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Risk Identification in the Chilean Tunneling Industry

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Abstract: This article aims to identify the main risk factors that are threats to meet the objectives of tunnel construction projects by using the Chilean construction industry as a case study and proposes a methodology to evaluate risk factors in this type of project. Surveys were used to generate probability and severity indexes to rank 36 risk factors. Data were collected from 14 companies that are members of the International Tunneling and Underground Space Association. The results indicate that the main risk factors that hinder achieving the tunneling construction project objectives are (1) inaccurate cost estimation or lack of detail in budget preparation, (2) unexpected geological conditions, (3) inaccurate deadline estimation or insufficient breakdown of the project schedule, (4) frequent malfunction of construction equipment, (5) excessive delays in approval processes by government entities, and (6) unexpected soil conditions and water table. Furthermore, a comprehensive literature review is provided to compare these results to international perspectives to confirm the existence of risks inherent to tunnel construction projects. This article concludes with revisiting the risk factors, which are common for the construction industry in general.

Keywords: Risk Management, Probability–Severity, Project Management, Construction

EMJ Focus Areas: Decision Making; Risk Management.

The construction industry is one of the riskiest worldwide (Banaitiene & Banaitis, 2012) due to the inherent variability of processes and environmental uncertainties (Fang, Zhang, & Wong, 2011) that can interfere with a successful project development. Particularly, tunnel construction is problematic with extra complexities and difficulties including a high level of dependence on soil conditions, dewatering of groundwater, workzone access restrictions, and a strong interdependence of incremental project tasks (Wu et al., 2015; Yu, Zhong, Ren, Tong, & Hong, 2017; Zhang, Chettupuzha, Chen, Wu, & AbouRizk, 2017). Despite these difficulties, tunnel construction is an essential part of infrastructure development, and there are rarely alternatives to tunnel construction which is crucial for road networks, energy systems, and the mining sector.

Tunnel projects are risky for all parties involved (Eskesen, 2004), and therefore managers have to be committed to employ comprehensive risk management programs (Fouladgar et al., 2012). Reilly and Brown (2004) establish that it is necessary to use logical processes incorporating risk for tunneling and infrastructure projects. Chen, Chen, Lin, and Zhang (2015) recognize the importance of using reasonable methods to evaluate and

reduce the construction risks found in tunneling projects. Given the importance of risk management for successful project delivery, guidelines are needed for tunnel construction project to improve efficiency of risk management processes. This article aims to address this need by identifying and classifying the most significant risk factors for tunnel construction projects and creating a risk quantifying and ranking method based on probability and severity of event occurrences (factors).

Data for this project were collected through surveys of construction professionals in Chile, which is home to some of the largest ongoing tunnel construction projects as described next. An example of an ongoing tunnel construction project is the addition of two new lines of the Santiago Metro, one of the 30 largest subway systems in the world (De Grange, 2010). Another substantial Chilean project is the construction of the Chuquicamata Underground Copper Mine, one of the largest underground copper mining projects in the world. It is anticipated that more than 1,000 km long tunnels will be built by the end of this project in 2060 (Vargas, 2016).

The following sections will address the literature review, methodology, analysis of results, implications for engineering managers, and conclusions.

Literature Review

A project can be defined as successful if it meets cost and time requirements, attains quality specifications, satisfies stakeholder expectations such as absence of claims and legal disputes, and adds value to the owner (Majid, 2006). To achieve success, it is imperative that effective risk management is a fundamental component of project execution that should permeate all areas, functions, and processes of the project (Schieg, 2006).

Despite this relatively simplistic set of performance criteria, meeting these demands takes significant coordination and planning due to the dynamics of the construction industry. There are a number of factors that make the construction industry unique in terms of risk exposure: (1) the complexities of interactions between the parties involved in a construction project (owners, contractors, subcontractors, suppliers, and project designers); (2) the low level of replication of each project (each construction project is unique); (3) the temporary nature of project teams; (4) political, economic, social, and cultural conditions which each project inherits; and (5) exposure to uncontrollable environmental conditions (El-Sayegh, 2008). Thus, sophisticated risk management methods are commonly used to deal with the inherent risk of the activities in a variety of business sectors; however, there is little willingness to use these methods in the construction industry. A possible explanation for this may be the difficulties related to on-time project completion, dynamism of construction processes, and organizational structures. These features make it difficult to generate a risk management

approach that is applicable to all types of construction projects (Banaitiene & Banaitis, 2012; Caiado, Lima, De Mattos Nascimento, Neto, & De Oliveira, 2016; Flanagan & Norman, 1993).

The risk management process is also complex due to the different roles that each party with varying interests and responsibilities plays within a project. This creates conflicts and attributes the liability of error to different project participants. For example, Al-Khalil and Al-Ghafly (1999) showed that project designers and owners attribute delays to constructors, while builders blame project designers and owners. Similarly, Kumaraswamy and Chan (1998) identified a strong alignment between the perspectives of project designers and owners but not between project designers and contractors or between owners and constructors. These different points of view change depending on project drivers such as cost, schedule, and quality.

Additionally, Frimpong, Oluwoye, and Crawford (2003) and Olawale and Sun (2010) discuss the differences in perceptions on project success criteria. These authors state that cost is the most important factor to measure the success of a project especially for construction companies whose profit margins are directly affected by this factor. Unsurprisingly, factors affecting cost have been more frequently and deeply studied than those affecting scheduling. This is, perhaps, due to immediacy of the impact of cost changes and the short-termed perspectives on project success as the overemphasis on cost appears to be indiscriminately determined in many instances. Some examples of identified risk factors that increase project costs are delays in planning phase (Kaliba, Muya, & Mumba, 2009; Rahman, Memon, & Karim, 2013), poor planning and scheduling (Doloi, 2012; Frimpong et al., 2003), unrealistic schedules (Zou, Zhang, & Wang, 2006, 2007), and erroneous construction procedures (Zou et al., 2006).

From a time perspective, early or on-time completion of a project is beneficial for all parties involved (Abd El-Razek, Bassioni, & Mobarak, 2008), while cost savings only benefit the party that receives these savings. However, time reductions are also seen as an indicator of success and considered one of the most important factors to measure project performance (Enshassi, Mohamed, & Abushaban, 2009). Despite this well understood significance, delays are normalized in the construction sector. Many explanations including dynamic nature of the projects and changes in project teams or conditions are suggested as a justification. Nevertheless, similar to the short-term cost-oriented approaches to risk management, a rather myopic approach exists in assessing the impact of delays on the success of construction projects, which undermines their overall impact (Sambasivan & Soon, 2007).

Studies that combine the risk factors that affect both construction cost and time performance have also been conducted. For example, Taroun (2014) conducted an exhaustive literature review about models and assessment of construction risks in which the author concludes that cost and time have been important factors since risk management appeared in construction literature in the 1960s. On the other hand, Choudhry, Aslam, Hinze, and Arain (2014) found that financial risks were a major factor that affected the cost and schedule objectives of a project. Also, Ansar, Flyvbjerg, Budzier, and Lunn (2014) studied the cost and schedule overruns of large projects (e.g., dams) and outlined suitable risk management measures to deal with those challenges. To provide a different perspective, Schaufelberger and Holm (2017) examined the risks associated with cost and schedule from the contractor's perspective.

It is clear from the reviewed literature that there is significant international research interest in risk management; yet, the analysis frameworks and findings are inconsistent among studies of similar projects. Thus, comparative studies have not been feasible. To address this gap, Al-Kharashi and Skitmore (2009) conducted a new study considering all the variables used in previous studies and generating an inventory of 112 risk factors that caused delays in construction projects in Saudi Arabia.

A similar discrepancy also exists in dealing with risk associated with different project objectives. Zou et al. (2006) in Australia and Zou et al. (2007) in China studied factors that prevent achieving the objectives of time, cost, quality, safety, and environmental sustainability by analyzing each objective individually. The authors found that a tight project schedule is the primary cause that affects all targets. The identified risk factors show that there is a clear tendency to assign less importance to the factors that affect the objectives of quality, safety, and environmental sustainability and more importance to those affecting schedule and cost. Similarly, Olawale and Sun (2010) analyzed the risk factors affecting schedule and costs of construction projects in the UK and found results similar to Zou et al. (2006, 2007).

Despite the abundance of research on a multitude of construction projects worldwide, there is limited evidence of the application of their findings on tunnel construction projects. Therefore, the Chilean tunnel construction industry is used as a case study in this research based on the experience and knowledge of project managers of some of the world's largest ongoing tunnel construction projects.

Research Methodology

Data Collection

A survey is the primary data collection tool used in this study, a technique that has been widely implemented in construction engineering and management research (Molenaar & Scott, 2003). The main benefit of survey data is that experts with in-depth knowledge of construction projects can provide valuable opinions on project uncertainties (Choi, Cho, & Seo, 2004). In this study, a 5-point Likert scale survey for risk probability and severity was developed and used in data collection. All survey respondents are members of companies associated with the Committee of Tunnels and Underground Spaces of Chile (CTES), which is part of the Technological Development Committee of the Chilean Chamber of Construction. CTES represents Chile in the Association Internationale des Tunnels et de L'espace Souterrain (International Association of Tunnels and Underground Space) and in the International Tunneling and Underground Space Association.

The survey respondents are senior personnel (CEOs, project managers, and construction superintendents) working in the mining and construction industry or related industries (civil engineers, geologists, builders, architects, and mining engineers) with more than two years of experience in the tunneling industry. Because of their vast experience (70.5% have worked for tunneling companies for more than 5 years, 41.1% for more than 10 years, and 17.6% for more than 20 years), respondents were asked to answer about the portfolio of all projects they have worked as a whole instead of focusing on a particular project to collect global perspectives about the inherent risks within the tunneling industry.

In contrast with previous risk management studies, suppliers were also included in the pool of survey recipients. Suppliers are an essential part of projects in the tunneling industry as they

are in charge of providing and, in some occasions, installing specific products and/or operating specialized machines or equipment, and their performance can directly affect the objectives of a tunnel project.

Survey Used in the Study

The survey consisted of questions associated with the probability and severity assigned to 36 recurrent risk factors in tunnel construction projects. Survey responses were used to prioritize these risks. This survey is available from the authors by request.

The 36 factors were synthesized by analyzing a series of scientific papers that use a similar methodology (probability and severity) in multiple construction projects worldwide. The criteria in consolidating the literature to be reviewed was to limit the article to (1) construction engineering and management papers published in indexed journals (primarily ISI Web of Knowledge and Scopus) and (2) those which described a relevant tunneling project in the world. This review of literature is summarized in [Exhibit 2](#), where it is possible to see the diverse authors who have studied the factors considered in this research.

From this comprehensive literature review, a preliminary risk inventory was created, which was then filtered by those factors with a higher rate risk (the highest risk indexes based on the probability and severity methodology which is explained later in the article). Based on this analysis, a preliminary inventory of 32 factors was obtained.

Given that the tunnel construction industry is a specialized field, it was necessary to send the preliminary factor inventory to senior professionals and researchers who are experts in tunnel construction projects for validation. The specialists agreed with preliminary inventory of 32 factors but requested 4 additional factors be included in order to meet better the singularities of tunnel construction projects. As a result of their request, a total of 36 factors was established including the 4 additional factors below as proposed by the experts:

- *Nationality of labor*: Unlike other segments of the construction industry that primarily employ local labor, the workforce in tunnel construction has generally included a broad spectrum of nationalities. Cultural and language differences can lead to small conflicts that may eventually trigger problems. This factor has been studied in prior works (Al-Kharashi & Skitmore, 2009; Assaf & Al-Hejji, 2006; Assaf, Al-Khalil, & Al-Hazmi, 1995).
- *Type of construction contract*: Responsibility and risk management vary depending on the type of construction contract in place. Thus, attention should be paid to implications of the contract type selection when creating a risk management plan. This factor was found to be useful in prior research (Al-Kharashi & Skitmore, 2009; Assaf & Al-Hejji, 2006; Fayek, 2012; Long, Ogunlana, Quang, & Lam, 2004).
- *Operating costs exceeding estimates*: Irrespective of construction method selection, tunnel construction projects use equipment and materials intensively. Poor estimates or changes occurred between bid and award pricing agreements can create conflicts (Banaitiene & Banaitis, 2012; Eskesen et al., 2004; Pritchard & Pmp, 2014).
- *Tunnel depth*: This variable determines the constructive method used and the amount of drilling tests that are done prior to design and construction. Tunnel depth can influence the selection of a design or construction method, which vary based on ground conditions (Ding, Zhang, Wu,

Skibniewski, & Qunzhou, 2014; Hirata, Kameoka, & Hirano, 2007; Yoo, Jeon, & Choi, 2006). Moreover, the uncertainty surrounding the project is likely to increase with a longer tunnel length.

Validation of Survey Results

Previous researchers (Chinowsky, 2001; Forcael, Glagola, & González, 2012; Oppenheim, 2000) recommend verifying the accurate understanding of the designed survey and designed the survey to be self-explanatory by conducting a series of tests applied to either executive-level individuals who are responsible for organization-level concerns or renowned researchers in the construction industry. For the current study, distinguished senior professionals and researchers reviewed the survey and made relevant observations in order to improve its comprehension, repeating the process until the survey instrument was fully debugged.

Once the data were processed, the Cronbach's alpha coefficient (α) was calculated to establish the reliability of the survey. This coefficient measures the ability of the survey to achieve the same results under the same conditions and be applied to the same subject to ensure objectivity of the survey. This test was performed for both aspects (probability and severity) under study. Subsequently, after determining the α values were within an acceptable range, differences in perceptions of the questions were analyzed through Spearman correlation tests.

The Spearman's rank correlation coefficient measures the degree of linear correlation between two variables (groups). A value of 1 as correlation coefficient indicates a perfect positive correlation between the two groups, that is, both groups have exactly the same ranking, while a value of -1 indicates a perfect and inverse correlation between the two groups, and finally, a value of 0 indicates that there is no correlation between the analyzed groups (Weinberg & Abramowitz, 2008). This test has the advantage of not requiring the assumption of normality of the data or homogeneity of variance (Assaf & Al-Hejji, 2006).

Data Analysis

In this study, the key objective of the data analysis is to identify and evaluate the risk in the tunneling industry. To accomplish this, the association between (1) the probability representing the frequency as an event occurs and (2) the severity representing the impact of the occurrence of such event was analyzed. This association was quantified and analyzed by the probability and severity methodology presented in the next section.

Probability and Severity Methodology to Represent Risk

Among a number of qualitative methodologies for assessing risk (Banaitiene & Banaitis, 2012; Eskesen et al., 2004; Flanagan & Norman, 1993; Pritchard & Pmp, 2014), the probability and severity methodology was chosen due to a number of advantages over other methods (Abd El-Razek et al., 2008; Akogbe, Feng, & Zhou, 2013; Assaf & Al-Hejji, 2006). Other methods such as direct allocation of risk methodology were discarded because the existence of bias, where the greatest importance is given to the severity of a risk over the probability of it. Hence, risks with high probability but low severity are overlooked in the direct allocation methodology (Lu & Yan, 2013).

The probability and severity methodology allows for a graphical representation of risk making it easier to identify the greatest impact causes in terms of their probability (factors

with low probability and high severity can produce the same impact as factors with high severity and low impact).

In addition, the probability and severity methodology allows for the survey to be implemented without inducing bias due to interviewer intervention because all questions are self-explanatory. However, to ensure the greatest understanding from respondents, an example that serves to explain the survey was included. It should be noted that, to avoid inducing any response bias, the example used (a question and its answer) was not related to any of the 36 factors used for analyses.

The Likert scale used for each of the 36 factors considered in this research consisted of 5 categories for severity of an event (disastrous, significant, moderate, minor, and insignificant) and 5 categories for probability of occurrence of that event (very likely, likely, expected, unlikely, and very unlikely).

Calculation of Indexes

Because the data are collected from Likert-type surveys, the standard deviation of each factor is not useful in generating factor rankings as it does not reflect any relationship between factors (Chan & Kumaraswamy, 1997). For this reason, based on the methodology proposed by Akogbe et al. (2013), the data were processed to calculate three indexes which jointly allow ranking the factors in terms of risk by using survey responses for probability and severity:

- Probability index (PI) represents the frequency as an event occurs, takes values between 0 and 1, and is calculated as shown in Equation (1):

$$PI = \frac{\sum_1^5 a_i \times n_i}{5N}, \quad (1)$$

where a_i represents the weight assigned to each of response (5 for very likely, 4 for likely, 3 for expected, 2 for unlikely, and 1 for very unlikely); n_i represents the frequency of each response; and N represents the total number of responses.

- Severity index (SI) represents the severity of the occurrence of a factor, takes values between 0 and 1, and is calculated as shown in Equation (2):

$$SI = \frac{\sum_1^5 b_i \times n_i}{5N}, \quad (2)$$

where b_i represents the weight assigned to each of response (5 for disastrous, 4 for significant, 3 for moderate, 2 for minor, and 1 for insignificant); n_i represents the frequency of each response; and N represents the total number of respondents.

- Risk index (RI) represents the total risk of a factor, considers the frequency of occurrence (probability) of a factor and its severity if occurs. High values represent high risk, and low values represent low risk. It is calculated as shown in Equation (3):

$$RI = PI \times SI \quad (3)$$

Risk Factors

Construction industry dynamics vary from country to country. Because of culture, laws, and construction methodologies, significant variations are common. However, there are a number of factors which do not depend on geographical region such as problems with planning and control of projects (Assaf et al., 1995), where risk management plays an important role.

Because there is limited literature on risk identification in tunnel projects, it was needed to use a mixed methodology to generate an inventory with as much factors as possible (see Exhibit 1). This methodology demanded respondents provide two responses for each of the factors, first to assess their severity and second to assess their probability of occurrence.

Exhibit 1 provides the complete inventory of risk factors along with the corresponding “origin” of their category (constructor, project designer, owner, labor, materials and equipment, project itself, or external factors). This classification is based on the categories used by Assaf and Al-Hejji (2006), Akogbe et al. (2013), Sambasivan and Soon (2007), Gündüz, Nielsen, and Özdemir (2012), Long et al. (2004), and Le-Hoai, Dai Lee, and Lee (2008) with some adjustments to adapt the inventory developed specifically for this study. Exhibit 2 summarizes the articles that utilize each of the factors studied in this article.

Although Exhibit 2 does not indicate a defined pattern where certain factors stand out from others, it is possible to draw some insights about the factors. For example, Exhibit 2 shows that one of the most common factors cited by researchers refer to difficulties in payment to monthly progresses by the owner. This factor is cited in 22 studies. Unpredictable weather condition is identified as a significant risk in 21 studies, and financial difficulties of constructors and lack of labor are each cited in 20 articles. In addition, 10 factors are cited in more than half of the reviewed articles, and 26 factors are cited by more than 10 authors. This shows plausible evidence that the selected factors are appropriately supported by the literature.

Analysis of Results

After contacting 39 companies, a response rate of 35.9% was reached (17 professionals representing 14 companies), which exceeds the minimum response rate suggested for this type of study (Aibinu & Odeyinka, 2006; Akogbe et al., 2013; Chinnowsky, 2001; Zou et al., 2007).

Correlation of Responses

The Spearman’s rank correlation test was performed to analyze perception differences related to the questions asked to the survey respondents. This test measures the differences between the values assigned to the probability of occurrence of an event (factor) and the severity of its impact on projects. Data collected for this article resulted in a correlation coefficient value of 0.523, which is considered moderate to strong (Becker, 1995; Martínez, Tuya, Martínez, Pérez, & Cánovas, 2009). Since this coefficient is greater than zero, there is a positive correlation between respondents’ answers indicating that despite some differences of perception, they remain within a range of positive correlation, thus ensuring consistency. In addition, at a 0.05 significance level, the p -value of the test was 0.0015, which shows the null hypothesis is rejected and correlation exists.

Exhibit 1. Inventory of Risk Factors

ID	Factor	Category
C1	Poor contract management	Contractor
C2	Inaccurate cost estimation or lack of detail in budget preparation	Contractor
C3	Inaccurate deadline estimation or insufficient breakdown of the project schedule	Contractor
C4	Financial difficulties of the constructor	Contractor
C5	Inadequate project scheduling	Contractor
C6	Errors during construction	Contractor
C7	Operating costs higher than estimated	Contractor
C8	Hazardous working conditions (danger of accidents)	Contractor
D1	Variations in the original design (required by project designers)	Project Designer
D2	Inspections and/or testing delays by project designers	Project Designer
D3	Lack of experience by project designers	Project Designer
D4	Delays in approval of permits and tests	Project Designer
O1	Difficulties for paying monthly progresses	Owner
O2	Variations (change orders) in the original design (introduced by owners)	Owner
O3	Type of construction contract	Owner
O4	Methodology of contract award and method for setting fines and bonds	Owner
L1	Lack of labor	Labor
L2	Lack of qualified professionals and technicians	Labor
L3	Nationality of labor	Labor
L4	Low labor productivity	Labor
L5	Lack of skilled labor	Labor
M1	Variability of material prices	Materials and Equipment
M2	Dependence on imported materials/lack of local material availability	Materials and Equipment
M3	Frequent malfunction of construction equipment	Materials and Equipment
M4	Suppliers unable to deliver products or services on time	Materials and Equipment
M5	Low productivity and efficiency of the equipment used	Materials and Equipment
M6	Materials do not meet technical specifications	Materials and Equipment
P1	Occurrence of disputes between stakeholders	Project
P2	Lack of communication and coordination among project participants	Project
P3	Environmental restrictions	Project
P4	Tunnel depth	Project
E1	Lack of information or inaccurate information regarding the construction site	External Factors
E2	Unpredictable weather conditions	External Factors
E3	Excessive delays in approval processes by government entities	External Factors
E4	Unexpected soil conditions and water table	External Factors
E5	Unexpected geological conditions	External Factors

The correlation results indicate that the probability and severity are related positively. The only 6 exceptions were factors with probability and severity ranking separated by 15 or more positions in the ranking scale. The largest difference is found for the factor “Financial difficulties of the constructor” with a 29 positions difference (fifth place in severity and 34th in probability). Therefore, the results show a tendency by respondents to similarly perceive the greatest risk factors related to tunneling construction.

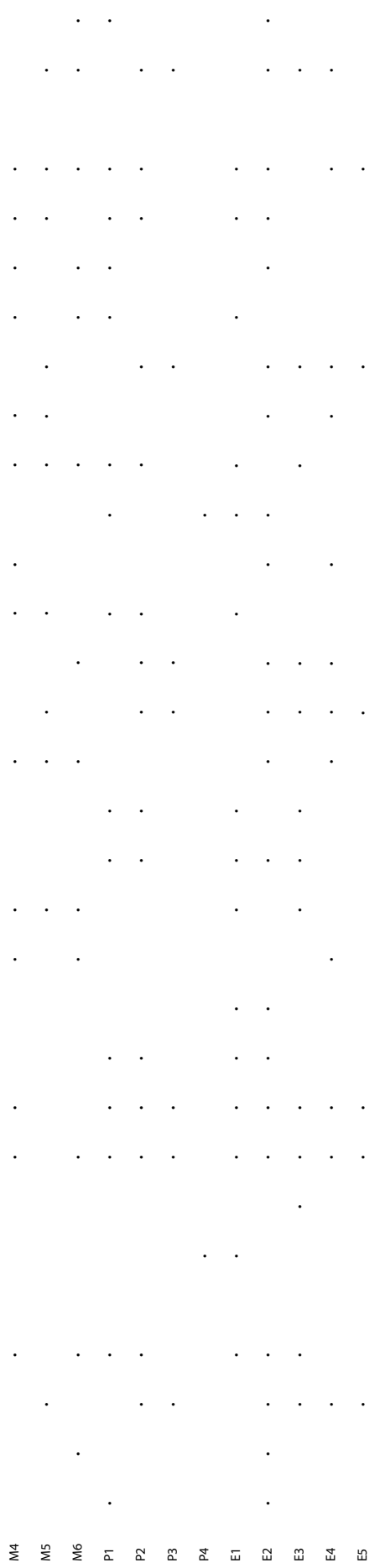
Risk Analysis

The Cronbach’s alpha values obtained are 0.913 for questions associated with probability and 0.932 for questions associated with severity. According to Nunnally (1978) and Doloi (2008), both values represent excellent reliability. Exhibit 3 shows the rankings of risk factors in tunneling projects.

“Excessive delays in approval processes by government entities” is the highest probability (83.5%) risk factor identified

Exhibit 2. Risk Factors and Their Use in Earlier Articles

ID factors	Abd El-Razek et al.(2008)	Abdul Rahman et al. (2013)	Abinu and Odeyinika (2006)	Akogbe et al. (2013)	Al-Kharashi and Skitmore (2009)	Assaf et al. (1995)	Assaf and Al-Hejji (2006)	Aziz (2013)	Chan and Kumaraswamy (1997)	Doloi et al. (2012)	Doloi (2012)	El-Sayegh (2008)	Enshassi et al. (2009)	Fang, Li, Fong, and Shen (2004)	Faridi and El-Sayegh (2006)	Frimpong et al. (2003)	Ghosh and Jintanapaknont (2004)	Gundüz et al. (2012)	Kaming et al. (1997)	Kartam and Kartam (2001)	Kazaz et al. (2012)	Le-Hoai et al. (2008)	Long et al. (2004)	Lu and Yan (2013)	Odeh and Battaneh (2002)	Okpala and Anikwu (1988)	Olawale and Sun (2010)	Sambasivyan and Soon (2007)	Sweis, Sweis, Abu Hamad, and Shboul (2008)	Tang, Qiang, Duffield, Young, and Lu (2007)	Toor and Ogunlana (2008)					
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by survey participants, followed by “Inaccurate cost estimation or lack of detail in budget preparation” (80.0%), and “Operating costs higher than estimated” (78.8%) and “Variations in the original design (required by project designers)” (78.8%) that shared the third place (Exhibit 3). It should also be noted that all these factors are among the top 10 in the risk ratings, which is not surprising considering the strong positive correlation between probability and severity indices.

In terms of severity of factors, first place is shared by “Inaccurate cost estimation or lack of detail in budget preparation” and “Unexpected geological conditions” (severity index = 84.7%) followed by “Unexpected soil conditions and water table” (83.5%), “Inaccurate deadline estimation or insufficient breakdown of the project schedule” (82.4%), and “Frequent malfunction of construction equipment” (80.0%). As in the previous PI results, all the factors are found among the top 10 of the ranking of risk importance.

Finally, the RI provides an overall measure of the impact that each factor has towards the project objectives. Thus, the most important factors or causes according to their ranking of importance are “Inaccurate cost estimation or lack of detail in budget preparation,” “Unexpected geological conditions,” “Inaccurate deadline estimation or insufficient breakdown of the project schedule,” “Frequent malfunction of construction equipment,” and sharing fifth place are “Excessive delays in approval processes by government entities” and “Unexpected soil conditions and water table.” Except for “Excessive delays in approval processes by government entities” in all the other top five RI factors, a predominance of the SI is found, which may indicate that severity has more relevance when considering risk in tunneling construction.

Tolerances vary from project to project; however, for this research, any RI value that exceeds the median of the RI value range is classified as relevant. As previously mentioned, the highest RI value is found for the factor “Inaccurate cost estimation or lack of detail in budget preparation” (RI = 67.8%), while the factor “Nationality of labor” had the lowest RI value (28.1%) as shown in Exhibit 3. All factors listed in the ranking are appropriate under the notion that RI values exceeding the median of the data set are relevant factors. This is consistent with a study conducted by Zou et al. (2006), where factors of risk are identified in the Australian construction industry.

To graphically observe the results, Exhibit 4 shows that all factors have rates higher than 50%, both for probability and severity, except for “Nationality of labor” PI = 45.9%). Exhibit 4 also shows that the RI of factors are in a compact configuration located in the upper position of the graph with high levels of severity and high levels of probability. This graph confirms the perception that tunneling projects have high levels of risk.

Comparison with Other International Studies

A comparison with international studies was performed to identify commonality of the factors worldwide. Based on an extensive literature review, a comparison was conducted to establish the factors related specifically to the tunnel construction industry and those that belong to the construction industry. It should be noted that these comparisons are only referential because each study is based on a series of assumptions, methodologies, assessments scales, and geographic contexts, which make it difficult to extrapolate results between countries. However, it is possible to find some points of concurrence and draw conclusions about these. The comparison was performed taking

Exhibit 3. Ranking of Risk Factors in Terms of Probability Index (PI), Severity Index (SI), and Risk Index (RI)

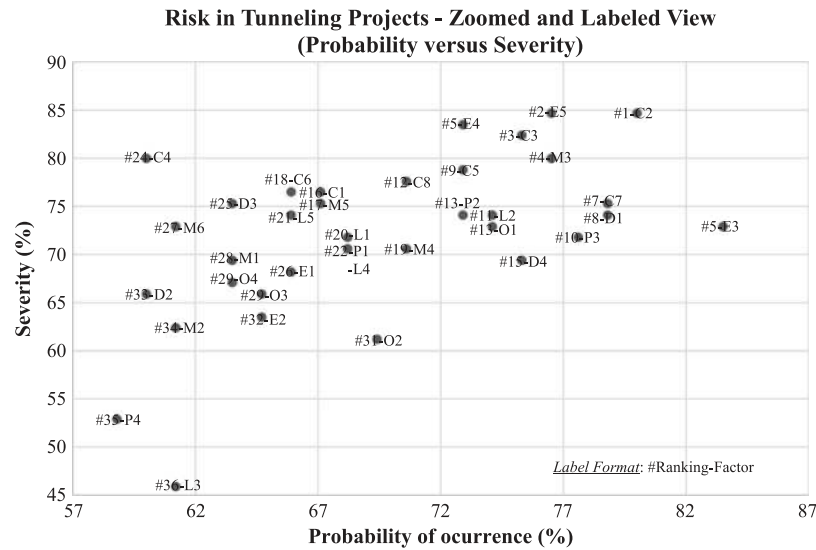
Factor	P.I. (%)	Ranking P.I.	S.I. (%)	Ranking S.I.	R.I. (%)	Ranking R.I.
Inaccurate cost estimation or lack of detail in budget preparation	80.0	2	84.7	1	67.8	1
Unexpected geological conditions	76.5	6	84.7	1	64.8	2
Inaccurate deadline estimation or insufficient breakdown of the project schedule	75.3	8	82.4	3	62.0	3
Frequent malfunction of construction equipment	76.5	6	80.0	5	61.2	4
Excessive delays in approval processes by government entities	83.5	1	72.9	18	60.9	5
Unexpected soil conditions and water table	72.9	12	83.5	3	60.9	5
Operating costs higher than estimated	78.8	3	75.3	11	59.3	7
Variations in the original design (required by project designers)	78.8	3	74.1	14	58.4	8
Inadequate project scheduling	72.9	12	78.8	7	57.5	9
Environmental restrictions	77.6	5	71.8	21	55.7	10
Lack of qualified professionals and technicians	74.1	10	74.1	14	54.9	11
Hazardous working conditions (danger of accidents)	70.6	15	77.6	8	54.8	12
Difficulties for paying monthly progresses	74.1	10	72.9	18	54.1	13
Lack of communication and coordination among project participants	72.9	12	74.1	14	54.1	13
Delays in approval of permits and tests	75.3	8	69.4	26	52.3	15
Poor contract management	67.1	21	76.5	9	51.3	16
Low productivity and efficiency of the equipment used	67.1	21	75.3	11	50.5	17
Errors during construction	65.9	23	76.5	9	50.4	18
Suppliers unable to deliver products or services on time	70.6	15	70.6	23	49.8	19
Lack of labor	68.2	18	71.8	21	49.0	20
Lack of skilled labor	65.9	23	74.1	14	48.8	21
Occurrence of disputes between stakeholders	68.2	18	70.6	23	48.2	22
Low labor productivity	68.2	18	70.6	23	48.2	22
Financial difficulties of the constructor	60.0	34	80.0	5	48.0	24
Lack of experience by project designers	63.5	28	75.3	11	47.8	25
Lack of information or inaccurate information regarding the construction site	65.9	23	68.2	28	45.0	26
Materials do not meet technical specifications	61.2	31	72.9	18	44.6	27
Variability of material prices	63.5	28	69.4	26	44.1	28
Type of construction contract	64.7	26	65.9	30	42.6	29
Methodology of contract award and method for setting fines and bonds	63.5	30	67.1	29	42.6	29
Variations (change orders) in the original design (introduced by owners)	69.4	17	61.2	34	42.5	31
Unpredictable weather conditions	64.7	26	63.5	32	41.1	32
Inspections and/or testing delays by project designers	60.0	34	65.9	30	39.5	33
Dependence on imported materials	61.2	31	62.4	33	38.1	34
Tunnel depth	58.8	36	52.9	35	31.1	35
Nationality of labor	61.2	31	45.9	36	28.1	36

into account the top five factors found in this study and other investigations conducted in other countries.

In terms of the factor “Inaccurate deadline estimation or insufficient breakdown of the project schedule,” several authors (Kaming, Olomolaiye, Holt, & Harris, 1997; Le-Hoai et al., 2008; Okpala & Aniekwu, 1988; Zou et al., 2006, 2007) coincide that this factor could be triggered by design changes (eighth in RI ranking) and may also imply an increment in costs (Zou et al., 2006, 2007), which is closely related to the main factor found in the current

research “Inaccurate cost estimation or lack of detail in budget preparation.” Another important factor found is “Difficulties for paying monthly progresses” (13th in RI ranking), which would explain the factors “Inaccurate deadline estimation or insufficient breakdown of the project schedule” and “Inadequate project scheduling” (Kaliba et al., 2009; Kazaz, Ulubeyli, & Tuncbilekli, 2012; Okpala & Aniekwu, 1988). Finally, another factor regularly identified in many studies is “Variations (change orders) in the original design (introduced by owners),” which can explain risks

Exhibit 4. Risk in Tunneling Projects for the 36 Factors Considered



related to the factors “Inaccurate deadline estimation or insufficient breakdown of the project schedule” and “Inadequate project scheduling” (Gündüz et al., 2012; Zou et al., 2006, 2007), to the factor “Inaccurate cost estimation or lack of detail in budget preparation” (Zou et al., 2006, 2007), and to the factor “Environmental restrictions” (Zou et al., 2006), thus affecting the overall project (El-Sayegh, 2008).

Additionally, other international researchers show that problems associated with the factor “Inaccurate deadline estimation or insufficient breakdown of the project schedule” have also been found in Turkey (Gündüz et al., 2012), United Arab Emirates (Faridi & El-Sayegh, 2006), Vietnam (Long et al., 2004), Australia (Doloi, 2012), and China (Zou et al., 2007). On the other hand, problems relating to the factor “Inaccurate cost estimation or lack of detail in budget preparation” have been found in Egypt (Rahman et al., 2013), and problems associated with the factor “Excessive delays in approval processes by government entities” can be found in Vietnam (Le-Hoai et al., 2008), India (Doloi, Sawhney, Iyer, & Rentala, 2012), and Australia (Zou et al., 2006). Finally, problems associated with the factors “Unexpected geological conditions” and “Unexpected soil conditions and water table” were not found among the top five risks in other construction projects, which may indicate these problems have a higher relevance in tunneling construction than in other construction projects.

Implications for Engineering Managers

According to Latham (1994), risk can be managed, minimized, shared, transferred, or accepted; however, it cannot be ignored. Despite the high consensus about this statement, project managers that commit the organization to a particular level of risk may never have implemented risk management or even consulted a risk management specialist (Chapman, 2016). This is particularly problematic in the construction industry because of the incipient use of advanced management tools such as lean construction which began as a new management philosophy during the 1990s (Koskela, 1997). Even worse in the tunnel construction, in which some emblematic projects such as the Channel tunnel between France and UK, the Alp tunnels in

Switzerland, the world’s longest road tunnel in Norway, China’s Qinling tunnel, and Sydney’s harbor tunnel have faced high levels of risk, becoming part of the calamitous history of cost overruns (Flyvbjerg, Bruzelius, & Rothengatter, 2003). No tunnel construction project is risk free.

From a theoretical and methodological point of view, this study contributes to the body of knowledge by providing a practical tool to identify risks in the tunneling industry through four simple steps: (1) to utilize the list of risk factors in tunnels found in this research (Exhibit 1); (2) to apply a survey about probability and severity for each of those risk factors and record the answers in terms of percentages; (3) to calculate the risk impact by multiplying the percentages obtained for probability and for severity for each factor; (4) to order the factors in terms of the risk impact calculated from the highest to the lowest values to determine the riskiest ones. Even more, this methodology may be used by engineering managers from other industries by replacing the list of risk factors with those risks found in their own industries and following the same steps presented here.

In terms of contributions for practice, this study aims to provide a consultation tool that allows project and engineering managers: (1) to have a first approximation of the most recurring risks in tunnel construction, (2) how to quantify them, and (3) how to rank them according to their impact. This identification and ranking of risks in tunnel construction could bring multiple benefits to project and engineering managers in broader, complex project settings. Some of these benefits are (1) to increase their understanding of the technical requirements of the project; (2) the value engineering process and the allocation of the project budget could be conducted taking into account the key risks; (3) early detection of risks could imply that additional specialist consultants for the project could be identified and appointed on time; (4) the project development and delivery process could be improved; and (5) potential expensive mistakes could be removed. Although the findings of this article are based on survey responses of tunnel construction projects, they can be extended to complex projects with higher levels of uncertainty.

As expected, this study shows that cost and time-related factors are important risk factors (i.e., “Inaccurate cost estimation or lack of detail in budget preparation” and “Inaccurate deadline estimation or insufficient breakdown of the project schedule”) and supports the prior literature findings since the 1960s. This supports that a good project manager should focus on cost estimation and schedule preparation. From a technical point of view, unexpected geological and soil conditions and malfunction of equipment arise within the top 10 of riskiest factors in tunneling projects; therefore, as previously mentioned, project and engineering managers could benefit from better understanding of the technical aspects related to the risk factors found here. Finally, the fifth risk factor found, “Excessive delays in the approval processes by government entities,” accounts for the importance of having competent project managers to deal with public authorities and face this risk properly.

In summary, the abovementioned benefits for project and engineering managers can be potentially achieved by considering the risks found in this research because the managers can focus on the technical risks of a project along with cost and time issues (as indicated by the top 10 risks in tunneling construction projects found in this study).

Conclusions

The primary risk factors found to be important to tunnel construction are: “Inaccurate cost estimation or lack of detail in budget preparation,” “Unexpected geological conditions,” “Inaccurate deadline estimation or insufficient breakdown of the project schedule,” “Frequent malfunction of construction equipment,” “Excessive delays in the approval processes by government entities,” and “Unexpected soil conditions and water table.” Only the factor “Excessive delay of approvals by government entities” is not exclusive of tunnel construction, but rather is typical of the construction industry as a whole.

Although it has to be reiterated that the comparisons with international studies are referential only (due to the different conditions under which these studies were conducted), it is possible to highlight the existence of similarities in some of the factors studied. In particular, attention should be paid to factors related to deadlines and scheduling, costs, design changes, and environmental restrictions.

On the other hand, since the studied factors were clustered at the upper extreme of the probability–severity graph, that is, high levels of severity and high probability of occurrence, it was possible to confirm that tunnel construction shows evidence of high levels of risk. Despite these findings, additional efforts are warranted to increase the number of participating companies which, although sufficient for this analysis, could be expanded.

Finally, this article also contributes to the body of knowledge by providing data and a methodology for risk identification within the tunneling construction industry, which is valuable because it is one of the largest mining industries in the world. This work also newly incorporates data from suppliers who are critical for successful completion of tunnel construction projects and have been excluded from prior research in this field.

Disclosure statement

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