ISGSR2007 First International Symposium on Geotechnical Safety & Risk
Oct. 18~19, 2007 Shanghai
Tongji University, China

The Application of Quantitative Risk Assessment in Talus Slope Risk Analysis

Z. Q. Liu, H. W. Huang, Q. F. Hu
Department of Geotechnical Engineering, Tongji University, Shanghai, China

ABSTRACT: Quantitative Risk Assessment (QRA) is a method of quantifying the degree of risk through a systematic examination of the factors contributing to slope stability and affecting the severity of the consequences , as well as the definition of probabilities for the individual factors. It has become an important tool for the management of landslide risk analysis and for planning risk mitigation measures. In this paper, QRA method is described in detail. There are multidisciplinary procedures for the quantitative risk analysis of talus slopes: hazard analysis, identification of the elements at risk, analysis of the vulnerability of the elements at risk and calculation of the risk. Basing on the method of QRA, the risk of talus landslides of Shuima freeway is analyzed in Yunnan province. Some risk mitigation measures are also suggested. Through the application, the merits and limitations of the QRA method are discussed.

1 INTRODUCTION

Traditionally, geotechnical engineers evaluate the stability of slopes using a deterministic approach in which the slope reliability is estimated by calculating a factor of safety using limit equilibrium techniques. In recent years, qualitative landslide risk analysis is commonly carried out by devising a rating scheme to evaluate the relative likelihood of landslide and the relative severity of the consequence of failure. Many different qualitative methods are performed by engineers, such as the use of a scoring system, flow charts, and qualitative descriptors, a risk matrix, or a combination of these methods. But both of the deterministic and qualitative methods may not adequately optimize the allocation of available resources. In order to supply quantitative data related to landslide risk and obtain the explicit assessment of the risk, it is necessary to use quantitative risk assessment (QRA) for landslide problems.

It has been about 30 years since QRA was firstly applied to large technological systems. QRA is a method of quantifying the order of risk through a systematic examination of the factors contributing to the landslide hazard and affecting the severity of consequence, and establishing probabilities for the individual factors. For civil engineering, geotechnical application of QRA emerged in the 1990s, particularly in relation to the mining industry, dam management and slope safety. At present, QRA is very popular in the landslide risk management in HongKong. Some notable application cases have been performed, such as the 1995 Fei Tsui Road Landslide, the 1997 Thredbo Landslide, the 1999 Shek Kip Mei Landslide, etc. Besides, the European Commission Fifth Framework Programme has also presented the results obtained by the IMIRILAND project using QRA method, in which eight landslide site were selected in the countries involving Italy, France, Spain, Austria and Switzerland.

This paper discusses hazard analysis and risk studies of talus landslide within the QRA method and suggests some mitigation measures. The approach is applied to a talus slope failure that occurred in the construction of Shuima freeway in Yunnan province. Some useful results are gained.

2 QUANTITATIVE RISK ASSESSMENT METHODOLOGIES

Geotechnical application of QRA emerged in the 1990s, when some experts discussed it. The result of QRA which we can obtain is an estimate of the probability of occurrence of different types of adverse consequences, such as the death of individuals (i.e. individual risk), multiple deaths (i.e. societal risk), and damage to property or closure of a major road for a certain period of time (i.e. economic risk).

There are usually two types of QRA, Global QRA and Site-specific QRA. Global QRA is aimed at assessing the overall risk of the hazards posed to the community. It also serves to provide the total risk of various hazards, which can provide a reference for landslide risk management and consideration of resources allocation and policy making. Detailed site-specific data are not normally required for a Global QRA (Wong & Ho, 1998; Ho et al, 2000). Site-specific QRA method is useful for the determination of the ranking of sites in terms of geotechnical risk. The consideration of whether the risk levels are acceptable and the evaluation of different risk mitigation measures are facilitated.

In simple terms, the following processes are addressed in order in a QRA performance for landslides or slope failures, with the view of risk quantifying:

(1) Data collection

This consists of collection of relevant data and knowledge of the landslide processes to facilitate the formulation of various models for conducting frequency and consequence analysis. These data can serve to hazard analysis, frequency analysis and occurrence assessment. The information of data usually includes historical documents, aerial photographs, monitoring investigations, etc. Generally, these data should be identified by experienced engineers to check the reliability and usefulness of available. Certainly, it is very useful to set up a database to manage these data. Data collection is the basis of QRA.

(2) Hazard analysis

In order to assume some useful risk analysis for the constructers and decision-makers, a total hazard analysis of landslides should be carried out. In the process of hazard analysis, geometry conditions, historical information and these monitoring investigations should be obtained. For the geological analysis, on-site and around-site analysis can serve to realize the complete hazard. Basing on the hazard analysis, some specific hazard scenarios can be distinguished and chosen. After that, occurrence probability of these scenarios can be assessed. Usually landslides are sprung by many preparatory and triggering causes and their mechanisms are very complex, so we should select different danger and different scenarios.

(3) Consequence assessment

In the following of hazard analysis, consequence analysis of the selected scenarios should be performed. Consequence analysis is to estimate the consequence, both immediate consequence and know-on effects that could result from the hazards, taking due account of any existing mitigation measures and conditions that will have an effect on the consequence. In this analysis, four steps should be involved, identification of elements at risk, estimation of the value of elements at risk, evaluation of the vulnerability and consequence computation. Elements at risk are usually classified in two different categories, material assets and persons. In this paper, the parametric value appraisal of the elements at risk, generally, is carried out according to material assets and persons. (Table 1, Table 2)

Table 1 Relative values for exposed objects in the talus landslide analysis (modified from Amatruda, etc)

Element at risk	Assets relative value	Relative value of interruption of economic activity	Environmental relative value
Residential areas	4	1	1
Productive or industrial areas	4	4	1
Strategic lifelines	3	4	1
Heavy traffic or strategic roads	3	4	1
treasured forests	4	3	4
Rural areas-farming and domestic animals	1	2	2
Secondary roads	1	2	1
Secondary lifelines	1	2	1
Ordinary forests	1	1	3
Special risk objects			
bridges	3	2	2
tunnel	3	3	2

Table 2 Assessment of values for exposed person (modified from Amatruda, etc)

Human lives affected	number of persons involved	Relative value of human lives
Homeless persons	0~9	1
	10~49	2
	50~199	3
	>200	4
Wounded persons	0~4	1
	5~14	2
	15~49	3
	>50	4
Dead persons	0~1	1
	2~9	2
	10~19	3
	>20	4

Vulnerability is defined as the "manifestation of the inherent states of the system that can be exploited by an adversary to harm or damage the system" (Haimes & Horowitz, 2004). As for landslides, vulnerability represents the degree of loss to a given element at risk, resulting from the occurrence of a given magnitude. Usually it is expressed by relative terms, using the numbers between 0(no damage) and 1(completely damage), or the words such as "no damage", "some damage", "serious damage", "completely damage". Traditionally, it can be divided into four partitions, physical, social, economic and environmental vulnerability. These four terms represent respectively structural and operational failure, exposed personnel danger (homeless, wounded, dead), direct and indirect economic loss, destroyed nature and endangered animals. (Table3)

Table 3 Vulnerability evaluation as a function of estimated effects on elements at risk for the talus slope (Quoted from Amatruda, etc)

Physical vulnerability		Social vulnerability	
Vulnerability description	Index	Vulnerability description	Index
Intact structure	0	Non affected persons	0
Local damages	0.25	Non physical damages; evacuated persons	0.25
Seriously damages(possible to repair)	0.5	Physical damages (person continue their activities)	0.5
Mostly destroyed(difficult to repair)	0.75	Seriously wounded persons(50% disability)	0.75
Total destruction	1	Died,51-100% disability	1
Economical vulnerability		**Environmental vulnerability**	
Non interruption	0	Intact element	0
Short temporary(hours to day)	0.25	Local loss	0.25
Average temporary interruption(days to week)	0.5	Seriously damages(possible to repair)	0.5
Long temporary interruption(weeks to months)	0.75	Mostly destroyed(difficult to repair)	0.75
Permanent interruption	1	Total destruction	1

After that, the assessment of consequence can be computation with the following formula

$$C = V_e \times V \tag{1}$$

Where, Ve represents the value of elements at risk, while V represents the vulnerability.

In this formula, each value of element at risk is multiplied by a relative vulnerability .

(4) Risk evaluation

From the analysis of the above, risk is the product of the occurrence probability of landslide hazard and its consequence. In order to grasp the total risk for the studied area, many separately risks (physical, social, economic, environmental risk) of the specific scenario should be considered and summed up.

$$R = P \times C \tag{2}$$

Where, P represents the probability of the landslide, while C represents the assessment of occurrence.

(5) Risk mitigation

For every quantitative risk analysis of landslide, the final objective is to mitigate its negative effect and make sure the safety of the slope. From the analysis above, the risk can be reduced by two aspects: the probability of failure and the consequence of the failure. As for the measures of the mitigation, there are four ways:

(i) mitigate its physical effects through building and land-use regulation
(ii) evacuate and/or intervene the landslide hazard
(iii) restore the essential community services
(iv) provide effective search and rescue assistance immediately after a landslide

3 REGIONAL FRAMEWORK OF TALUS SLOPE FAILURE

There are 75 sections of talus slope having been found along the line of Shuima freeway. The total length reaches nearly 3.4 km. Ancient landslide of K51+859 bridge locates in Contract 11 in Shuima freeway , which was constructed in August, 2004. When the slope had being active, the piers of bridge at the toe of the slope were constructed. On March 3, 2005, many cracks in the talus slope had been found in the toe. Partially, the wall of houses in the slope crazed and distorted due to the failure of the slope. As follow, it is the regional framework of talus slope.

3.1 Climatic and water condition

The climatic conditions are influenced by Torrid and Mid-Temperate Zone climate. The average annual temperature is 17℃, and the minimum occurs in January with a value of 7℃, while the maxima in August can reach +26℃. The average annual rainfall is about 1170mm, but mainly from May-October, which accounts for 82 percentages. The frost occurs in the year, less than 60 days.

3.2 Groundwater conditions

In the area, there is a major river named Guan river, with some embranchments, such as Miaokou river, Chuansi river, Shangqing river, etc. So the groundwater is very abundant, and surface water also develops. Observed by Dou shaguan hydrology station, from 1960 to 1976, the catchment area reaches 8931 sq.km, the average of flux is about 141.84 stere per second.

3.3 Regional morphology

The geotectonics belongs to Yangtse mesa area, located at the combination of Southeast Drape and Dianqian Drape. Due to strong rising-up of lithosphere, the area comes to be a V valley physiognomy.

4 QUALITATIVE RISK ASSESSMENT FOR TALUS LANDSLIDE

In order to identify the reasons of the failure of the landslide and provide some measures for decision-makers, qualitative risk assessment of the talus slope is performed.

4.1 Danger identification

Judging from the outline, the talus slope belongs to a big ancient landslide. Although suffering from the weathering erosion, water erosion and a multi-phase transformation of falling, they still keep a clear physical characteristic of ancient landslide.

Overall, the talus slope inclines NE, whose natural gradient increases from the base to crest. The terrain is very steep near the river, where the natural slope reaches 35°. In the middle, a central platform is developed, inhabited seven houses (37 persons involved). This section is gentle, and the gradient is between 5 ° and 10 °. In the top, the terrain is gradually steep, between 25° and 30°. (Fig.1)

Fig.1 The panorama of the ancient landslide

The lithology of the landslide area is composed of gravel soils, brown red and purple colour. (Fig.2) Deducing from the colour, the ancient landslide possibly results from J2 mudstone segments. The content of gravel is around 30%, mudstone, the size is 2~5cm generally, with a small sandstone almost 15~20%, with the element of rubble, 20~40cm diameter. In the surface, there are some caving Boulders, up to 3 ×4m (Fig.3). Soil structure is uneven from top to bottom, the surface is slightly close-grained, deep compaction, a maximum thickness is about 20~25m.

Fig.2 Gravel soils of the landslide

Fig.3 Big boulder in the surface

(1) From the analysis of the plane of the ancient landslide, the average length is about 155m, while the width is about 220 m, level projection area is 33,000 square meters, distribution, suggesting an average depth of 17m, landslide's volume is 561000m3.

(2) According to the results of the in investigation and geological studies, three possible scenarios have been detected.

(3) failure and detachment of the area near the under-constructed bridge

(4) failure near the resident

(5) reactivation of the top of ancient landslide

Scenario1: failure and detachment of the area near the under-constructed bridge

In the area above the bridge about 20 m, three cracks are found:

L1 crack: locating in the left of the slope near the No.7 pier, extending about 15 ~ 20m, a seam is about 2cm wide, whose nature is the tension cracks. (Fig.4)

L2 crack: locating in the right side of L1 cracks, position is lower, the size is large, the length extends 65m and a seam is 5cm wide, locally up to 10 cm, the depth in vision is about 0.5m, a" sawtooth "shape extension, the nature is tensile cracks.

L3 crack: Locating in the ancient landslides near the left side of the border, extending about 55 m, a seam is between 1cm and 3cm. The depth in vision is about 0.2 ~ 0.5m, with a shear nature.

There is a mutual connectivity trend among L1, L2, L3 cracks. The whole of them form lateral margin sector and side of the revival landslide. Near the pier, the retaining wall has cracked. (Fig.5)

Fig.4 L1 crack near No.7 pier

Fig.5 the cracked retaining wall

Scenario2: failure near the resident

In the residential area, a number of cracks are also been found, developping along the ground of the residential housings and cutting through walls, which has resulted in the deformation of the walls. (Fig.6)

Fig.6 Cracks in the residential area

Scenario3: reactivation of the top of ancient landslide

In the top of the ancient landslide, the rock mass is full of fragmentations. And there is a transmit electricity tower. (Fig.7) The failure of the top area will influence the electricity transmit of the whole construction of Contract 11, which will result in large economic loss.

Fig.7 a electricity transmit in the top of the ancient landslide

4.2 Occurrence probability

Scenario1: in the two-year construction of the shuima freeway, one landslide had occurred.

Scenario2: from the investigation of the people in the resident, two landslides had occurred in the history of their living time about 500 years.

Scenario3: deducing from the lithology of the top of the slope, occurrence period for Scenario3 is 100000 years

Table 4 Occurrence probability of three scenarios

Scenario	Observation period(years)	Recorded events	Frequency (event/year)
1	2	1	1/2=0.5
2	500	2	2/500=0.004
3	Historic times(1000)	none	1/100000=0.00001

5 QUANTITATIVE RISK ANALYSES

5.1 Element at risk

The elements at risk are recognized through the selected area affected in the three scenarios previously specified.

Table 5 the recognized elements at risk in the scenarios

scenario	Elements at risk	notes
1	bridges	Length affected(m): 200 Persons affected: 5
	Heavy traffic or strategic roads	Under-construction Shuima freeway Length affected(m): 300 Persons affected: 4
	Ordinary forests	Area affected(kmP^{2P}): 0.01
	Secondary lifelines	Length affected(m): 300
2	Rural areas-farming and domestic animals	Area affected (kmP^{2P}): 0.02
	Residential areas	Area affected (kmP^{2P}): 0.02 Persons affected: 37
	Ordinary forests	Area affected (kmP^{2P}): 0.02 Persons affected: 10
	Heavy traffic or strategic roads	Under-construction shuima freeway Length affected(m): 200 Persons affected: 1

3	Strategic lifelines	Length affected(m): 200
	Heavy traffic or strategic roads	Under-construction shuima freeway Length affected(m): 150 Persons affected: 1
	Ordinary forests	Area affected (kmP^{2P}): 0.03
	Residential areas	Area affected (kmP^{2P}): 0.01 Persons affected: 5

5.2 Vulnerability

The vulnerability of the elements at risk have been discussed above. The following tables show the considered values of the element at risk and the evaluated vulnerability for each scenario.

Table 6 Scenario1: considered values of the elements at risk

Elements at risk	physical	economic	environmental	social
bridges	3	2	2	2
Heavy traffic or strategic roads	3	4	1	2
Ordinary forests	1	1	3	1
Secondary lifelines	1	2	1	0

Table 7 Scenario1: vulnerability

	physical	economic	environmental	social
vulnerability	0.5	0.5	0.25	0.75

Table 8 Scenario2: considered values of the element at risk

Elements at risk	physical	economic	environmental	social
Rural areas-farming and domestic animals	1	2	2	1
Residential areas	4	1	1	4
Ordinary forests	1	1	3	3
Heavy traffic or strategic roads	3	4	1	1

Table 9 Scenario2: vulnerability

	physical	economic	environmental	social
vulnerability	0.25	0.5	0.75	0.75

Table 10 Scenario3: considered values of the element at risk

Elements at risk	physical	economic	environmental	social
Strategic lifelines	3	4	1	0
Heavy traffic or strategic roads	3	4	1	1
Ordinary forests	1	1	3	1
Residential areas	4	1	1	2

Table 11 Scenario3: vulnerability

	physical	economic	environmental	social
vulnerability	0.25	0.5	0.25	0.5

5.3 Expected occurrence

The expected occurrence can be obtained by multiplying the values of the elements at risk, and the vulnerability, which are obtained above.

Table 12 Scenario1: expected occurrence

Elements at risk	Physical consequence	Economic consequence	Environmental consequence	Social consequence
bridges	0.75	1.0	0.5	1.5
Heavy traffic or strategic roads	1.5	2.0	0.25	1.5
Ordinary forests	0.5	0.5	0.75	0.75
Secondary lifelines	0.5	1.0	0.25	0

Table 13 Scenario2: expected occurrence

Elements at risk	Physical consequence	Economic consequence	Environmental consequence	Social consequence
Rural areas-farming and domestic animals	0.25	1.0	1.5	0.75
Residential areas	1.0	1.0	0.75	3.0
Ordinary forests	0.25	0.5	2.25	2.25
Heavy traffic or strategic roads	0.75	2.0	0.75	0.75

Table 14 Scenario3: expected occurrence

Elements at risk	Physical consequence	Economic consequence	Environmental consequence	Social consequence
Strategic lifelines	0.75	2.0	0.25	0
Heavy traffic or strategic roads	0.75	2.0	0.25	0.5
Ordinary forests	0.25	0.5	0.75	0.5
Residential areas	1.0	0.5	0.25	1.0

5.4 Risk assessment

The last phase that we especially concerns is the assessment of risk. Table15, 16 and 17 show the risk assessment results for each scenario. From the results, we can know that the risk of scenario 1 is very high, including physical, economic, environmental and social risk. We also know that for the assessment of the risk, the occurrence probability P is more important for the evaluation.

Table 15 risk assessment for scenario1 $R=C\times P=C\times 0.5$

Elements at risk	Physical risk	Economic risk	Environmental risk	Social risk
bridges	0.375	0.5	0.25	0.75
Heavy traffic or strategic roads	0.75	1.0	0.125	0.75
Ordinary forests	0.25	0.25	0.375	0.375
Secondary lifelines	0.25	0.5	0.125	0

Table 16 risk assessment for scenario2 $R=C\times P=C\times 0.004$

Elements at risk	Physical risk	Economic risk	Environmental risk	Social risk
Rural areas-farming and domestic animals	0.001	0.004	0.006	0.003
Residential areas	0.004	0.004	0.003	0.012
Ordinary forests	0.001	0.002	0.009	0.009
Heavy traffic or strategic roads	0.003	0.008	0.003	0.003

Table 17 risk assessment for scenario3 $R=C\times P=C\times 0.00001$

Elements at risk	Physical risk	Economic risk	Environmental risk	Social risk
Strategic lifelines	7.5e-06	2e-05	2.5e-06	0
Heavy traffic or strategic roads	7.5e-06	2e-05	2.5e-06	5e-06
Ordinary forests	2.5e-06	5e-06	7.5e-06	5e-06
Residential areas	1e-05	5e-06	2.5e-06	1e-05

5.5 Risk mitigation measures

In the above, the risk is quantitatively assessed. In order to reduce the risk, some measures should be taken.

(1) In order to reduce the impact of human activities and avoid the death of people and the loss of property, some people should be specifically responsible for tracking and monitoring and early warning, especially during the rainy season. For long-term consideration, the complete implementation of the relocation of settlements is the best.

(2) The original cracks should be fill-hammered, and the simple horizontal catchwater is constructed, the rain Runoff concentrated period immediately row diarrhea to reduce infiltration.

(3) Near the bottom of housing, the slope is appropriately fathered with Sliding piles. The shear wall should be set up with anti-export pressure slope to enhance the overall stability.

6 BENEFITS AND LIMITATIONS OF QRA

6.1 Benefits of QRA

QRA has been found useful for the talus landslide, because it:

(1) Considers many scenarios that involve multiple failures, thus providing an in-depth understanding of landslide modes. Such an enormous number of possible accident scenarios are not investigated by traditional methods. The completeness of the analysis is significantly enhanced by the QRA investigation.

(2) Increases the probability that complex interactions between events/systems/operators will be identified.

(3) Focuses on uncertainty quantification and creates a better picture of what the community of experts knows or does not knows or does not know about a particular issue, thus providing valuable input to decisions regarding needed research in diverse discipline

(4) Facilitates risk management by identifying the dominant accident scenarios so that resources are not wasted on items that are insignificant contribution to risk.

6.2 Limitations of QRA

There are several items that are either not handled well or not at all by current QRA, such as human errors, digital software failures, design error, etc. In some practical cases, the resources available for QRA are less than satisfactory, so rendering the results unreliable, and potentially misleading, and likely to do more harm than good. The limitations are very obvious, because:

(1) Assessment process is not very transparent

(2) It also involves lumped judgment

(3) It is difficult to value judgment in risk acceptability

(4) It also lacks basis for assessing the cost-benefit of different options

7 SUMMARY AND CONCLUSIONS

In this paper, QRA method was applied to a talus slope failure that occurred in the construction of Shuima freeway in Yunnan province. Three different scenarios of the site were selected for the risk analysis. Physical, social, economic, environmental risk is different in each scenario. Basing on the risk assessment of each scenario, some important hazard zones can be obtained. Some measurements for the mitigation of risk are given respectively. However, quantification does not necessarily improve accuracy and reliability. The approach of QRA also has many limitations.

REFERENCES:

Ch. Bonnard, F.Forlati & C.Scavia (2004) Identification and Mitigation of Large Landslide Risks in Europe. London, New York

George E.Apostolakis and Douglas M.Lemon (2005) A Screening Methodology for the Identification and Ranking of Infrastructure Vulnerabilities Due to Terrorism. Risk Analysis, Vol.25, No.2, p361-376

G.L. SIVAKUMAR BABU and M.D. MUKESH (2003) Risk analysis of landslides-A case study. Geotechnical and Geological Engineering 21 p113-127

A.Cubito, V.Ferrara, G.Pappalardo (2005) Landslide hazard in the Nebrodi Mountains (Northeastern Sicily). Geomorphology 66(2005) p359-372

U.S. Nuclear Regulatory Commission.(1975) Reactor Safety Study, an Assessment of Accident Risk in U.S. Nuclear Power Plants, WASH-1400. Report, NUREG-75/014.Washington, DC.

P.Aleotti and R.Chowdhury (1999) Landlide hazard assessment: summary review and new perspectives. Bull Eng Geol Env (1999) 58 p21-44

George E.Apostolakis (2004) How Useful Is Quantitative Risk Assessment? Risk Analysis, Vol.24,No.3 p515-520

ERM-Hong Kong, Ltd (1998) Landslides And Boulder Falls From Natural Terrain Interim Risk Guidelines. Report, Hong Kong

D.O.K.Lo (2002) Interim Review Of Pilot Applications Of Quantitative Risk Assessment To Landslide Problems In Hong Kong . Report, GEO Technical Note No. TN 4/2001.Hong Kong

H.N.Wong and F.W.Y.Ko (2006) Landslide Risk Assessment-Application and Practice. Report, GEO Special Project No. SPR 4/2005. Hong Kong.