Risk Management in Smart Civil Infrastructure

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Abstract—**The following key elements: Expert Judgment, Wireless-Sensor Networks and promoting Internet work-shopping will be demonstrated in the two modules e-Experience and e-Experiment that can be integrated into the created collaborative e-Learning environment. They will be able to better act to improving safety and reducing potential malfunctioning during construction and operation of the civil infrastructure. The e-Learning environment will provide location independent knowledge sharing and exploration, and allow for efficient real time data processing. One can expect from this risk management tool that scientists, engineers and students gain valuable experience and expertise in the wake to globalisation with regard to IT technologies.**

I. Introduction

The civil transportation infrastructure including roads and bridges, railways, subways, airports, harbors, pipelines and cables is crucial for society's vitality, health and individual development. In a permanent contest with ever growing demands, there is a strong need to extend these networks today, particularly in the underground, as a consequence of lack of space and ailing on-ground transport system. But reliable construction and functioning of the civil infrastructure is jeopardized by (1) severe and uncertain ground conditions, (2) aging and rapid deterioration of reinforced concrete systems, (3) severe constraints in management in terms of time and finance and (4) the increasing threat of natural disasters.

The sustainability of the developments in this field is at stake, particularly since it concerns the underground, which is a dominant factor in risk management, and because materials and methods must comply with strict regulations concerning environment and energy. It is an opportunity to apply and modify available advanced methods for improving and maintaining the civil infrastructure, in collaborative efforts of different disciplines.

The essential approach in risk management during construction is using specific experiences learned from practice and standard site investigation. The purpose is to reduce failure rates and construction costs. Failure rate during construction is relatively high and for 50% due to ground conditions. A database with appropriate information plus a suitable forecast model is required operational in real-time to provide a prompt and reliable answer to such safety and financial questions.

For safe operation and maintenance of the entire infrastructure the problem is an adequate and quick response to potentially malfunctioning of key elements in the most critical sections of the infrastructure, in particular bridges, tunnels and pipelines in metropolises. Real-time monitoring of the functioning of these key elements and corresponding swift remedial measures are the best solution for this problem. The costs for such smart monitoring systems are a real problem. Investigation of similar systems in other fields of technology, i.e. informatics and sensing, will provide payable solutions.

The research work presented in this paper comprises the development of two modules: e-Experience and e-Experiment, as well as their integration in an e-Learning environment with a focus on multi-disciplinary knowledge structure and transfer for enhancing safety and sustainability of the civil infrastructure. It will firmly embed the concept of integral risk assessment in the traditional safety control of the civil infrastructure, and it will allow the two modules, which include risk analysis tools and validated techniques in sensing the civil infrastructure, to be taught to younger generations by showcases.

II. Tunnel Risk Management

A. *Moden Observation Method*

In urban area the tunnel construction in soft ground is probably the most sophisticated and dangerous civil engineering work. For instance, one of the worst civil engineering disasters in the United Kingdom in the last quarter of a century occurred during the night of 20-21 Oct 1994 when tunnels in the course of construction beneath Heathrow airport's Central Terminal Area collapsed[1]. The No.4th subway in Beijing was commissioned one year later than the scheduled time, i.e. the 2008 Beijing Olympic Games since the tunnel collapsing incidents took place frequently and those engaged in the construction work were exposed to great risk of injury and death. The so-called observation method, one of important legacies of Terzaghi has been applied during the underground construction for risk control since long time ago. The observational method requires the behavior of a structure

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to be monitored at intervals during construction to ensure that settlements or deflections of the substructure or superstructure comply with the constraints established before construction commences[2]. The intervals should be sufficiently short to enable corrective measures to be taken with the due allowance for time taken in recording and interpreting data from the monitoring instruments. Although this method is frequently applied to the construction of embankments and tunnels on soft ground, often with frustration and annoyance to contractors when their programme becomes uncertain or is delayed, the method has little application to structures such as bridges or buildings where design changes or delays in occupancy could have serious financial consequences. On one hand the observational method has evolved to a more modern one based on the rapid development of site instrumentation and data mining; on the other hand, some progresses are available to the practicing geotechnical community and clients that allow for the better interpretation of data in time and even a failure forecast using the updated measurement data. The latter includes the inversed finite element analysis and other back analysis methods such as Bayesian methods etc. For a benchmarking problem in the NATM (New Austrian Tunnel Method) tunnel construction, a Bayesian Belief Network (BBN) model was developed below for the collapsing risk control.

B. Bayesian Belief Network for Tunneling Risk Analysis[3]

The cover to diameter ratio and type of tunnels, as well as the initial ground conditions were selected for the root layer nodes of BBN according to engineering experiences and expertise gained (the top layer in Figure 1). Based on the mechanics of tunnelling stability, the arching effect of stress distribution around tunnel and the mobilised strength of surrounding ground were chosen to be key parameters for the BBN-based risk analysis model. Variables *Arching* and *Soilstate* were constructed in the middle layer of the BBN (two nodes in the middle layer in Figure 1). The BBN techniques developed in Netica® was then applied for the model construction. This BBN model was calibrated using 14 case studies simulated by ABAQUS that permitted the conditional probability table (the histogram charts in Figure 1) obtained for all nodes (stochastic variables) through the maximum likelihood estimation method.

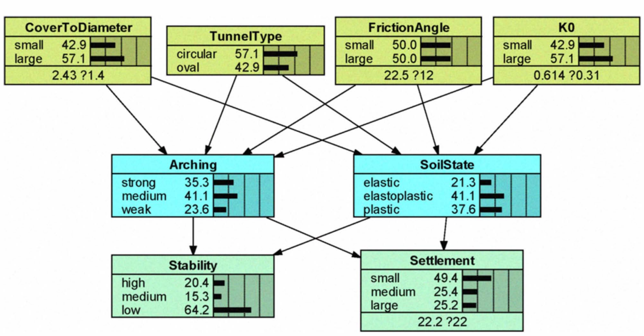

Figure 1: BBN Model for Tunnelling Risk Anlysis

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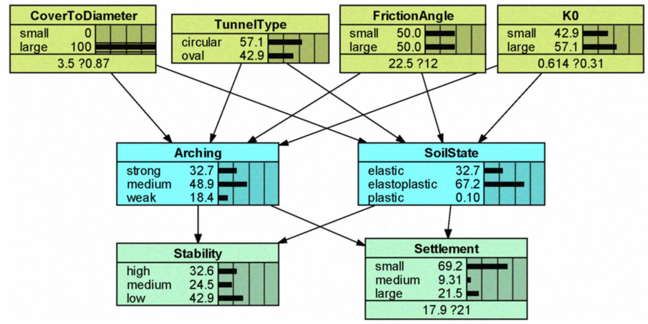

Figure 2 Scenario 1: when *CoverToDiameter* = 3

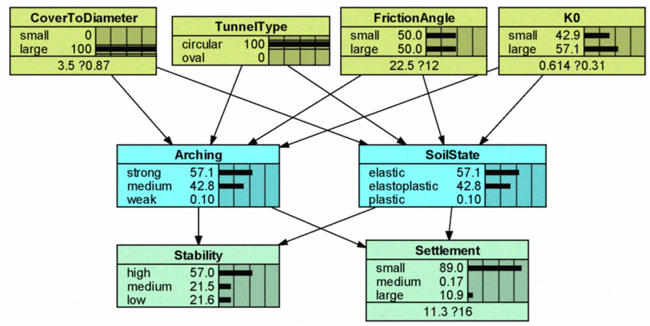

Figure 3 Scenario 2: when *CoverToDiameter*=3 *TunnelType*= circular

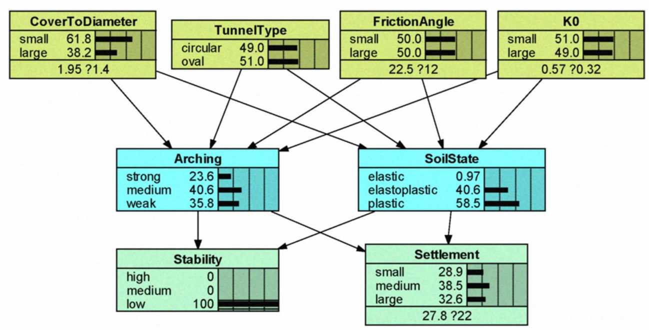

Figure 4: Scenario 3: what may cause a tunnel collapse?

C. Realization of Estabilished BBN[3]

The trained model was applied for scenario analyses where the probability inference, the most probable explanation and sensitivity analysis were calculated. The model established was demonstrated somehow realistic by the calculated results.

- Scenario 1 was when *CoverToDiameter*= 3 so that the large cover to diameter ratio realized (Figure 2). The other three root conditions remained unchanged. The updated probability of variable *Stability* (represents the tunneling stability) was raised from a *prior* of 20.4% to 32.6% based on the Bayesian inference analysis, so the tunnel was highly stable. The settlement of ground surface due to the tunneling may be small with a probability of 69.2% that was also raised up from 49.4% (represented by *Settelment*).

- Scenario 2 was when the cover to diameter ratio was 3 and the tunnel was circular. The other two root conditions remained unchanged (Figure 3). The updated probability for the tunnel was highly stable was continually raised from 32.6% to 57%; the settlement of ground surface due to the tunneling may be small with a probability of 89% that was also raised up from 69.2% .
- Scenario 3 was to find out the cause of a tunnel collapse. If there was a tunnel collapsing, then the tunnel stability should be low (Figure 4). The Bayesian inference indicated that both probabilities of low cover to diameter ratio and small K_0 were raised up. They were probably the causes of the tunnel collapsing.
- Sensitivity analysis was performed for the stochastic variables of *Stability* and *Settlement*, separately. As shown in Table1 and Table 2, the tunnel stability was very sensitive to the *SoilState* in the first place. But the sensitivity analysis regarding to the ground settlement however showed it was considerably sensitive to the K_0–values of the ground.

TABLE 1: SENSITIVITY ANALYSIS FOR TUNNEL STABILITY

Variables	**Mutual**	**Variance**
Stability	1.29	0.32
SoilState	0.79	0.16
Arching	0.46	0.06
Settlement	0.30	0.06
CoverTodiameter	0.21	0.05
K_0	0.10	0.01
Tunnel type	0.10	0.01
Friction Angle	0.00	0.00

TABLE 2: SENSITIVITY ANALYSIS FOR SETTLEMENT

Varibles	Mutual	Variance
Settlement	401.10	0.41
K_0	95.96	0.03
Arching	83.90	0.07
Stability	68.57	0.06
SoilState	59.07	0.06
CoverToDiameter	23.75	0.03
TunnelType	6.94	0.02
FrictionAngle	0.00	0.00

D. *Remarks on the developed BBN*

The key issues for constructing a BBN include the establishment of reasonable network structure and the condition probabilities for each nodal variable. The sound mechanics knowledge and engineering experiences of tunneling ensure the network logic and efficiency. A *prior* given by tunneling experts and experienced engineers could be collected and directly used. Although there are tremendous literatures documented case studies for tunneling problems, it is however difficult to collect, clean and reanalyze them since most of them are incomplete or inadequate or useless at all. So a literature study will not help a lot in the determination of the *prior* for a BBN. The FEA simulation approach was followed in the present work to consider the basic construction scenarios. A *prior* obtained from this approach should be better examined and adjusted by the assessable real projects or well documented case studies.

The stochastic variable of *Arching* was introduced to the middle layer of the developed BBN. The mechanics of this consideration needs further to be explained hereafter. The "arching" as soon as developed in the structure is considered to prevent the collapse or continued deformation of the structure. The elasto-plastic FEM simulations performed for a given cover-to-diameter circular tunnel clearly indicated the arching effects shown in Figure 5. The distribution of shear stress around the tunnel for a stronger ground (φ=40 degrees) resembled the "arches" while the less arch-like distribution of shear stress for a normally strong ground (φ=20 degrees) was observed (See Figure 5). However there was a debate about the quantifiable description of the observed "arching" effects. It is expected that the accuracy of BBN model would be improved by the better formulation of this important structural feature of tunneling problem.

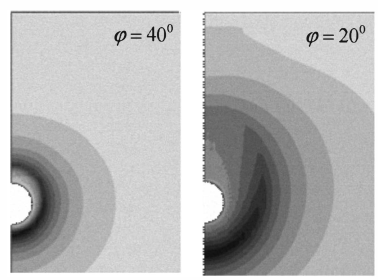

Figure 5: Contours of shear stress around tunnel

III. BRIDGE SAFE OPEARTION MONITORING

For safe operation and maintenance of the entire infrastructure, the problem is an adequate and quick response to potentially malfunctioning of key elements in the most critical sections of the infrastructure, in particular bridges in metropolises. Real-time monitoring of the functioning of these key elements and corresponding swift remedial measures are the best solution for this problem. However, the costs for such smart monitoring systems are a real problem. Investigation of similar systems in other fields of technology, i.e. informatics and sensing, will provide payable solutions.

Besides the traffic load and ambient conditions, a bridge structural health monitoring system should be designed to measure the following quantities. (1) Dynamic properties and responses of bridges such as natural frequencies, and critical damping ratios are essentially monitored by accelerometers. The 3D and μ-accelerometers are comparably expensive and the wireless MEMS-type accelerometers are being developed and showcased in practices. (2) Strain distribution of bridge structural elements is commonly monitored by vibrating string transducers or strain gauges or more recently fiber optic strain gauges. (3) Cable tension forces measurements can be performed by load cells or indirect methods such as tension force induced frequency shift measurements and (4) the displacement and geometry timely monitoring however present a challenging job. A prototype low cost deflection probe are being developed at Tsinghua for the vertical displacement monitoring of cable-stayed bridges.

E. *From settlement probe of excavation to deflection probe of bridge deck*

The vertical settlement probe consists of a fixed reservoir head on one end and pressure transducer (hydraulically connected to reservoir via small tubing) embedded in the ground[4-6]. The ground movement in the pressure transducer end will cause the changes in pressure head relative to the fixed end fluid head datum (reservoir). Settlement results in increased positive pressure and vice versa. Ground movement at the pressure end can be calculated by dividing the measured pressure by the liquid density. This design offers an easy and convenient way of designing small points wireless sensors that can be easily installed at the measuring points while maintaining a reliable point of reference on a stable ground. By contrast the extensometer used in the ground movement measurement will have to be deeply anchored in the ground and many GPS sensors will be expensive for the measurement accuracy of mm-level movement. Silicone oil is commonly used due to its low freezing temperature and will not freeze in winter. This liquid-based settlement probe can be installed into the box girder of cable-stayed or suspension bridges for monitoring the deck deflection along the longitudinal or transversal direction with the stable point of reference on the bridge tower shaft. The schematic layout of this deflection probe can be shown in the Figure 6,7 and 8. Motorola MPX2100 series device, a silicon piezoresistive pressure sensor, serves as pressure transducer. Each sensor modular is enclosed in a waterproof 8cm×8cm×8cm steel box.

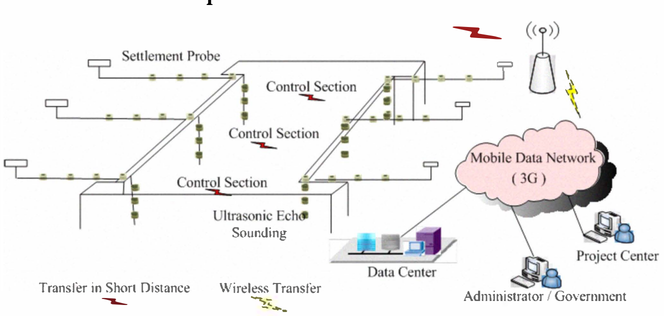

Figure 6 Monitoring of geometry of excavation by settlement probe and ultrasonic echo sounding installed

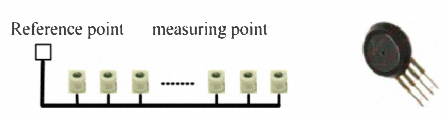

Figure 7 Schematic layout of the settlement probe and Motorola MPX2100 pressure transducer

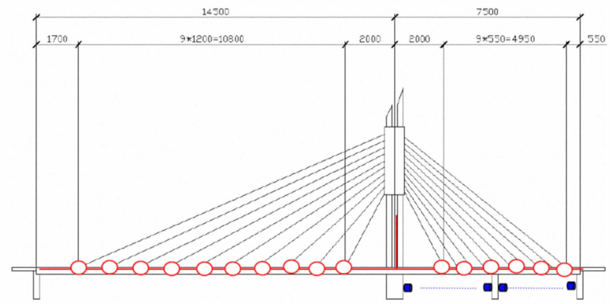

Figure 8 Deflection meter shown in red proposed for the cable-stayed bridge

F. *Evaluating a collision of a ship against Bridge piers*

Frequent collisions of ships with bridge piers threaten the safe operation of bridges, in particular due to busy shipping traffic and bad weather conditions. The monitoring system installed in the bridge as aforementioned should be acting during the collisions. But a quick and sound evaluating analysis is more or less lacking in practices. A dynamic model developed at MPile from Deltares® that is dedicated calculation model for dynamic analysis of a collision of a ship against the pile cap can be used for the quick analysis for this kind of accidents (Figure 9)[7]. It can be used for both single-pile and multi-pile dolphins. It accounts for the inertia effects due to the mass of the cap and the piles. The loading is restricted to a mass (ship) impacting the cap at a point, in a direction and at a speed which can be selected. It also incorporates a special soil reaction model that accounts for undrained lateral loading in sand. Besides this model the 3D bridge piled foundation analysis model developed as MPile from Deltares® (Figure 10) offers a handy tool for the bridge health managers and evaluators since such kind of analysis by FEM is usually very complicated.

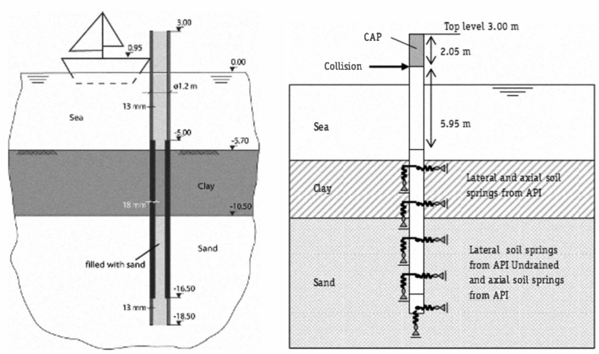

Figure 9 Dynamic model developed for ship collision analysis

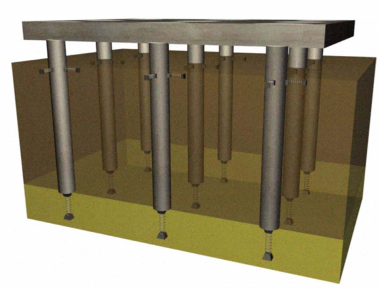

Figure 10 Poulos Model developed for the analysis of 3D piled foundation

IV. CONCLUDING REMARKS

The safety control culture of civil infrastructures is evolving from the concept of uncertain safety towards the safe uncertainty. Risk/uncertainties analysis and management should be implemented in whole life cycle of large civil infrastructure. Although risk analysis tools developed in the world of mathematics and science emerged decades ago, it should be noted that the gap between the theory and applications still need to be filled and risk analysis tools are not easily accessible. This is therefore the focus of the present study. Development of low cost real-time displacement sensing techniques for large scale civil infrastructures and cost effective evaluation models for the data interpretation is essential to put forward the practical framework of smart civil infrastructure that is more or less missing on the operational level. It is also proposed that the e-Experiment (Monitoring moudule) and e-Experience (BBN) could be integrated with the Internet-based Database (i.e. a case studies Database) in an e-Learning environment so that the younger generation of student and engineers would like to be trained and educated in a contextualised, personalised and ubiquitous way, mostly via Internet. Last but not least, leaned and applied risk management from the past experience and lessons do suggest that the good acceptance of risk management by involved human should be a prior.

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