

THE OVERVIEW AND STUDY ON THE MODELING OF RISK ACCEPTANCE CRITERIA FOR TUNNEL AND UNDERGROUND ENGINEERING

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Abstract: The importance of risk acceptance criteria research and the calculation principle for determining them are analyzed in accordance with the present state of art. And some fundamental risk acceptance criteria, such as the individual risk (IR), societal risk (SR), economical risk and environmental risk, are comprehensively introduced. The paper furthermore addresses and discusses some key points, future application and development of these criteria for tunnel and underground engineering. Finally a number of problems are highlighted and the needs for further research are stressed.

Keywords: risk acceptance criteria; individual risk; societal risk; environmental risk; economic risk; tunnel and underground engineering.

1. INTRODUCTION

The 21st is the big century of the utility and development for tunnelling and underground works [1]. Due to the inherent uncertainties, including ground and groundwater conditions and their variability, it might be significant cost overrun, fatalities and time delays as well as environmental risks during the tunnelling construction. Also, for the complexity and immaturity of tunnelling technique in urban areas there is a risk of damage to a range of third party about property and persons, which will be of particular concern by public where heritage designated buildings are involved. Furthermore, there is a risk to public protests affecting the course of the projects. Finally, there has been an increasing societal concern on sustainable developments focusing on the conservation of the environment, the welfare and safety of the individual during the last decade. As demonstrated by spectacular tunnel collapse and other fatal disasters in the recent past like Shanghai [2] (2003), there is a potential for large scale accidents during tunnelling. In order to reduce and mitigate the risk, the research and application of some methods of risk management and risk control for tunnelling and underground works are paid attention in recent years.

As a consequence the methods of risk analysis in civil engineering, mainly developed during the

last decades, are increasing gaining importance as a useful tool in tunnelling engineering applications [3]. It is important to realize that risk analysis is very complex theory which is often entwined with not only many technical aspects but also some political, psychological and social processes. A number of issues that risk analysis attempt to resolve include [4]: What information is required for 'scientific and rational' risk management and how to make a decision? Where is the line to be drawn between that are to be managed by individuals, group or corporations? Who is to bear what level of risk? What actions make what difference to risk outcomes? These matters or problems are not easily resolved, are not for risk analysis to solve alone and are all related to risk acceptance criteria; namely, what risks are acceptable? And some risk acceptance criteria for decision-making should be established qualitatively or quantitatively in advance [5]. The paper attempts to summarize broadly an overview of some risk acceptance criteria irrespective of the type of applicable risk (individual, social, environment and other risk). It ends with some discussion and conclusion of the need to establishing some risk acceptance criteria for tunnelling and underground engineering.

2. THE MODEL OF THE RISK ACCEPTANCE CRITERION

In the study of risk analysis and assessment, the risk control and reduction measures are taken involving some money, techniques and labours. And these risk measures are determined based on the balance of loss (damage) or benefit. It is obvious that risk is in interrelation with investment and benefit. How to draw a line or play game between the risk and investment or benefit for decision-making is complied with a risk acceptance criterion. The development and implementation of risk acceptance criteria involves [3]: (1) Perception of risk, ensure that levels of system risk, such as safety, economy and environment, is acceptance (or tolerable); (2) Formal decision analysis: analytical techniques to balance or compare risks against benefit (e.g. risk cost-benefit analysis, life-cycle cost analysis); (3) Regulatory safety goals: legislative and statutory framework for the development and enforcement of risk acceptance criteria.

As is known to us, the risk acceptance criteria are the foundation of risk analysis for decision-making. They generally are adopted by the U.S Nuclear Regulatory Commission (NRC), U.K Health and Safety Executive (HSE), Dutch Technical Advisory Committee on Water Defenses (TWA) and other regulatory authorities. Mainly, there are two basic principles for defining the risk level used for a qualitative or quantitative risk analysis [6], [7]: 'As Low As Reasonably Possible (ALARP)' and 'As Low As Reasonably Achievable (ALARA)'. The definition for such terms as 'Low', 'Reasonably', 'Possible' and 'Attainable' are highly subjective and prone to being interpreted in a conservative manner. Some expressions and models have been made to define these criteria in more tangible limit in terms of quantitative risks.

3. THE CLASSIFICATION OF RISK ACCEPTANCE CRITERIA

The risk acceptance criteria are a complex attribute that results from three influenced factors, safety (personal risk and social risk), economy (potential economical loss, construction schedule) and environment, from a technical perspective of the basic classification of engineering risk [8]. And they are established based on not only some quantitative indexes like economical loss or time delays, but also many unquantized indexes such as potential environment damage, the monetary

valuation of human life and the public influence, etc. Therefore, the establishment of risk acceptance criteria is a complicated, difficult and controversial task [9]. The risk acceptance criteria can be classified into four elementary categories from the recent overview of recent research around the world [8], [10]: (1) Individual Risk (section 3.1); (2) Social Risk (section 3.2); (3) Economical Risk (section 3.3); and (4) Environmental Risk (section 3.4). Every section starts with an overview of the risk mathematical definition, and then the risk acceptance criteria and their application are described as follows.

3.1 Individual Risk

The individual risk (IR), as used by the Dutch Ministry of Housing, Spatial Planning and Environment (VROM), is defined as the probability that an average unprotected person, permanently present at a certain location, is killed due to an accident resulting from a hazardous activity [11].

$$IR = P_f \cdot P_{d|f} \quad (1)$$

Where P_f is the probability of failure and $P_{d|f}$ probability of dying of an individual in the case of failure, assuming the permanent unprotected presence of the individual.

The risk individual is highly subjective, which is determined by the individual predilection whether or not the individual is actually voluntary or involuntary. Besides the individual risk as mentioned above, four other expressions are described [12]. (1) The Loss of Life Expectancy shows the decrease of life expectancy due to various causes; (2) The Delta Yearly Probability of Death computes the intensity at which a given activity is to be performed (in suitable units) to increase the yearly probability of death by 10⁻⁶; (3) The Activity Specific Hourly Mortality Rate reflects the probability per time unit while engaged in a specified activity. (4) A variant is the Death per Unit Activity, which replaces the time unit by a unit measuring the amount of activity. A different definition is used by the UK's health and safety executive (HSE) [13] that is the risk which a typical user of a development is exposed to a dangerous dose or worse of toxic substance, heat or blast overpressure. To limit the risks, there are many criteria such as ALARA, Risk Matrix, AFR (Annual Fatality Risk), AIR (Average Individual Risk) and AI (Aggregated Indicator) etc.

(1) The Dutch Ministry of Housing, Spatial planning and Environment (VROM) has set the following standard for populated areas [11].

$$IR < 10^{-6} \text{ (Per Year)} \quad (2)$$

Risks lower than 10^{-6} per year may be equal to a level which is As Low as Reasonably Achievable (ALARA). The criterion is set for more or less involuntary imposed risks related to the locating of hazardous activities.

(2) The standard is proposed by the Dutch Technical Advisory Committee on Water Defenses (TWA), which gives the opportunity to limit a broader set of risks ranging from voluntary, such as mountaineering, to more involuntary risks, such as those of hazardous installations [14], [15].

$$IR < \beta \cdot 10^{-4} \text{ (/Per Year)} \quad (3)$$

In the above expression the value of the policy factor β varies according to the degree to which participation in the activity is voluntary and with the perceived benefit (See Figure 1).

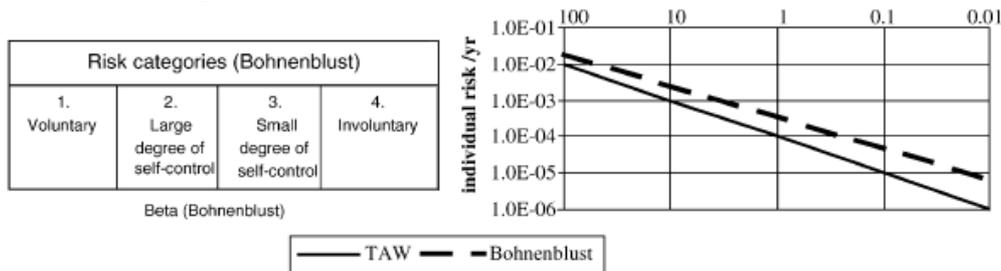


Figure 2 Individual risk standard according to Bohnenblust and TAW

(4) The UK'S Health and Safety Executive [17] also uses a framework for judging the tolerability of risks, considering an unacceptable, a tolerable and a broadly acceptable region by defining the individual risk as IR_{HSE} .

$$IR_{HSE} \leq 10^{-6} \quad (4)$$

The boundary between the tolerable and the unacceptable regions no widely applicable criterion is given for both workers and the public. An HSE document [18] on the tolerability of risks in nuclear stations suggests IR_{HSE} values of 10^{-3} for workers and 10^{-5} for the members of the public, as a boundary between the tolerable and the acceptable regions.

3.2 Social Risk

The societal risk is defined as “the relationship between frequency and the number of people suffering from a specified level of harm in a given population from the realization of specified hazards” [19]. Where individual risk gives the

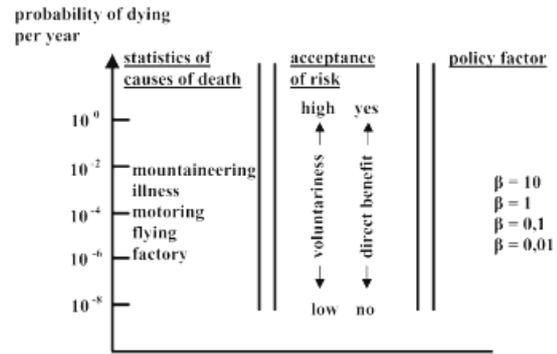


Figure 1 Policy factor for different activities and various degrees of voluntary participation and benefit

(3) Bohnenblust [16] studies the safety of the railway system in Germany and proposes a standard which is comparable with the TWA standard (See Figure 1). He limits the acceptable IR, taking into account of which participation in an activity is voluntary and the degree of self-control.

probability of dying on a certain location, the societal risk gives a number for a whole area, no matter precisely where the harm occurs within that area. To limit the social risks, there are many criteria such as ALARP, Risk Matrix, F-N curve, PLL (Potential Loss of Life), FAR (Fatal Accident Rate), VIIH (Value of Injuries and Ill Health), ICAF (Implied Cost of Averting a Facility) and LQI (Life Quality Index) etc.

The societal risk is often represented graphically in an F-N curve which is first used by Farmer F.R. (1967) [20] and originally introduced for the assessment of the risks in the nuclear industry [21]. This famous curve displays the probability of exceedance as a function of the number of fatalities on a double logarithmic scale.

$$1 - F_N(x) = P(N > x) = \int_x^{\infty} f_N(x) dx \quad (5)$$

Where $f_N(x)$ is the probability density function (PDF) of the number of fatalities per year; $F_N(x)$ is the cumulative probability distribution function (CPDF) of the number of fatalities per year,

signifying the probability of less than fatalities per year.

A simple measure for societal risk is the expected value of the number of fatalities per year, $E(N)$ which is often referred to as the potential of life (PLL) in some literature.

$$E(N) = \int_0^{\infty} x \cdot f_N(x) dx \quad (6)$$

From the formula (5) and (6), the relation between $F_N(x)$ and $E(N)$ can be got.

$$\begin{aligned} \int_0^{\infty} 1 - F_N(x) dx &= \int_0^{\infty} \int_x^{\infty} f_N(y) dy dx \\ &= \int_0^{\infty} \int_0^y f_N(y) dx dy = \int_0^{\infty} y f_N(y) dy = E(N) \end{aligned} \quad (7)$$

In several countries, the F-N curve criteria lines limit the risks of various hazardous activities. These standards can be described with the following general formula.

$$1 - F_N(x) < \frac{C}{x^n} \quad (8)$$

Table 1 some international standards limiting the FN-curve

Country	n	C	Risk Property
U.K (HSE)	1	0.01	Risk Neutral
Hong Kong of China	1	0.001	Risk Neutral
Netherlands (VROM)	2	0.001	Risk Averse
Demark	2	0.01	Risk Averse

3.3 Economic Risk

Besides the loss of life due to certain activities, the economic risks play an important role in risk analysis. A FD-curve displays the probability of exceedance as a function of the economic damage [10]. The FD-curve and the expected value of the economic damage can be derived from the PDF of the economic damage ($f_D(x)$).

$$1 - F_D(x) = P(D > x) = \int_x^{\infty} f_D(x) dx \quad (9)$$

$$E(D) = \int_0^{\infty} x \cdot f_D(x) dx \quad (10)$$

Where $F_D(x)$ is the cumulative probability distribution function of the economic damage and $E(D)$ is the expected value of the economic damage.

Novgorodsky's study on the economic risks in the Russian region [25] is an example of the use of a FD-curve. Jansen [26] has tried to obtain a financial economic risk limit in the form of a FD-curve. The expected value of the economic damage is used as part of cost benefit analyses of flood

Where n is the steepness of the limit line and C the constant that determines the position of the limit line. A standard with $n=1$ is called risk neutral. If $n=2$ the standard is named risk averse [22]. Commonly, as a part of the standard, an ALARA (or ALARP) region has been determined below the limit line, in which the risk should be reduced to a level that is as low as reasonably achievable (or possible). Table 1 gives the values of the coefficients for some international Criteria.

The expected number of fatalities $E(N)$ is used in the regulation of the risks of dams or offshore platforms. Criteria proposed respectively by British Columbia Hydro [23] and the United States Bureau of Reclamation [24] are $E(N) < 10^{-3}$ and $E(N) < 10^{-2}$ (fatalities/year).

prevention measures in the UK [27] and in The Netherlands [28]. A limit for the expected economic damage per year for dams has been proposed by BC Hydro [29], in which the financial risks for one dam should not exceed: $E(D) < 10000$ (U.S \$/per year).

3.4 Environmental Risk

The Environmental Risk (ER) is different with the individual risk and social risk for engineering construction activities in a certain circumstance. There is a risk of damage to a range of third property and persons and of pollution to environment. The competitive standing of the Norwegian offshore sector (NORSOK) has proposed the probability of exceedance of the time needed by the ecosystem to recover from the damage as a measure for environmental risk [30].

$$1 - F_T(x) = P(T > x) = \int_x^{\infty} f_T(x) dx \quad (11)$$

$$E(T) = \int_0^{\infty} x \cdot f_T(x) dx \quad (12)$$

Where $F_T(x)$ is the cumulative probability distribution function of the recovery time; $f_T(x)$ is the probability density function of the recovery time of the ecosystem.

A Limit for the environmental risks of offshore activities are set by NOR-SOK. The following limit to determine the acceptable risk for oil platforms is derived from the quoted criterion [30].

$$1 - F_T(x) < \frac{0.05}{x} \quad (13)$$

The Institute of Canada Standard [31] has set a criterion for assessment the ER of oil in sea: highly potential ER is $E(T) < 10^{-5}$ /per year, and lowly $E(T) < 10^{-3}$ /per year. The criteria set by the Norwegian Technology Standards Institution are showed in Table 2.

4. DISCUSSIONS AND CONCLUSIONS

It is worthwhile to recognize that the criteria and calculations of risk acceptance has a

Table 2 Acceptance risk criteria for ER based on the insignificant interpreted as 5%

Environmental Risk (ER)	All equipments in a year	A suit of equipment in a year	One operation
Insignificant	<0.02	<0.01	<0.001
Considerable	<0.005	<0.0025	<0.00025
Serious	<0.002	<0.001	<0.0001
Disastrous	<0.0005	<0.00025	<0.000025

(1) The loss consequences of risk in tunnel and underground engineering may be mainly categorized into four types: economic loss, personnel fatalities, work time delays and the damage to environment. The unitive model of risk occurrence mechanism in tunnel and underground

fundamental and special bearing to different industries and engineering. The determination of risk acceptance criteria is a complex task which is entwined with comprehensive several courses and much technique knowledge. And there are many problems on which need to spend more research. At the present time, the study of risk acceptance criteria of risk analysis is a hot research point to which a great number of researchers pay attention in the world [3], [8]. Furthermore, it is the beginning stage of the risk analysis that is applied currently in the tunnel and underground engineering. Although it is fortunate that we have started and made some progress of the application of risk management in tunnel and underground engineering, we still have a great deal of work problems to be resolved. As explained in the above of the paper, I have some own discussions and conclusions about the risk acceptance criteria in tunnel and underground engineering.

engineering is showed as follow (See Figure 3). Therefore, according to the above risk standards and the model, we can build up a calculation model of risk acceptance criterion for unifying the standard.

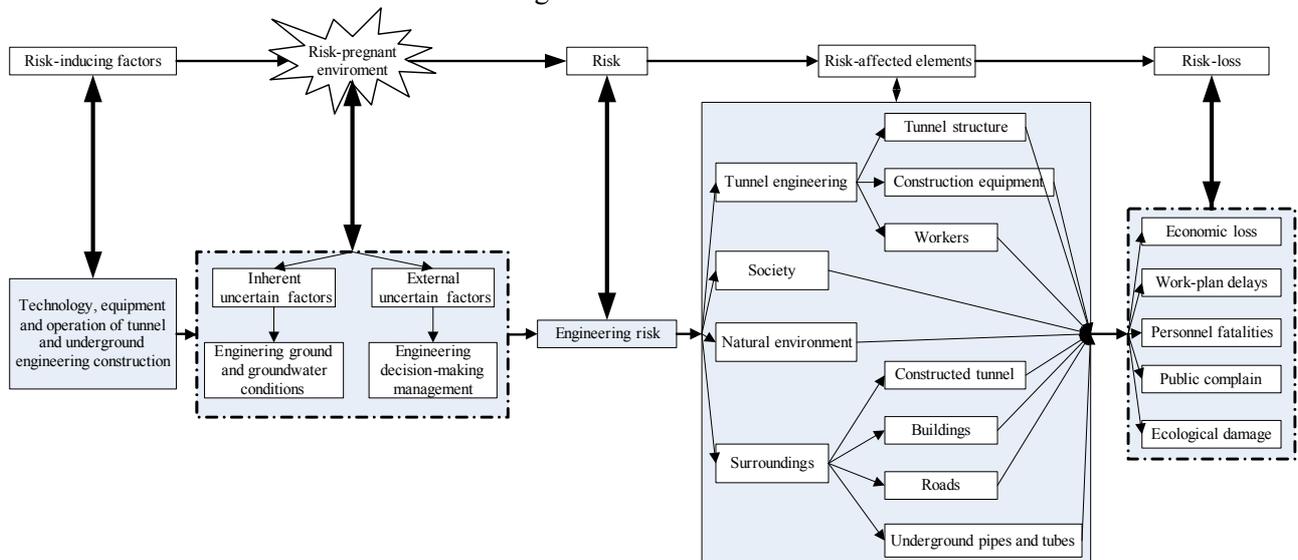


Figure 3 the model of risk occurrence mechanism in tunnel and underground engineering

$$1 - F_R(x) = P(R > x) = \int_x^{\infty} f_R(x) dx \quad (14)$$

$$E(R) = \int_0^{\infty} x f_R(x) dx \quad (15)$$

$$1 - F_R(x) < \frac{C}{x^n} \quad (16)$$

Where $f_R(x)$ is the probability density function (PDF) of the risk loss per unite engineering; $F_R(x)$ is the cumulative probability distribution function (CPDF) of t the risk loss per unite engineering, is the expected value of the risk loss, is the steepness of the limit line and the constant that determines the position of the limit line.

(2) In order to establish the unitive model of risk acceptance criteria in detail, we should design a database, which is use for storing some risk events investigation and record data, and do some research work based on the existing risk acceptance criteria all over the world. At the present time, we all lack the foundation data and need to do much work of investigation and collection. If we have accumulated enough useful engineering risk data and much experience, the parameter value of formula (14), (15) and (16) can be got from doing statistical study. Moreover, the relation of risk acceptance criteria and the development of national economy will be analyzed and established.

(3) At present time, there is not a technical risk acceptance criterion for the risk analysis in tunnel and underground engineering in China. Furthermore, it is difficult to establish a new one without some basic research in the area. Therefore, in order to carry out the risk management and control and promote the future risk research in tunnel and underground engineering, it is an imperative task for all engineering risk researchers nowadays. And we can get some reference from the reliability-based design theory. The failure rate of tunnel structures can be calculated by the reliability methods considering the variability of design parameters.

(4) According to the domestic and international risk acceptance standards and their research experience [3], [8], [33], the vexing question is how the risk events investigation information be used to establish allowable risks for some special projects? There is no general answer to this question. I think, a unitive risk acceptance criterion should be established based on some fundamental principle: ①Independence, that is to say that the risk acceptance criteria have an independent and explicit the definition of risk; ② Adaptability,

namely it is easily suitable for the requirement of risk analysis engineers with good understanding of its theory and meaning; ③ characteristicness, namely the risk acceptance standards should be established to match the concrete state of our country, and have clearly special features considering the difference between all countries engineering construction realm at the same time; ④Comparability, namely there are some formulas which can be used for calculating and comparing the risk assessment conclusions of some different tunnel projects; ⑤ Operability, namely there are many uncertain factors which may affect the quantitative risk analysis, so the risk acceptance criteria is implemented to help to reduce and ameliorate those uncertainties as far as possible

(5) Human error is an important source of risk. It is typically found that actual failure rates of engineering construction exceed predicted failure rates through the reliability methods, perhaps as much ad three orders of magnitude. Further research reveals that most of the risk events are the result if human error, for example, some structures not built according to the work plans, materials not meeting the design specification, etc. It is inherently difficult to include human errors involving design, construction, organization and management. Therefore, how to assess the human errors and whether it can be accepted that depend on the context of risk acceptance. But it is a blank research area that needs us to pay attention

5. FINAL REMARKS

The application of risk analysis into tunnel and underground engineering in China is a little later than other developed countries. The risk analysis and assessment of Changjiang Channel Tunnel in Shanghai is the first example which is began in 2002 and finished in 2003 [34]. Risk analysis is a systematical science which is composed of three main subjects: risk identification and measure, risk assessment and decision-making, and risk management and control. The core of risk in the three subjects is the risk acceptance. Risk analysis involving workers or public or nature resources or economy should be analyzed and assessed based on some risk acceptance criteria, especially when the balance of cost, benefit, risk loss and the public's concerns are to be considered. The application of risk management and control in tunnel and underground engineering is the beginning. And I wish the paper can push and promote the further

research of the risk acceptance criteria in tunnel and underground engineering.

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