The paper was published in the proceedings of the 1st International Symposium on Geotechnical Safety and Risk (ISGSR 2007) and was edited by H. Huang and L. Zhang. The conference was held in Shanghai, China 18-19 October 2007.

A risk-based life cycle design approach for tunnel lining

Y. Wang, H. W. Huang
Tongji University, Shanghai, China

ABSTRACT: The purpose of this paper is to develop a framework transforming the traditional tunnel lining design approach into a risk-based life cycle design approach. Firstly, shortages existing in traditional design method are illustrated. Then risk theory and life cycle cost analysis are adopted to deal with these problems such as the high degree of uncertainty and complexity in tunnel lining design. In response to the features of tunnel lining design, the application of life cycle cost analysis, risk assessment and decision-making in tunnel lining design are discussed. And a general design flowchart is presented, which can provide decision makers an informed way to make their choices through evaluating the design options by life cycle cost and risk assessment during its lifetime and obtain an optimum design alternative balanced with safety, durability and cost.

1 INTRODUCTION

There exist a lot of uncertainties in tunnel engineering, such as uncertainty in rock mass behavior, uncertainty in ground-structure interaction, variable in construction material properties and geometry of structure during construction, degeneration of material during operation. Uncertainty dominates the lifetime of tunnel. How to deal with uncertainties in tunnel engineering is a matter of importance related to safety, durability, economy and environment.

The traditional tunnel lining design practice, particularly the dimensioning of primary and final lining, is to use deterministic approaches based on indirect management of potential risks through a series of predetermined project decisions, incorporating engineering judgment and established design principles. The analysis of tunnel lining system is conducted with the assumption that the behaviours of the ground and the lining system are well understood and quantifiable.

While the above method is simple, it is not well suited to describe uncertainty in tunnel engineering. Only one definite value is input for each numerical parameter in deterministic process, despite many assumptions required in fixing its value, which can't reflect the influence of uncertainty very well and often induces time and cost overruns. Several reports state that cost and time overruns commonly occur in infrastructure projects, especially in tunnel engineering. Examples of large cost growth for tunnel projects include the Great Belt Link Tunnel (54% over budget), London's Jubilee Line Metro Project (67% over budget), Boston's Central Artery Tunnel (approximately 100% over budget) and the Channel Tunnel (80% over budget). Furthermore, worldwide experience in tunnel construction shows that major cost and time overruns occur due to factors not considered in the planning stage. These factors do occur with a higher than negligible probability and often have great consequences for the success of the project. In addition, engineering judgment has played an important role in treatment of unavoidable uncertainties that characterize the tunnel lining design. To assure safety in an uncertainty environment, engineers often choose conservative values of rock mass properties. In most cases, they adopt a safety factor in the design based on their unexpected deviation in the predicted performance. Finally, different decisions about the tunnel lining which are made in the different phases including planning, designing, constructing and operating have not been regarded as a coherent optimizing problem, rather many individual tasks which are solved one by one. And more emphasis has been put on construction cost without considering operation cost, which leads to the high operation cost and results in great loss. American society of civil engineers news stated in its April 1998 issue that: ASCE has given the nation's infrastructure an average grade of D and it estimates that it will take $1.3 trillion and a new public-private partnership to fix the longneglected problem. The tunnel committee of Japan road association has made a questionnaire survey about the deterioration of road tunnels throughout the country. The result showed that about 24% of the tunnels suffer from deterioration, whereas water leaks in more than half the tunnels, and deterioration occurred within 30 years of use in 90%, which may lead to high cost.

All the above discussion leads to the conclusion that the risks inherent in the lifetime of tunnel lining should be considered in the design stage to improve the design level. And not only the construction cost but also the operation and maintenance cost, especially the potential loss caused by risk should be considered in the tunnel lining design decision. Furthermore, the long-term performance will have to be taken into account to balance with respect to cost, safety and durability. The purpose of this paper is to develop a framework transforming the traditional tunnel linings design approach into a risk-based design approach integrating life cycle evaluation.

2 RISK ASSESMENT IN TUNNELLING

2.1 Definition of risk

The very nature of tunnel project implies considerable risks, which might be significant cost overrun and delay risks as well as environmental risks. There is also a potential for large-scale accidents during tunnelling work. Considering these risks, the path to follow is efficient management of them. Risk management and related approaches provide such procedures. Risk management was first attempted in civil engineering in the 1960's. Up to now, there have been many attempts to apply it to the tunnel projects. It has been demonstrated that the management of risk is notably improved by systematic use of risk management approach.

Risk has been defined in a variety of ways. The definition of risk given by ITA is a combination of the frequency of occurrence of a defined hazard and the consequences of the occurrence. It can be expressed as performance uncertainty combined with potential worth of loss, where loss involves life loss, capital loss or non-monetary environment effects. The simplest way to calculate risk can be expressed as follows:

$$\text{Risk} = \text{Probability[Failure]} \times \text{Cost of Consequences} \quad (1)$$

Risk assessment is defined in this study as a technique that aims to identify and estimate risks in the lifetime of tunnel lining. Generally, risk assessment process includes the following phases:

① Identification of risk.

The aim of risk identification is to identify all conceivable hazardous events threatening the project including those risks of low frequency but of great consequence. Normally we use our imagination, experience and engineering skill to identify potential risks. The types of risks that may encounter in the lifetime of tunnel lining can be divided three categories: natural risks due to natural variability which include the spatial variation and behaviour of rock mass, climatic change and so on, artificial risks due to human shortcomings and incomplete knowledge which include scientific ignorance, measurement uncertainty, management uncertainty and so on, material risk due to the uncertainty of material properties.

② Quantification of the risk.

Quantification of the risk through evaluation of probability of its occurrence and its impact (in terms of security, time and costs). Probabilities for different hazards or events may be assessed based on testing, statistical data from previous projects and expert judgment.

③ Risk classification

According to the quantification result and the corresponding risk ranking methods, assignment of an order of priority to the identified risks.

2.2 Risk Assessment Considering Life Cycle of Tunnel Linings

For effective risk management in the design stage of tunnel lining, risk assessment should be carried out at each stage in the lifetime of it. The flowchart of life cycle risk assessment for tunnel lining is illustrated in Figure 1.

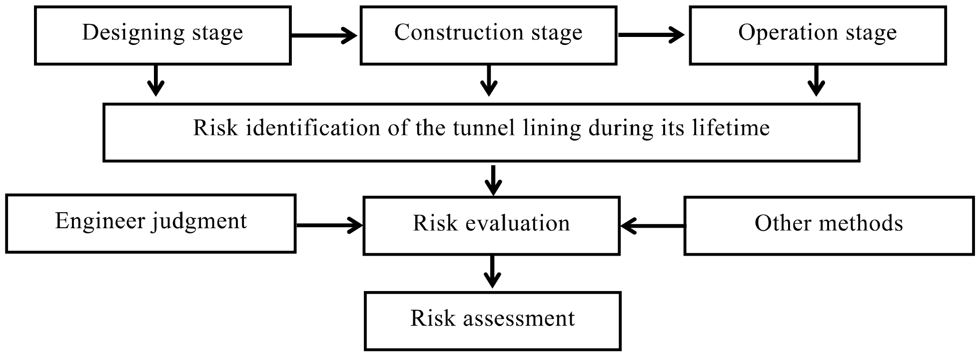

Fig 1. The flowchart of life cycle risk assessment for tunnel lining

At the same time, for the dynamics of tunnel lining design and tunnelling operation, the risk assessment should be a dynamics process to assure the timely identification of the potential problems.

3 LIFE CYCLE COST ANALYSIS

Life cycle cost analysis is an economic evaluation technique that determines the total cost of owing and operating a facility over its lifetime. It serves as a tool to improve decision-making. The United States national institute of standards and technology handbook 135, 1995 edition, defines life cycle cost as the total discounted cost of owing operating maintaining and disposing of a building or a building system over a period of time. When evaluating the tunnel lining alternatives, it is imperative that life cycle costs should be considered.

According to the definition of life cycle cost and the cost components of tunnel lining, the general expression of tunnel life cycle cost can be given as follows:

$$LCC(T) = C_C + pwf\left(C_{Mo}(T) + C_{Ma}(T) + C_{\mathrm{Re}}(T) + C_D(T) + C_U(T)\right) \qquad (2)$$

where C_C represents the initial cost of tunnel lining (including planning cost, designing cost and construction cost). $C_{Mo}(T)$, $C_{Ma}(T)$, $C_{\mathrm{Re}}(T)$ and $C_D(T)$ are the cost of monitoring, maintenance, repairing and disposing during the life cycle of tunnel lining, respectively. $C_U(T)$ is the cost of users and pwf is the discount rate.

It should be noted that the evaluation of life cycle costs should be related to the process of failures of tunnel lining and account for the uncertainty involved. But, obviously, the opponent of risk loss is not included in the traditional expression see Equation (2). Considering the loss of potential risk, it is necessary to add it to the expression. Then the life cycle cost can be rewritten as:

$$LCC(T) = C_C + pwf\left(C_{Mo}(T) + C_{Ma}(T) + C_{RE}(T) + C_D(T) + C_U(T) + C_R(T)\right) \qquad (3)$$

The procedure for evaluating life cycle costs can be simply summarized as follows:

① Identifying all the costs, including initial costs, maintenance and operational costs, rehabilitation costs, and potential risk loss for each alternative.

② Determining total cost per year of the analysis period.

③ Discounting all costs to a common timeline according to the discount rate pwf .

④ Alternatives assessment.

4 DESCISION PROCESS

Designing of tunnel lining preferably should result in an optimal solution, which means that the design of tunnel lining is basically a decision problem. However, choice of the optimal design solution is not straightforward due to the high degree of complexity and uncertainty in establishing such a solution. In other words, people will have to make decisions under risks. Thus it is important to balance the risk-taking. In addition to risks, another significant factor in the decision process is the decision makers' risk attitude. Considering the factors mentioned above, an efficient decision system should provide the decision makers with an informed way to evaluate various alternatives with the available information. Borrowing ideas from Sturk et al. (1998), a possible decision-making process used in this paper is shown in Figure 2.

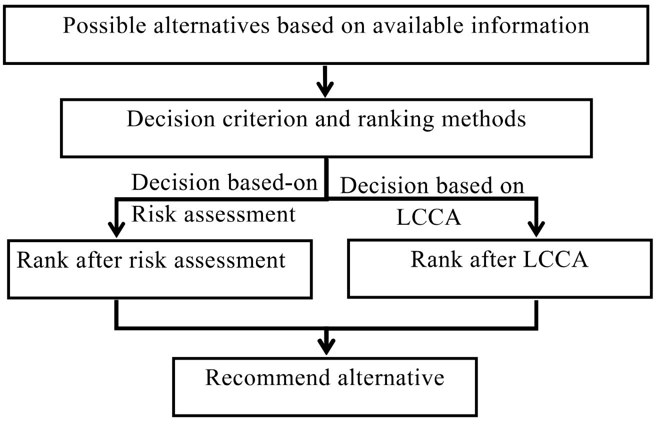

Fig 2. Decision process for tunnel lining

This process includes: establishing the possible alternatives based on available information, selecting decision criterions and ranking methods for evaluating the alternatives, assessing the alternatives using risk assessment and LCCA, and choosing the optimum alternative. By using LCCA, we can make an evaluation of the design solutions through economic evaluation considering the influence of risks to some extent. On the other hand, since it is very difficult to assess every effect in terms of monetary value, risk assessment may be a favourable complement. Based on an overall consideration of the analysis of risk and LCCA, decision makers can make their own choice, certainly which is the optimum alternative depend on the decision maker. Decision maker’s risk attitude can be integrated into the decision-making by using such a decision process. In addition, it should be noted that the decision process shown in Figure 2 is a dynamic process that involves updating the parameters and collecting more information.

5 RISK-BASED TUNNEL LINING LIFE CYCLE DESIGN PROCESS

On the basis of the above discussion, a general tunnel lining design approach is proposed, see Figure3. It mainly includes four parts: establishing design alternatives, risk assessment, life cycle cost analysis and decision process.

① Firstly, the initial design alternatives are established according to the geological investigation and the design requirements. It should be noted that stochastic methods would be employed in this stage to allow uncertainty related to parameters to be integrated in the analysis as early as possible.

② Then risk assessment will be carried out to evaluate different alternatives. During the procedure of risk assessment, potential hazards should be identified through brainstorming sessions or other methods, and their magnitude should be assessed using qualitative assessment or quantitative assessment. The quantification of risk should make full use of existing mechanical methods, mathematical methods and engineering experience. According to the results of risk assessment and the corresponding ranking methods, risk classification can be given.

③ On the other hand, life cycle cost analysis is implemented. The objective of this process is to provide predictions of life cycle costs for tunnel lining alternatives, taking into consideration the risks involved in the lifetime of tunnel lining. To some extent, it allows decision makers to select an alternative with knowledge of the inherent risks.

④ Through evaluating the various alternatives with respect to different costs and risk classification, the decision makers would make their choices based on their own risk attitudes.

And it is necessary to update the whole approach while construction is in progress with more information from the actual project available.

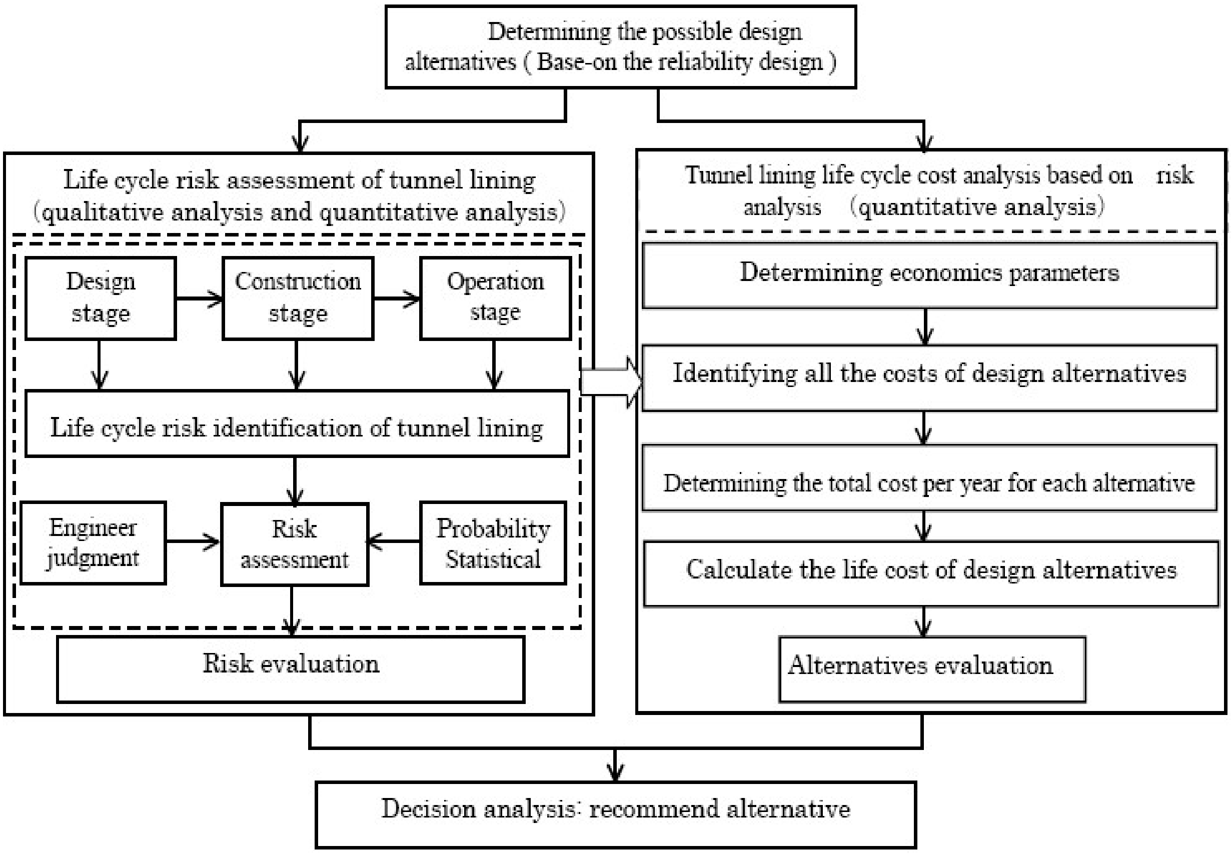

Fig3. The flowchart of risk-based life cycle design for tunnel lining

6 DISCUSSIONS

Based on discussions about the shortages existing in the traditional tunnel lining design method, it has been concluded that there is a need for treating problems connected with uncertainty in the tunnel lining design. In this paper, we mainly focus on developing a risk-based life cycle tunnel lining design approach. Theories of risk analysis and life cycle cost analysis are introduced into tunnel lining design approach to deal with the inherent uncertainty in the lifetime of tunnel lining and the difficult decision problems in designing. Risk-based design means that risks arising from all life phases can be taken into account in the design stage. Life cycle cost analysis implies that costs arising from all life phases including the potential loss of risk can be taken into account based on risk evaluation. Design solutions can be easily and effectively compared based on the above analysis. And decision makers can make informed decisions based on their preference. It should be noted that the whole approach is a dynamics process for the dynamics of tunnel lining design and tunnelling operations. A consequence use of this method will result in tunnel lining, which is balanced with respect to costs, safety, durability and other specified aims.

Since this approach is very complex, which involves many problems to be solved including statistical analysis of material properties, prediction of variability of geology and deterioration of concrete, stability analysis of tunnel, selection of proper evaluation criterions and so on. Just a general framework for tunnel lining design is given in this paper and further analysis need continued study.

❑ REFERENCES

Luo Y.J. (1997) *Numerical simulation and analogy method for tunnel structural design*. J. Underground Space. Vol. 5, p8-12 (in Chinese).

Isaksson T. and Stille H. （2005） *Model for estimation of time and cost for tunnel projects*. J. Rock mechanics and rock engineering. Vol. 38, p373-398.

Gransberg D.D. (2004) *Life cycle evaluation criteria for design-build highway pavement projects*. Colorado: Colorado University.

Inokuma A and Inano S. (1996) *Road tunnels in Japan - deterioration and counter-measures*. Tunneling and underground space technology. Vol. 11, p305 -309.

Huang H.W. (2006) *State of the art of the research on risk management in construction of tunnel and underground works*. Chinese Journal of Underground Space and Engineering. Vol. 2, p13-20.

Einstein H.H. (1996) *Risk and risk analysis in rock engineering*. Tunneling and underground space technology. Vol. 11, p141-155.

You K., Park Y.J. and Lee J.S. (2005) *Risk analysis for determination of a tunnel support pattern*. Tunneling and underground space technology. Vol. 20, p479-486.

Eskesen S.D., Tengborg P., Kampmann J. and Veicherts T.H. (2004) *Guidelines for tunnelling risk management*. Tunneling and underground space technology. Vol. 19, p217 -237.

Kerzner H. (1997) *Project management : a system approach to planning ,scheduling and controlling*. John Wiley & Sons, Inc.

Shao X.D., Peng J.X. and Yan B.F. (2006) *Framework research on design method for bridge life cycle*. Highway. Vol. 1, p44-49.