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Modeling tunnel construction risk dynamics: Addressing the production versus protection problem

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ABSTRACT

Accidents remain a pervasive problem in tunnel construction. A major contributor to these accidents is a construction contractor's inability to determine an appropriate trade-off between production and protection goals. Thus, to examine this issue, a systemic model, which integrates System Dynamics (SD), Bayesian Belief Networks (BBN) and smooth Relevance Vector Machines (sRVM) (referred to as 'Organizational Risk Dynamics Observer' (ORDO)), is developed to investigate the mechanism of risk migration that resulted from the interactions between a contractor's organizational and technical systems. The model is demonstrated on an urban metro tunnel project that was constructed in Wuhan, China. It is revealed that when attention focused upon production, the propensity for minor accidents to occur increased, which triggered management to focus on protection. This increasing emphasis on protection may have muted the safe systems of working as incidents may be unreported, which can inhibit the motivation for safety awareness. When coupled with an increase in production pressure, the tunneling project could become prone to experiencing a major accident. Based on the results, it is suggested that the whole organization must continue to foster a sound safety culture by resisting production pressure at the expense of compromising safety.

1. Introduction

Geotechnical conditions, adjacent structures and underground pipelines can induce significant risks during the construction of tunneling projects. Such risks must be controlled to mitigate rework and accidents, and ensure that projects are delivered successfully (Eskesen et al., 2004). Yet, according to Sousa (2010) and Sousa and Einstein (2012) accidents during tunnel construction are frequent and can adversely influence project performance. For example, Love et al. (2014) identified that cost overrun for tunnel construction projects can range from 20% to 110%. Examples of infamous tunnel accidents include the Sasago Tunnel (1977) in Japan, Boston's Big Dig (2006) in the United States of America, and Hangzhou Metro (2008) in China.

Sousa (2010) classified the underlying causes of tunnel accidents as: internal causes, such as management and control errors, and external causes, such as unpredicted geology. These causes are not mutually exclusive because accidents encapsulate an array of circumstances (i.e. technical, managerial and organizational factors) that combine to produce the event (e.g., Perrow, 1984; Reason, 1990, 1997; Pidgeon and O'Leary, 2000; Dekker, 2006). Construction and engineering projects are complex systems that are bounded by protection and production axes (Reason, 1997; Goh et al., 2012a). To ensure projects met performance specifications, organizations often face trade-offs between multiple (and sometimes conflicting) goals, which shape management decisions, policies or strategies (Marais and Saleh, 2008; Love and Edwards, 2013). Under such circumstances, an organization's safe system of working can erode from a state of being 'safe' to 'hazard', and to 'loss of control' where safety margins evaporate (Rasmussen, 1997; Howell et al., 2003).

Due to limited prior knowledge of geotechnical conditions, tunnel projects are prone to failures due to collapse and excessive deformation as work progress (Cárdenas et al., 2013). In urban areas, tunneling also elevates the risk of damage to adjacent structures and pipelines (Eskesen et al., 2004). Thus, safety is imperative for contractors during construction despite pressures to meet performance specifications.

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Despite advances being made in tunneling technology and safety management measures, accidents still occur (Sousa, 2010). To eradicate tunneling accidents requires a deeper understanding of the underlying dynamics that contribute to a phenomena referred to as strategic project drift (SPD) which elevates the risk of accidents. In the context of this research, SPD represents a movement away form a safe system of working due to schedule pressure and is similar to the 'production' versus 'protection' problem (e.g., Marais and Saleh, 2008; Goh et al., 2012a). Against this contextual backdrop, the paper commences with providing a strategic oversight of relationships between different organizational goals and technical risks that may arise during tunnel construction. A systems-based model that integrates System Dynamics (SD), Bayesian Belief Networks (BBN) and smooth Relevance Vector Machines (sRVM), called Organizational Risk Dynamics Observer (ORDO), is established. The developed model is applied to an urban metro tunnel project that was constructed in Wuhan, China and used to provide insights into effective accident prevention strategies.

2. Systems-based safety risk models for tunnel construction

2.1. A brief review on the development of safety risk models

A number of safety risk analysis models for complex systems have been developed over the past few decades (e.g., Rasmussen, 1997; Mohaghegh, 2007; Saleh et al., 2010). These models can be broadly categorized into three phases according to their underlying research paradigms (Table 1).

The prescriptive models are developed based upon the defense-in-depth concept, which uses multiple safety barriers and redundancies to achieve a safe system of working; however, their effectiveness is limited due to the additional complexity caused by these barriers and redundancies themselves (Perrow, 1984). The second-phase models, or events-based models, aim to estimate the likelihood of an accident scenario according to the causal relationships between adverse events such as human error or technical failure. Using such models enables causes to be traced back so that remedies can be designed to fix the problem at hand. Nevertheless, explanation of an accident in terms of events has been criticized for not being able to incorporate complex relationships such as delays and feedbacks. In addition, the underlying pattern that drives systems toward risks when subjected to cost-effectiveness pressure is still not revealed (Rasmussen, 1997; Leveson, 2004). In contrast, the descriptive models in terms of actual behavior, also known as systems-based models, treat safety as a control problem under an adaptive socio-technical environment. In this instance emphasis is shifted to the mechanism that progressively pushes the system toward a hazardous state and ultimately accidents (Saleh et al., 2010).

Table 1
Safety risk models at different phases.

Phase	Category	Focus	Definition of accidents	Representative models
1	Prescriptive models	Safety barriers	Results of an absence or breach of defenses along the accident trajectory	Defense-in-depth protection (Nuclear Regulation Commission, 2000)
2	Descriptive models in terms of deviations from norms	Errors or failures	Results of a series of adverse causal events	Swiss cheese model (Reason, 1997)
3	Descriptive models in terms of actual behavior	Systemic and collective nature of system behavior	An emergent phenomenon that arise from the interactions between multiple agents within a socio-technical system	Systems-Theoretic Accident Model and Processes (STAMP) (Leveson, 2004)

Tunneling projects are characterized by the complex geology, on-site production, and a high turnover of project personnel. Events-based models that attempt to identify the causes are unable to accommodate a learning mechanism to prevent future accidents. Evidence reveals that even if the problems are fixed (e.g., people are dismissed for their mistakes), similar accidents may occur as the organizational and management settings that drive behavior remain unchanged (Ouyang et al., 2010; Dekker, 2011). Thus, there is a need to build a systems-based model to address the system deficiencies, rather than causes, for complex tunneling environment.

2.2. Challenges of building a systems-based model in the tunnel construction context

It is acknowledged that there is an intrinsic risk associated with tunnel construction (Sousa and Einstein, 2012). Many efforts have been dedicated to assessing the risk of a potential accident scenario during tunneling (e.g., Sturk et al., 1996; Hong et al., 2009; Nývlt et al., 2011). However, most extant models can be classified as being events-based. Only a small number of systems-based models have been developed in construction, specifically for tunnel projects (Mitropoulos et al., 2005; Kazaras et al., 2012). Moreover, most systems-based models that have been developed tend to be qualitative and generic in nature. As a result, Pasquini et al. (2011) have suggested that there is a lag between theoretical advancements and the development of methods and techniques for quantitative analysis in practice. This gap can be ascribed to three major challenges when developing a quantitative systems-based model:

2.2.1. From proximal factors to distal factors

Major accidents generally do not originate from a single technical failure (Reason, 1997). Research on the organization provides a promising way for improving safety and for better understanding the 'context' of accidents (Le Coze, 2005; Leveson et al., 2009). However, it is difficult to integrate the organizational aspects into the existing technical failure models because technical and organizational systems are different. Organizational systems are open and non-linear, and therefore require a systemic approach to their analysis. Conversely, those of a technical nature are closed and linear and can be examined using analytical methods (Le Coze, 2005). Tunneling projects are a socio-technical system and their performance is determined by the interaction between the physical construction processes and organizational elements. Therefore, integrating technical and organizational systems into one single model is critical to accurately determining the management shortcomings that elevate safety risk.

2.2.2. From static analysis to dynamic modeling

Tunneling works are dynamic processes where organizations involved are continually adapting in response to the external environmental and local pressures (Marais et al., 2004; Leveson, 2011). Accidents are, therefore, not the immediate result of a discrepant event, but rather a cumulative effect of various causes that materialize after a period of incubation (Turner and Pidgeon, 1997; Pidgeon and O'Leary, 2000). Moreover, unlike nuclear or petrochemical industries which are highly complex and tightly-coupled systems, tunneling projects are highly-complex but loosely-coupled which do not respond quickly to perturbations and may contain time delays (Perrow, 1984). Analysis that focuses