information source for various countries, locations, and types which will reduce duplication work, increase accident data accuracy, and collect all data into one database so that accidents can be eliminated worldwide.

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