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CATASTROPHIC RISK ANALYSIS AND MANAGEMENT FOR PUBLIC-PRIVATE PARTNERSHIP (PPP) INFRASTRUCTURE SYSTEMS

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Abstract

Globally, there is an increasing trend in adopting a Public-private partnership (PPP) scheme to develop large-scale infrastructure. However, little efforts are made to assess the impact of catastrophic risk on the economics (i.e. cash flows) of PPP infrastructure projects. Therefore, this study on catastrophe model for PPP infrastructure projects was undertaken with the aim to bridge the gap, what's more important, catastrophic risk management strategy is developed for concessionaire and government respectively based on the results from catastrophe model.

Based on hazard module, vulnerability module and loss module, a pro forma cash flow model would form a useful basis for quantifying seismic risks and measuring the dynamic financial demand of the project. As a pilot study in this area, this research developed its model based on assumptions because of limited engineering data available. Monte Carlo simulation through MATLAB programming was carried out to incorporate the uncertainty of seismic risk in frequency and severity. The estimated loss derived from the model may have less importance because it is largely depended on the quality of the input data. However, the changing trend of the results derived from sensitivity analysis which indicates the relationship between impact factors and catastrophic losses will guide development of risk management strategy. The model is developed to assess the financial losses due to earthquake for highway projects. It can also be applied to other types of PPP infrastructure projects depended on the similarity of cash flow generation. Respective revisions may be made to the MATLAB program if the model is applicable to other types of PPP infrastructure projects and catastrophes as well.

A scenario case study based on several given scenarios simplifies the impact of temporal uncertainty of occurrence. It is carried out to find the optimal mitigation

strategy for concessionaire. Most concessionaires (run for efficiency maximization) will select mitigation in the beginning as the optimal strategy given no financial constraint. The results from the model also indicate the merits and different incentive of dynamic risk management with varying impact factors.

The focus of this research aims to structure catastrophic risk management strategies for government and concessionaire respectively. Such strategy is developed based on an in-depth understanding of the project's risk exposure derived from catastrophe model, layered risk financing portfolio setup decided by concession agreement, cost and benefit analysis between different risk financing instruments and mitigation efforts, and last but not least, a good understanding of dynamic financial demand.

Catastrophic risk management includes ex-ante and ex-post risk management. Ex-ante risk management is always better than ex-post measures since it need less costs and may prevent or decrease potential losses. However, given lack of cognition of catastrophic risk or inappropriate/insufficient arrangement of ex-ante risk management, ex-post risk management is necessary to be included as a complementary tool.

Catastrophic risk management can be divided into risk mitigation and risk financing. Risk mitigation including loss control and risk reduction for government and concessionaire are explored respectively. Based on the estimated losses derived from catastrophe model, three-layer catastrophic risk financing is introduced. The lower layer is shared by all the private sectors according to contractual arrangement. The middle layer is absorbed by financial instrument such as catastrophe insurance/bond subsidized by government. The upper layer is taken over by government.

Chapter 1 Introduction

1.1 Research Problem Statement

Globally, there is an increasing trend in adopting a Public-private partnership (PPP) scheme to develop large-scale infrastructure projects not only for developing countries but also for developed economies. At the same time, natural catastrophes, especially weather-related events, are increasingly dramatically in number and magnitude. Loss potentials have reached new dimensions (Munich 2007). A better understanding of catastrophic risk of PPP infrastructure projects is essential for both government and private sector to manage such risk respectively.

Concession contracts for developing and operating PPP infrastructure projects are highly complex and typically span up to 30 years. During the project lifecycle, they are exposed to various types of risks, including political, legal, regulatory, currency, inflation, construction, operation and maintenance risks. However, there is currently a lack of effort in assessing the impact of catastrophic risk on the economics (i.e. cash flows) of infrastructure projects and the contractual relationships governed under the PPP scheme.

Traditional quantitative models in risk management focused more on the study of high frequency/low severity risks. Formalized quantification methods are a more recent occurrence to cope with the unique characteristics of catastrophic risks with low frequency/high severity. Since the 1990s, several modeling companies including Risk Management Solutions Inc. (RMS), Applied Insurance Research (AIR) and EQECAT began providing third-party clients with tools necessary to estimate the dimensions of catastrophic exposure. However, the services provided by these modeling companies mainly target the insurance/reinsurance sector and therefore tailored towards the business of underwriting. Naturally, their economic assessments generally focus on properties like buildings due to the demand of property insurance coverage for hurricanes, flooding etc. in the U.S. and Europe. The models discussed above are all proprietary models created by commercial firms; it would be more justified if similar efforts are pursued in the academic world to promote the diffusion of knowledge in this area.

Besides commercial companies, the public sectors and some research centers also take great efforts to develop catastrophic modeling. The Federal Emergency Management Agency (FEMA) developed Hazards U.S. Multi-Hazard (HAZUS-MH) to estimate potential losses from disasters including earthquakes, hurricane winds, and floods. Taiwan developed HAZ-Taiwan based on HAZUS especially for earthquake risk modeling. Pacific Earthquake Engineering Research Center (PEER) designed seismic assessment models for building systems and transportation systems. Australia also developed Earthquake Risk Model (EQRM) to calculate scenario loss of buildings. This kind of models is set up from the engineering's point of view, and is based on integration of the information from seismology, geology, topography and structure etc. The accuracy of estimated loss calculated from this kind of model is depended on the accuracy of data source. The focus of these models is to estimate accurate loss due to catastrophe events, while risk financing and risk mitigation strategy normally are not involved.

Although there was a fair amount of research done in the past in assessing loss due to natural catastrophe events especially for earthquakes, limited application was extended either to infrastructure projects or the PPP settings. This research aimed to bridge the gap lied in the current models. Understanding the impact of natural catastrophes on cash flows is obviously important to develop catastrophic risk management strategies for the infrastructure projects under PPP settings. In addition, the proposed research further extends downstream to include risk mitigation and financing so as to explore the possibility of developing an optimal risk management strategy that would help to spread the risks in an economically efficient manner.

1.2 Scope of Research

Similar to most management research, the effects of catastrophic risks have to be studied in both qualitative and quantitative dimensions. The scope of qualitative issues is broad and they can cover issues ranging from business planning to social interactions, and to contractual issues. Since this study focuses on the PPP settings, risk management strategies stands out to be the more important qualitative aspects. The quantitative issues of catastrophe model based on assumptions will provide guide for qualitative analysis.

The scope of catastrophic risk analysis and management is broad due to the wide-ranging impact of infrastructure projects. For example, it may include issues as diverse as emergency response, evacuation, structural strengthening, security policies etc. However, this research will focus on the project itself and only the project-related aspects will be discussed emphatically in this research.

As Figure 1.1 shows, this research is made up of two parts: upstream and downstream with greater emphasis and focus on the downstream aspects. Upstream study consists of hazard assessment, vulnerability and loss assessment, and downstream study refers to the risk management strategy which includes risk mitigation and risk financing.

Among the different kinds of risks such as political risk, catastrophic risk (force majeure), financial risk, construction risk and commercial risk, etc faced by the infrastructure projects, only catastrophic risk will be studied in this research. Some natural catastrophes, such as earthquakes, are governed by the natural laws and are better understood. It would be harder to make parallel modeling efforts for man-made catastrophes, particularly terrorism, since these are governed by human behavior, geopolitics, religions and many other dynamic socio-economical factors.

Natural catastrophe especially earthquake will be the focus of this research. At the same time, since it is impossible to cover all types of infrastructure projects in a detailed level, this research study focuses mainly on highway projects but some of the concepts of catastrophic risk management remain applicable to other types of infrastructure/catastrophes.

The upstream of this research aims to develop a methodology for assessing the financial impact of catastrophic risks on infrastructure projects. Loss estimation including direct and indirect losses will be calculated based on the assumptions on the hazard and vulnerability assessment combined with the original cash flow model.

As the focus is not on geology, topography and seismology etc., the hazard assessment will be based on assumptions. Although upstream study is not the main focus of this research, assumptions made involving upstream aspects are inevitable in order to provide some basis for the downstream research. Techniques such as scenario and sensitivity analysis are then utilized to assess the impact of varying assumptions.

Downstream study aims to develop appropriate risk management strategies including risk mitigation and financing for infrastructure projects. These strategies ensure availability of funds during the aftermath of catastrophic events and sustain the operations of the facility or system. Since this research is from the project's standpoint, perspective of various stakeholders will be taken into consideration. Catastrophic risk management strategy, set up for government and concessionaire respectively will be the focus of this research. All the non-financing risk management measures including loss control and risk reduction are categorized as risk mitigation. All the risk management measures are characterized as "ex ante" and "ex post" measures according to different execution time.

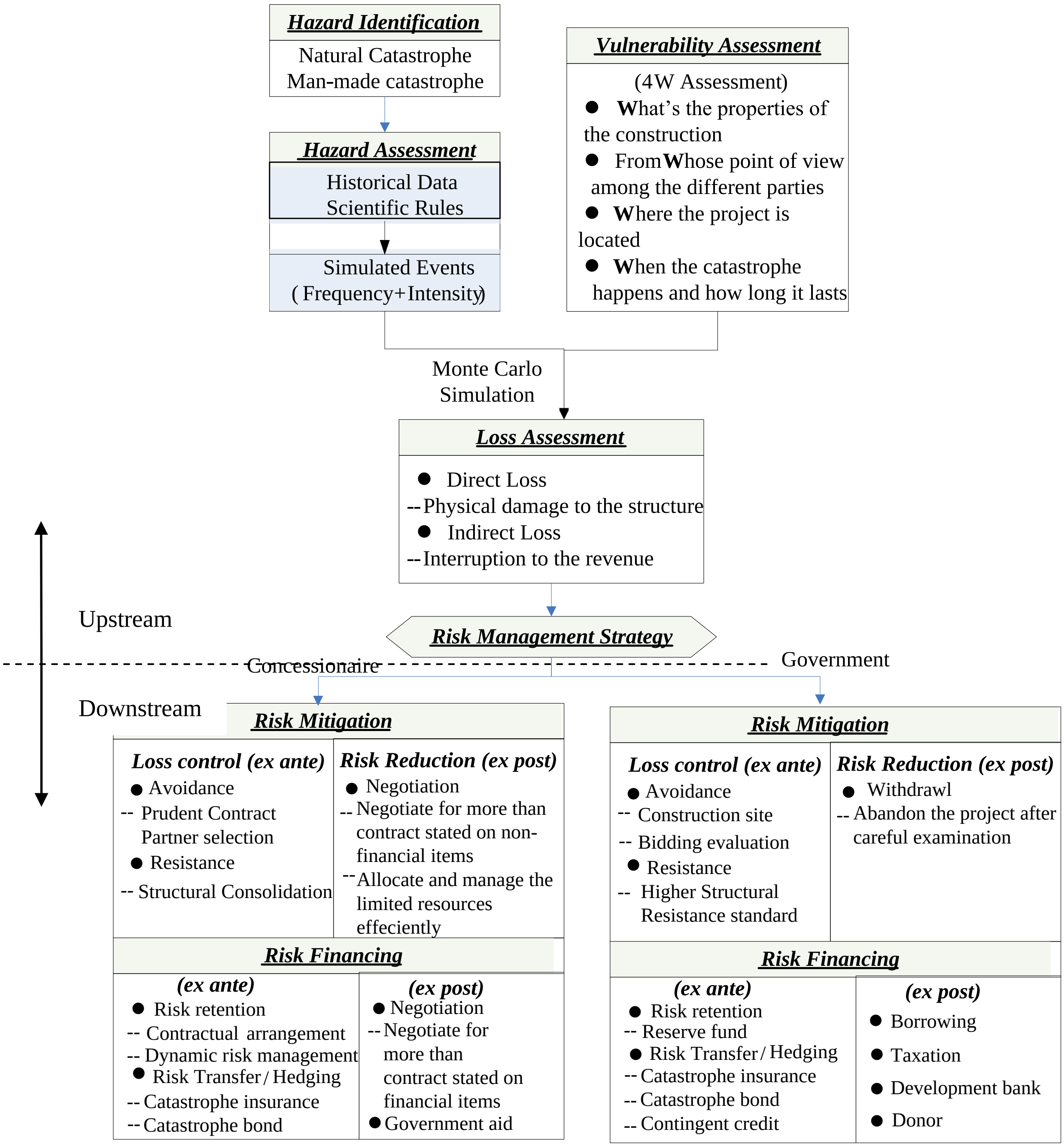


Figure 1.1 Research Framework on Catastrophic Risk Management

1.3 Research Objectives

This research is to provide a methodology for contributing to establishment of catastrophe model and catastrophic risk management strategies for infrastructure projects under PPP settings from various stakeholders' perspective. Both catastrophe model and risk management strategy will be studied in this model with the focus on the latter. This research needs an integration of knowledge sets available in the science, engineering and management fields. The main objectives of this research are listed as follows.

1. To study the impact of seismic risk on the operational and financial performance of transportation infrastructure projects based on their cash flows;
2. To develop optimal catastrophic risk management strategies for infrastructure projects from various stakeholders' perspectives, particularly in a PPP setting.

1.4 Organization of the Thesis

This thesis is presented in eight chapters, and the logic sequence is shown as illustrated in Figure 1.2.

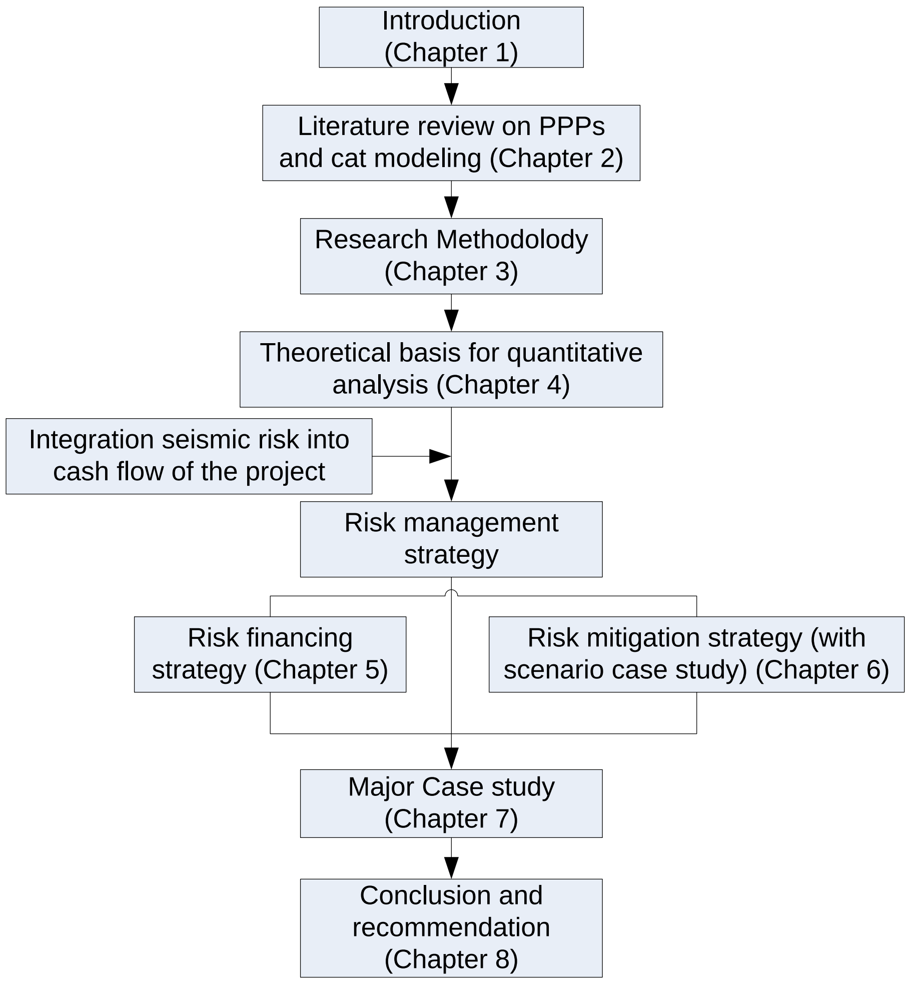


Figure 1.2 The Structure of Thesis

Besides the introduction chapter, this thesis consists of seven other chapters, and the brief introduction of each chapter is presented below.

Chapter 2 introduces the characteristics, risk allocation of PPPs, types of catastrophic risks and gives an overview of the catastrophe risk modelling based on the literature review.

Chapter 3 introduces the development of research methodology used in the thesis.

Chapter 4 discusses the catastrophic risk in the context of infrastructure projects. The fundamental concepts of seismic hazard analysis are introduced, and highway project as one kind of infrastructure is discussed. Furthermore, from the general measurement of seismic impact to integration with PPP cash flows, quantitative analysis of seismic risk assessment is presented from concessionaire's perspective.

The subsequent two chapters present two important components of risk management strategy respectively.

Chapter 5 involves the development of risk financing strategy including risk retention and risk transfer from government and concessionaire's perspective based on three layered risk financing. All the embedded catastrophic risks have to be allocated among all the stakeholders through ex-ante contractual arrangement. Cost benefit analysis of each risk financing measures as well as dynamic risk management will be used to find the optimal financing strategy. Ex-post risk financing measures are not advocated but introduced as complementary tools for ex-ante risk financing measures. In order to develop an optimal risk financing strategy, a combination which includes contractual arrangement, catastrophe insurance, catastrophe bond and other financial instruments may be utilized.

Chapter 6 presents risk mitigation strategy including loss control and risk reduction mainly from government and concessionaire's perspective. A simplified scenario case study is carried out to find the optimal mitigation strategy for concessionaire. The results from the model also indicate the merits and different incentive of dynamic risk management with varying impact factors.

Chapter 7 conducts a major case study to assess the seismic impact on a highway project in China. Based on the assumptions about hazard and vulnerability assessment, loss estimation is calculated through Monte Carlo simulation by MATLAB programming. Catastrophic risk management strategy is developed for concessionaire and sponsor respectively. Results from sensitivity analysis may be used to provide suggestion on strategy development.

Chapter 8 outlines the limitation and results of this thesis and provides recommendations for future research. Based on the estimated loss derived from developed catastrophe model and results of sensitivity analysis, this chapter proposes methodology to develop a risk management strategy for government and concessionaire respectively. Finally, some recommendations for further research are given.

Chapter 2 Literature Review

2.1 Public-Private Partnerships (PPPs)

There are many different types of PPPs and the models applied differ from country to country. In fact, the PPP concept is evolving in different ways in each country in which the arrangements are being implemented. Some countries have a central body dealing with PPPs (e.g. the Netherlands), some do so for particular applications (e.g. the UK), while others leave it to individual states or municipalities (Australia, United States). China is experimenting with a different system for auctioning franchises (the least-present-value-of-revenue or LPVN system). Given this diversity, PPPs here have the following key elements:

- A long-term contract between a public-sector party and a private-sector party;
- The private-sector party is responsible for the design, construction, financing, and operation of public infrastructure;
- The payments over the life of the PPP Contract to the private-sector party for the use of the Facility is made either by the public-sector or by the general public as users of the Facility; and
- The Facility remains in public-sector ownership, or is reverted to public-sector ownership at the end of the PPP Contract.

2.1.1 Types of PPPs

PPP is an evolving concept which takes different forms around the world. There are many forms of contractual arrangements such as Build-Operate-Transfer (BOT), Build-Own-Operate (BOO), Design-Build-Finance-Operate (DBFO) and Build-Own-Operate-Transfer (BOOT) (Thomas 2003). Table 2.1 provides a summary of the different contractual arrangements, and shows how PPPs lie on the spectrum from wholly public-sector projects to wholly private-sector projects

(E.R.Yescombe 2007).

Table 2.1 Contractual Arrangements in PPP Projects

Public project ←→ Private project						
	← Public-Private Partnership →					
Contract Type	**Public-sector Procurement**	**Franchise (Affermage)**	**DBFO***	**BTO****	**BOT*****	**BOO**
Construction	Public sector	Public sector	Private sector	Private sector	Private sector	Private sector
Operation	Public sector	Private sector	Private sector	Private sector	Private sector	Private sector
Ownership	Public sector	Public sector	Public sector	Public sector during construction, then public sector	Private sector	Private sector
Who pays?	Public sector	Users	Public sector or users	Public sector	Public sector	Private sector
Who is paid?	n/a	Private sector	Private sector	Private sector	Private sector	Private sector

* Also known as Design-Construct-Manage-Finance (DCMF) or Design-Build-Finance-Maintain (DBFM)

** Also known as Build-Transfer-Lease (BTL), Build-Lease-Operate-Transfer (BLOT) or Build-Lease-Transfer (BLT)

*** Also known as Build-Own-Operate-Transfer (BOOT)

(Source: (E.R.Yescombe 2007))

PPPs can be classified as BOT, BTO, DBFO and variants on these as shown in Table 2.1 according to different degree of private-sector involvement in the Facility. The main difference among them implies the change of legal ownership of the Facility between Project Company and Public Authority.

Such distinctions are legal technicalities and do not involve risk allocation of PPPs. Based on the nature of the service and risk transfer inherent in the PPP Contract, PPPs can be divided into two main categories: usage- and availability-based.

- For usage-based PPPs, usage risk is transferred to the private sector with user-paid tolls, fares or usage fees for the roads, bridges, and tunnels, and other transportation facilities such as ports, airports, trams and light rail networks. However, usage risk can also be transferred to Public Authority through payment of shadow tolls. Furthermore, there also be a mixture of the two approaches, whereby tolls or fares are paid by users with public sector subsidies.

- For availability-based PPPs, payments are generally made for making the Facility available for use by the public authority. Hospitals, schools, prisons, process plant, and water plant etc. fall into this category. Sometimes, they may also involve provision of long-term services such as cleaning, catering, maintenance, or even custodial services in a prison, as well as construction of a building, but this provision of services is secondary important compared with the construction of the building and its Availability to the Public Authority. The principles in such projects are payments based on availability, while payments based on usage are comparatively less important.

2.1.2 Risk Exposures and Allocation in PPPs

At least nine categories of risk face any infrastructure project (Kerzner 1989; Smith and Walter 1990; Chapman and Ward 1997; Thobani 1998; Grimsey and Lewis 2002). These include:

- Technical risk, due to engineering and design failures;
- Construction risk, because of faulty construction techniques and cost escalation and delays in construction;
- Operating risk, as a result of higher operating costs and maintenance costs;
- Revenue risk, e.g. because of traffic shortfall or failure to extract resources, the volatility of prices and demand for products and services sold (e.g. minerals, office space, etc.) leading to revenue deficiency;
- Financial risks arising from inadequate hedging of revenue streams and

financing costs;

- Force majeure risk, involving war and other calamities and acts of God;
- Regulatory/political risks, resulting from planning changes, legal changes and unsupportive government policies;
- Environmental risks, because of adverse environmental impacts and hazards;
- Project default, as a result of failure of the project from a combination of any of the above.

Risks may alter over the duration of the project; for example, the risks arising from construction may be different from those during the operation phase. Some technical design risks disappear once the engineering work is done. Other risks, such as political risks may continue over the life cycle of the project. Based on the timing of their occurrence in the PPP project life-cycle, the PPP risks are classified into three categories as shown in Figure 2.1: 1) Risks that exist in the design and construction phase of PPP project; 2) Risks that exist in the operation phase on PPP project; and 3) Residual risks that exist throughout the PPP project life-cycle (Ashuri, Kashani et al. 2010).

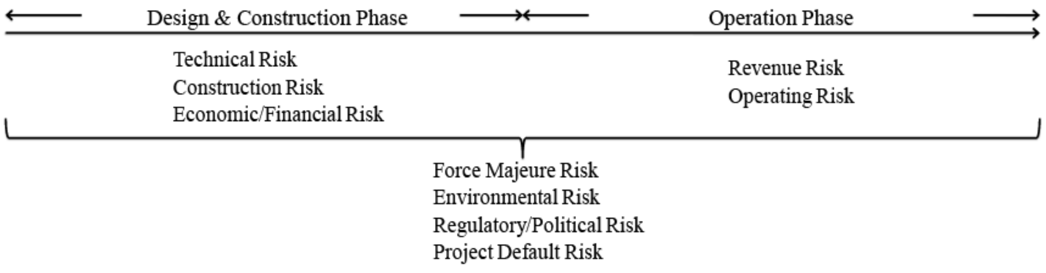


Figure 2.1 PPP Risks Classification According to the Phase of the Project Life-Cycle

2.2 Types of Catastrophic Risks

It is impossible to make informed choices with regard to managing the risk associated with any hazard unless the risk is first understood (Hamburger 2002). A catastrophe is defined as an "event that is believed to have a very low probability of materializing but if it does materialize will produce harm so great and sudden as to seem discontinuous with the flow of events that preceded it". In fact, catastrophe does not lend itself to a simple, universal definition. Standard & Poor's (1997) defines a catastrophe as "an event or series of related events that causes insured losses of $5 million or more." Swiss Re's sigma (2007) defines a natural "catastrophe" as "event caused by natural forces" and man-made "catastrophe" as "major events associated with human activities".

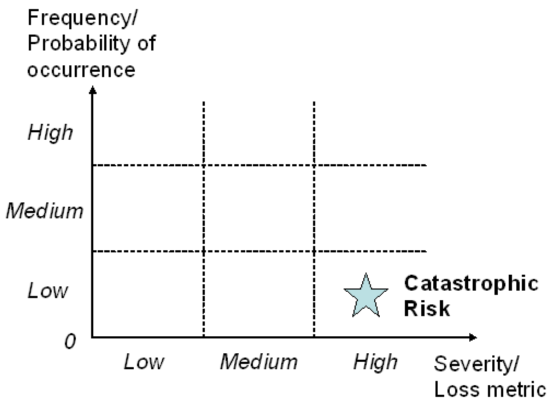


Figure 2.2 Probability/Severity Profile of Catastrophic Risk

There is no standardization of definition of catastrophe. Here, we define a catastrophe as a low probability event with high severity. This can be conceptualized as a simple diagram in Figure 2.2. A catastrophe as defined above may influence the function of existing social, economic, and/or environmental frameworks in a moment. The result might differ from small disruption to overwhelming destruction, and it has the potential of producing very significant human and/or financial losses.

The low probability of such disasters is among the things that baffle efforts at responding rationally to them. The number of extreme catastrophes that have a more than negligible probability of occurring in this century is alarmingly great, and their variety startling (Posner 2004).

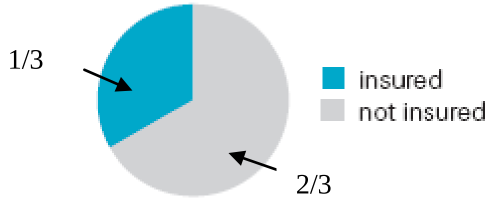
It is noted that the importance of catastrophic risk is not recognized and catastrophic risk is sometimes categorized as force majeure risk here. Among all of these risks, force majeure by its nature is the most difficult to fully mitigate. To minimize such risks, a party should conduct due diligence as to the occurrence possibility of the relevant circumstances of such events, allocate the risk to the other party as far as possible, and require adequate insurance. Moreover, it will be helpful to demand from the host government a clear and unambiguous guarantee or statement of support for the type of investment being made (MIZRACHI 2006).

Grimsey and Lewis (2004) pointed out that force majeure risk is shared by all the participants in the project, and appropriate risk allocation is necessary for efficient risk management. It is important to recognize that the appropriate distribution of risks is depended on the resources and capabilities of the parties to a contract and this can vary considerably.

For a PPP project, risks are allocated to the different parties and basically incorporated in the project's contractual and financial arrangements. The clauses should be as specific as possible. For example, it should explicitly state whether a force majeure event excuses performance permanently or only temporarily, and to what extent of impossibility is an excuse for nonperformance, categorize the risks according to the phase of project within which they may rise.

In most developed countries, insurance is one of the principal mechanisms used by individuals and organizations to manage risk. Some kinds of risks such as political risks can be easily insured, however, purchasing an insurance policy against force majeure events is much more complicated and expensive, especially after the terrorist attacks of Sep 11 2001. Mostly catastrophic risk cannot be insured to full extent. Even if it can be insured, the high premium may be an obstacle to access.

Figure 2.3 shows that about one third of the total catastrophic losses worldwide were covered by insurance in 2006. The directly attributable financial losses were around at around USD 48 billion. Natural catastrophe caused insured losses to the tune of USD 11.8 billion and man-made disasters insured losses of USD 4.0 billion (Zanatti, Schwarz et al. 2007).



(Source: Swiss Re, Sigma (2007))

Figure 2.3 Insured Losses Versus Uninsured Losses due to Catastrophe in 2006

Evidence shows that catastrophes, especially weather-related events, are increasing dramatically in number and magnitude. Loss potentials have reached new dimensions. Since modeling catastrophic risk is a complex process that depends heavily on subjective and objective inputs related to natural and man-made forces, it has to be adapted to the changing hazard situation.

Catastrophic perils are generally separated into natural and man-made catastrophes. Banks (2005) classified natural catastrophes into geophysical (e.g. earthquake, volcano eruption), meteorological (e.g. hurricane, typhoon, tornados) and others (e.g. fire, flood, landslide). Man-made catastrophes include terrorism, industrial contamination, technological failure and financial crisis/dislocation. Obviously, different infrastructure assets, depending on its physical and geographical characteristics, are exposed to varying degrees of catastrophic risks.

2.2.1 Natural Catastrophes

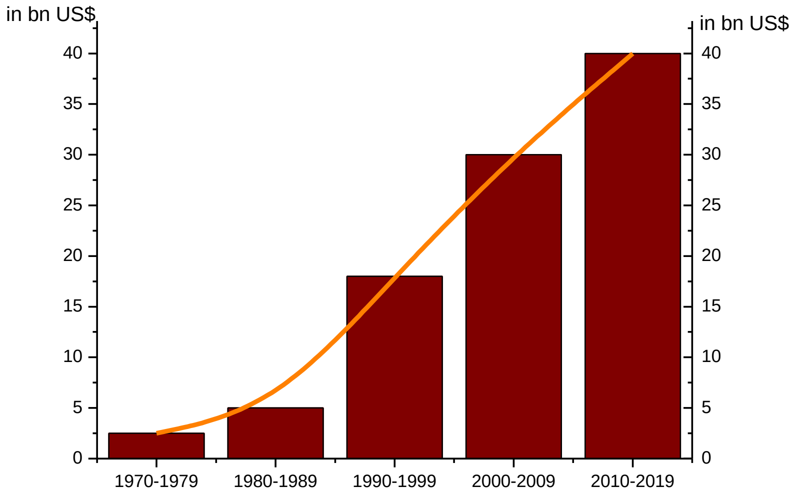
Natural Catastrophes are any natural occurrences that cause widespread distress, usually including loss of human life and notable damage to social systems or property. They are violent upheavals that usually impact a large number of people. They may cause large-scale damage from which recovery is either impossible or long-term (FEMA).

Natural disasters include, but not restricted to, the following: avalanche, drought, earthquake, fire, flood, tsunami, hurricane, landslide, snow storm and tornado etc. Natural disasters are increasing in both frequency and severity. In the past 40 years, there have been over 6000 documented natural disasters affecting more than 5 billion people. Three fourths of these events and 98% of the related expenses have occurred in the past 10 years. It is estimated that this trend will continue. We live in a world of multiple threats where each occurrence leads to a chain of events that affects infrastructure assets and construction projects. Because natural disasters are such an essential, and often overlooked, part of our lives, it is important to know how they function and how to prepare for them.

It is important to realize that, many times, one natural disaster triggers or is accompanied by another. For example, earthquakes and volcanoes sometimes occur together because they are both caused by geologic movements. Earthquakes can damage water pipes, causing wildfires. They will sometimes trigger tsunami, which in turn flood the land, causing landslides. Hurricanes can cause thunderstorms and heavy rain that causes avalanches. Each tiny change within earth’s atmosphere, including human activity, can affect something else in this dynamic system.

Among the main reasons for the continuing increase in the loss levels caused by natural disasters is the continuing growth of the world’s population, the increase in building density by the growing concentration of people and economic assets in urban areas, and by constant migration of people to coastal areas that are greatly are exposed to natural disasters. The development of industry in regions that are subjected to natural hazards, without appropriate protective measures being taken, is another reason for the growing increase in the loss levels caused by natural disasters (IDNDR-ESCAP 2002).

Recently the world has witnessed a string of natural catastrophes, from earthquakes in Haiti, Chile, New Zealand and Japan, to floods throughout Europe, Pakistan and Australia. Evidence shows that the frequency and severity of natural disasters is on the rise. Insured losses from natural catastrophes are rising as the world becomes more developed and economic growth increases, particularly in developing areas of Asia. The average annual cost of insured claims from catastrophes has risen eight-fold, from $5 billion in 1970 to $40 billion in 2010 as Figure 2.4 shows (2011).



(Source: Allianz, 2011)

Figure 2.4 Average Insured Catastrophic Losses Per Decade

Since the frequency of these events is low, historical data is usually insufficient to estimate future economic losses. In such cases, risk assessment needs to be prospective, anticipating scientifically credible events that could happen in the future, but have not yet taken place.

Using current computer technology and the latest earth and meteorological science information, catastrophe models of earthquake and other perils such as hurricanes, typhoons and floods have been developed by specialist consulting companies. Insurers, reinsurers and government agencies around the world normally use these models to assess the risk from such catastrophes.

Earthquake losses accounted for almost one-third of all insured losses in 2010. The earthquake in Chile cost the insurance industry USD 8bn, while the New Zealand earthquake cost insurers more than USD 4bn. Devastating earthquakes ranked among the deadliest, costliest and most powerful in history. Sigma reveals that the number of facilities and insured losses from earthquakes are rising because population growth and higher population density, especially in urban areas, exposes more people to a significant damaging earthquake. Many of the rapidly growing urban areas with high population densities are located in seismically active areas. Due to this, the probability for earthquake with a high death toll continuously increases, although the seismic threat itself remains unchanged (Swiss 2011). Given the increasing impact caused by earthquake, it is selected as the main target catastrophe in this study.

2.2.2 Man-made Catastrophes

Man-made catastrophes are disaster events originating from human activities or forces. Such events are important to analyze and manage in a society that has become heavily dependent on capital, technology, and industry to accomplish its daily activities, and which suffers from geopolitical conflicts that increase the threat of violent action. Normally speaking, man-made catastrophe includes following categories: terrorism, industrial contamination, technological failure, and financial dislocation. War, civil war and war-like events are excluded.

Terrorism has been lurking around the world. More and more attention has been paid to terrorism by governments and researchers since the 21st century, especially after the tragedy September 11th attacks in 2001.

2.3 Modeling Catastrophic Risk

The severity of catastrophe events is high because they are large-scale earthquakes or meteorological phenomena affecting infrastructure projects within thousands of square kilometers, sometimes hundreds of thousands kilometers. Using current computer technology and the latest earth and meteorological science information, catastrophic risk models of earthquake and other perils such as hurricanes, typhoons and floods have been developed by specialist consulting companies. These models are now deemed essential tools for use by insurers, reinsurers and government agencies around the world to assess the risk of loss from such catastrophes.

Natural catastrophic risk models are usually developed using probabilistic formulations that incorporate such uncertainties explicitly, since large uncertainties are inherent in modeled estimates of event severity, frequency and losses (Koduru and Haukaas 2010).

Although current catastrophic loss models are highly developed for earthquake losses in US and some other developed areas, there are limitations to them in respect of many other areas because there is generally a lack of reliable scientific data about the hazard risk. Information such as fault characteristics, soil mapping, flood risk mapping and topographical mapping is often very poor. There is also a growing appreciation for the limitations of models. The science and impact of natural hazards are not completely understood and models are an approximation of a very complex suite of physical phenomenon (RMS 2009). As for the infrastructure projects such as highway projects, data is often difficult to find and may not exist in a readily available form. Even if data exists, it may only exist in aggregated form at a relatively coarse geographical level or may not capture the characteristics of the infrastructure that are relevant to loss risk from the hazards. Unless there has been a recent major event causing losses that have been well researched, there will generally be very little, if any, information on the vulnerability of local infrastructure projects.

Another approach taken by some catastrophe researchers may link hazard impact such as ground motion or wind intensity directly to the level of monetary loss. In this case, damage functions are developed based on the opinions of experts and not on actual engineering analysis, and vulnerability assessment may be simplified or even omitted (Miura, Midorikawa et al. 2008). Structural engineers from private industry and academia are invited to estimate the damage ratio that would result a building or bridge of a specific construction type subjected to a given intensity catastrophe. Their responses, which are based on their personal knowledge and experience, are statistically combined (Askan and Yucemen 2010). One shortcoming of this approach is that the damage functions based on this method cannot be easily updated to reflect new construction techniques, building codes, repair costs or information gained in the aftermath of actual events.

Some researchers employed cost models to translate estimates of physical damage into monetary loss in earthquake loss modeling (Kadakal, Kishi et al. 2000). The model estimates the cost of repair or replacement for each damaged structural and non-structural components as identified by the engineering analysis, in which expert opinions and extrapolation from developed world models are heavily depended on. In practice, the models may not be completely relevant. For example, most existing models base their typhoon losses on wind damage, but in many Asian countries, the main typhoon losses are from flood. Another consequence is that because expert opinions as an important input element may easily differ significantly, the output from different models may vary with each other greatly.

Obviously loss estimation of different types of natural catastrophes varies from each other. Highway project of seismic risk is introduced for illustration in the catastrophe loss model discussed later. However, the risk management strategy is more generic for the PPP infrastructure assets and all types of catastrophes. Catastrophic risk model is structured as shown in Figure 1.2. Hazard identification, hazard assessment, vulnerability assessment, loss estimation and catastrophic risk management will be studied.

2.3.1 Seismic Hazard Identification

Defining seismic hazard requires levels of ground motion as well as ground failure quantified over the region of interest. Using the attenuation relationship is a way to estimate the ground motions, which are often expressed as peak ground motion parameters (i.e., acceleration, velocity, and deformation) or peak structural responses (e.g., peak spectral acceleration, velocity, and displacement) (Flyvbjerg 2006). Other essential components of hazard identification include soil amplification, liquefaction, landslide, and surface rupture.

Take soil liquefaction as an example, soil liquefaction and intense ground shaking often cause the most damage during an earthquake. Liquefaction occurs when strong earthquake shaking causes an immediate weakening of soils such that the soils take on properties similar to quicksand. Liquefaction most often occurs in artificial fill, and in highly saturated loose and sandy soils, such as low-lying coastal areas, lakeshores, and river valleys. Susceptibility to liquefaction is measured by the physical characteristics of a soil, such as grain, texture, compaction, and depth of groundwater.

Earthquake-induced ground shaking is strongest in river valleys and other soft-soil shorelines. Ground shaking in soft soils layered on stiffer soils or rock is more severe than in areas with little variation between layers.

The severity of soil-related natural hazards and ground failure phenomena often depends on status of groundwater, soil saturation, and drought conditions. Soils prone to liquefaction and amplified ground shaking will present the most severe hazards.

2.3.2 Seismic Hazard Assessment

The seismic hazard assessment module defines earthquakes by severity and frequency (probabilities of occurrence). Evaluation of the effects of earthquake at a particular site often requires quantification of strong ground motion that will affect the stability of structures and facilities. For engineering purposes, three characteristics of earthquake motion can significantly influence earthquake damage: 1) amplitude; 2) frequency content; and 3) duration of motion (Kramer 1996). These characteristics are commonly represented by ground motion parameters, such as the peak ground acceleration (PGA) which is one of the representations for amplitude. Ground motion parameters are often estimated using predictive relationships, which play an important role in seismic hazard analysis:

$$Y = f(M, R, P_i) \tag{2-1}$$

where Y is the ground motion parameter of interest;

M is the magnitude of earthquake;

R is a measure of the distance from source to the site considered;

Pi are other parameters that helps to characterize the source, wave propagation path, site conditions etc.

Equation (2-1) is normally developed by regression analyses of recorded strong motion databases.

Spatial uncertainty arises because earthquakes can occur at many different locations within a fault-plane. For example, depending on the relative geometry of the source and site of interest and quality of information about the source, a fault may be modeled as point sources, two-dimensional areal sources or three-dimensional volumetric sources. Accordingly, the uncertainty in source-to-site distance can be represented by a probability density function $f_R(r)$.

Generally, a source zone produces earthquakes of different sizes up to the maximum earthquake, with smaller ones occurring more frequently. For a given time frame, the distribution of earthquake sizes is assumed to follow a recurrence law, and commonly cited one is the Gutenberg-Ritchter calibration function (1944):

$$log\,\lambda_m = a - bm \qquad (2\text{-}2)$$

where λ_m is the mean number of earthquake occurrences exceeding of equaling magnitude *m* in a unit of time (usually taken as an annual rate);

10^a is the number of earthquakes exceeding or equaling magnitude 0;

b is a parameter representing the relative likelihood of large and small earthquakes.

a and *b* are also empirically determined by regression on seismological databases from different source zones.

The uncertainties in R and M imply that the predicted ground motion variable Y will also follow a certain distribution. However, there would still be uncertainties in Y even for a given value of m and r since the predicted relationship is derived empirically. Of particular concern is when Y exceeds a certain threshold y* (which may be perceived as a value that will intimidate the stability of the structure). In probabilistic terms, this is given by:

$$P[Y > y*] = \iint P\left[Y > y* \middle| m, r\right] f_M(m)\, f_R(r)\, dmdr \qquad (2\text{-}3)$$

where $P\left[Y > y* \middle| m, r\right]$ may be derived from the predictive relationship;

$f_M(m)$ may be derived from the recurrence law;

$f_R(r)$ captures the uncertainty in source-to-site distance as explained earlier.

Due to the mathematical complexity of Equation (2-3), numerical methods are often employed to perform the integration functions.

While the previous discussions consider the technical uncertainty of a structure subjected to earthquake damage, it is also important to consider the temporal uncertainty of earthquakes that would result in $\left[Y > y*\right]$. The distribution of earthquake occurrence over time can be assumed to follow a random process. Although the event independence assumption in Poisson model violates the elastic rebound theory of tectonic environments, this model is commonly applied since it provides a simple framework for evaluating probabilities of a particular event (e.g. Y>y* or M>m) during a certain time interval. For example, if one defines the risk R at a certain site as the probability of exceeding earthquake magnitude m over a time interval t, then one can combine the recurrence law with the Poisson model and write:

$$R = P\ [(\text{No. of earthquake exceeding m}) \geq 1]\ \text{over interval t}$$

$$= 1 - e^{-\lambda_m t} \quad (2\text{-}4)$$

Alternatively, one may also define the risk R as the probability of exceeding a ground motion variable y* over a certain time interval t, which simply changes λ_m to λ_{y*} in Equation (2-4), with λ_{y*} being the mean rate of exceedance of the ground motion threshold (Swearingen and Cakmak 1986; Kramer 1996).

2.3.3 Vulnerability Assessment of Transportation Infrastructure Projects

Although hazard assessments are complex, vulnerability assessments are more so. Not only must they consider variations in the physical event, but they must also consider differences in infrastructure and building stock, economic conditions, political climates, stakeholder perceptions, and preexisting preparedness strategies (Schellnhuber 2001), moreover, the location in relation to hazard as well as other risk-related factors (e.g. distance from an earthquake fault line or proximity to the coast in a earthquake-prone area) need to be taken into consideration (Kunreuther 2001).

The vulnerability assessment attempts to quantify the level of exposure of a particular region subjected to the peril intensity and frequency identified in the hazard assessment. This stage essentially overlays a local event of certain peril intensity onto an exposed region through a mathematical damage function. Vulnerability assessment evaluates the impact of catastrophe on the human-built environment, businesses, social structure and services, and the natural environment, considering the preparedness of an infrastructure project and its ability to respond to and recover from a disaster event.

Various vulnerability assessment methods have been proposed, differing by resource, scale, and technique. Vulnerability assessments may focus on resources or issues like critical facilities (Charland and Priest 1995), on social characteristics (Morrow 1999), or on the integration of biophysical and social systems (Cutter, Mitchell et al. 2000). Spatial scales of proposed vulnerability assessments vary from cities (FDCA 1997) to nations (Geohazards International2000). Vulnerability assessment techniques may be technical expert-based (Urban Regional Research1988), community based (FDCA 1997; FEMA 1997; NTHMP 2001), or GIS based (Risk Management Solutions1997; NOAA CSC1999; Cutter, Mitchell et al. 2000).

Since it is impossible to cover all types of infrastructure projects in a detailed level, this research study focuses mainly on transportation infrastructure projects but some of the concepts of catastrophic risk management remain applicable to other types of infrastructure projects. The vulnerability assessment includes component structural vulnerability and functionality of transportation infrastructure systems especially highway.

Significant work has been conducted to assess the potential seismic response of bridges and expected level of damage, often expressed as vulnerability or fragility curve. Such relationships between extent of damage to a bridge and the resulting loss of functionality of the network component are essential for understanding and the consequences of an earthquake event and developing catastrophic risk management strategy.

Currently, very little information linking bridge damage and subsequent functionality exists. These relationships may be developed through assimilation of empirical data from past earthquake events; however, this information is limited even in regions of high seismic occurrence probability. Analytical approaches to developing these relationships have been investigated for typical types of bridges in California, and are more prescriptive in the sense that they serve to indicate the available load carrying capacity of the bridge. While such information might be valuable for inspection and damage investigation purposes, it is not directly related to the primary objective of this research, which is to focus more on the anticipated financial impact on operating cash flows of highway and risk financing thereafter.

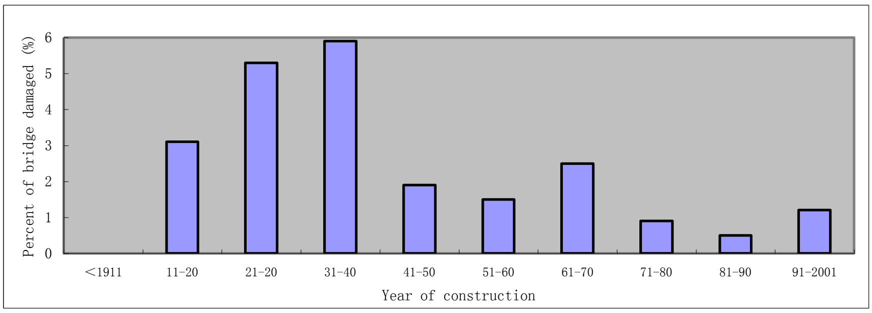
Another approach to collect information relating bridge damage to functionality may involve expert opinion. The FEMA-funded ATC-13 project recognized the need for this data in California and attempted to gather data on loss of function and restoration time for lifeline facilities. The survey participants were queried as to the number of days elapsed before restoring 30%, 60% and 100% functionality for a given damage state. Although there were only four respondents to the bridge survey, HAZUS uses this data to provide discrete and continuous curve fits to the ATC-13 responses. Hwang et al. (2000) conducted an initial study on bridge repair sequencing and downtime in mid-America through a survey of consulting engineers. Four descriptive damage states for bridges and reported potential repair strategies, estimated percent replacement costs, and stepwise functionality restoration curves are also presented.

Regardless of methodology, vulnerability assessments are conducted so that the project can develop targeted strategies to reduce their exposure and potential for loss. As for the highway system which will be discussed in the following case study in Chapter 7, vulnerability assessment may consist of the bridge property, stakeholder input, location in relation to hazard (also incorporated in "hazard assessment") and current mitigation measures which are in place or could be used (also included in "catastrophic risk management"). Since the latter two elements may be introduced carefully within the other part of this research, only the first two facets will be discussed as follows.

2.3.3.1 Bridge Fragility Curve

Damage progression in a bridge during an earthquake is a complex process that depends on details of the bridge that are not commonly available in bridge databases. For example, after regression analysis, Basoz et al. (1999) found that the most important bridge characteristics for classifying bridge vulnerability were peak ground acceleration, abutment type, skew, span length, and span continuity. The WSBI (WSDOT 2000) provided the following characteristics for each bridge: year of construction; span length; bridge length; latitude and longitude; structural system (e.g., movable, truss, simply supported, continuous); material used for the main span (reinforced concrete, prestressed concrete or steel).

From the damage data of the Nisqually earthquake, the year of construction of the bridge was one of the most important factors which influence the post-earthquake performance. Figure 2.4 shows the percentage of bridges damaged as a function of the decade of construction. The percentage of damaged bridges was largest before 1941 and smallest after 1970. The importance of year of construction is also apparent when this factor is considered in combination with spectral acceleration, as shown in Figure 2.5. One should note that the construction year here refers to the operation ages of the bridges, and the reaction of the bridges to the catastrophe within the construction period is more difficult situation and will not be discussed in this research.



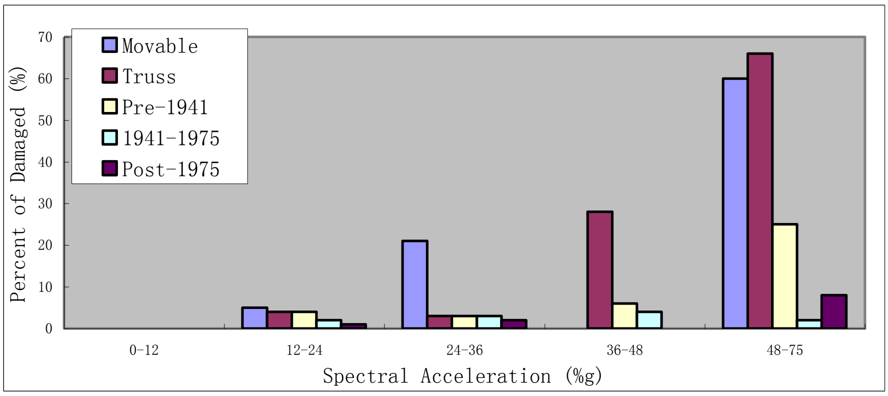
(Source: Ranf and M.EERI (2007))

Figure 2.5 Effect of the Year of Construction on the Percentage of Damaged Bridges

According to PEER Project report (Gordon), the number of damaged bridges varied slightly with the different year built. The bridges with 10-20 years' age will suffer additional 0.7% damage compared with those built within 10 years. The repair costs for the whole link, roughly deduced from Table 2.2, given as a percentage of CAPEX of the project, are shown as below.

Table 2.2 Link Repair Costs

Link State / Age of the link	Minor Damage (%)	Moderate Damage (%)	Major Damage (%)
within 10 years	25	65	100
10-20 years	25.7	65.7	100.7



(Source: Ranf and M.EERI (2007)

Figure 2.6 Effects of Spectral Acceleration (*T* = 0.3 *S*) and Year of Construction

Similar analyses shows that span continuity did not significantly affect the vulnerability of bridges at the low levels of damage, and the influence of span continuity may be more prominent at higher levels of deformation, at which point a continuous span redistributes forces to the end abutments. Although span length may also influence damage, the influence could not be evaluated with the Nisqually data. Only 2 of the 18 bridges with spans longer than 492 ft (150m) were damaged within the boundaries of the ShakeMap. (Ranf, M.EERI et al. 2007)

The factor which influenced the vulnerability of bridges most during the Nisqually earthquake were the estimated spectral acceleration (*T* = 3*s*), the age of the bridge, and the bridge type. As Figure 2.6 shows, movable bridges and steel trusses were particularly vulnerable.

For a given bridge, it is possible to predict, deterministically, the level of ground shaking necessary to achieve a target level of response and/or damage state. The fragility curves are used to represent the probabilities that the structural damages, under various levels of seismic excitation, exceed specified damage states (Cherng 2001). Bridge fragility curves are essential for evaluating the expected traffic capacity of bridges and assessing the seismic risk to the transportation network

(Padgett and DesRoches 2009).

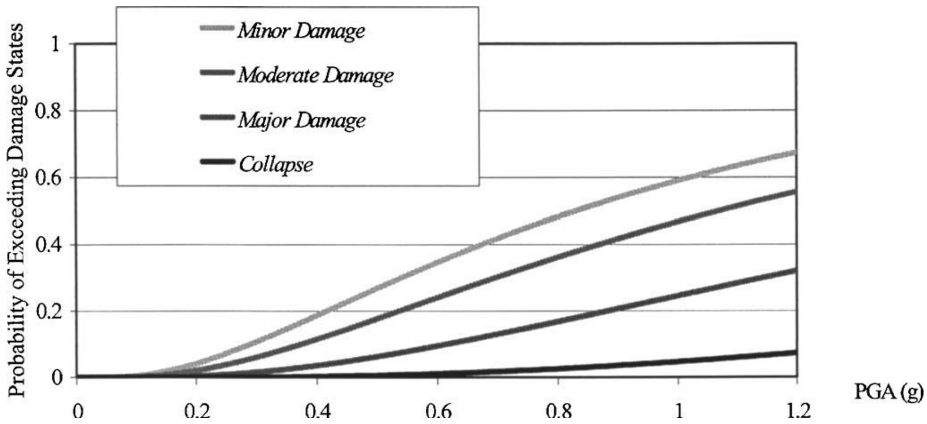
Fragility curves can be developed in several ways. Depending on the development data sources, fragility curves can be divided into four categories: judgmental, empirical, analytical, and hybrid fragility curves (Rossetto and Elnashai 2003).

- Judgmental or expert-based fragility curves are developed from expert opinions. For example, the Applied Technology Council (ATC) conducted a survey to collect expert opinions for estimation of structural damage from earthquakes. The survey results, basis of damage curve, were presented in a damage probability matrix which describes probabilities of a facility being in a specific damage state for different level of ground shaking. However, there are five experts who responded in total. It is easy to understand that these judgmental fragility curves from a small sample-based survey are usually sensitive to systematic sampling errors and prone to bias (Lindell and Whitney 2000).
- Fragility curves can also be developed based on observations of empirical structural damage data from past earthquakes. For example, empirical fragility curves for bridge with and without retrofit were developed based on the field inspection data collected after the 1994 Northridge earthquake (Shinozuka, Murachi et al. 2003). The major limitation of empirical fragility curves is the lack of sufficient empirical data for various types of bridges and damage levels.
- Without adequate empirical data, analytical fragility curves are developed based on the evaluation of structural response. Various approaches including elastic spectral method (Greenbaum and Thakor 2007) and capacity spectrum method (FEMA 2006) have been utilized to develop bridge fragility curves. However, such analytical models are only applied to the most critical components of infrastructure systems (i.e., bridges in transportation systems)

because of their requirements for larger information and computationally expensive analysis (Eguchi 1984).

- Hybrid fragility curves combine data from various sources and compensate for the scarcity of observational data, subjectivity of judgmental data, and modeling deficiencies of analytical procedures (Jeong and Elnashai 2007).

According to the principle above, the fragility curves simultaneously based on the PGA values and damage states reported by California Department of Transportation engineers for 1998 bridges damaged in the Northbridge earthquake are shown as below. Four nonintersecting curves are listed in the Figure 2.7, one for each of the damage states: 1) at least minor damage; 2) at least moderate damage; 3) at least major damage; 4) collapse. Each fragility curve describes the cumulative probability of achieving or exceeding a given damage state as a function of PGA.



(Source: Nobuhuko Shikaki and Masanobu Shinozuka etc (2007)

Figure 2.7 Bridge Fragility Curves Estimated from Northridge Earthquake Data

Table 2.3 defines bridge damage index value. Bridge damage is defined in accordance with Caltrans' reports on bridge damage in the Northridge earthquake (Caltrans1994).

Table 2.3 Bridge Damage States

Bridge damage state/ fragility curve	Bridge damage index	Median PGA	Log-standard deviation
No damage	0.00	-	-
Minor damage, j = 1	0.10	0.83	0.82
Moderate damage, j = 2	0.30	1.07	0.82
Major damage, j = 3	0.75	1.76	0.82
Collapse, j = 4	1.00	3.96	0.82

The damage to individual components of the network is expressed in terms of fragility curves as shown above. A distinct fragility curve is required for each component in the network. Furthermore, separate fragility curves are needed to estimate the damage from ground shaking and from ground deformation. Given the large number and diversity in designs of bridges, pavement segments, and tunnels that exist in a transportation system, it has become difficult to group into generic classes that capture the gross characteristics of the various components.

2.3.3.2 Functionality of Transportation Infrastructure Projects

The post-earthquake traffic carrying capacity of a component of transportation network (e.g., bridge) will be time-dependent in accordance to the relationship of structural damage and restoration of the component. Such relationship defines the residual traffic capacity of a component for a particular damage state. In other words, the relationship relates the structural damage states to the reduced traffic throughput capacities due to bridge collapse and lane or road closure, etc.

Similar to the approaches used for developing fragility curves, there are three ways including empirical, analytical, and expert opinion-based which link the bridge damage state and functionality.

- Damage and functionality relationship is based on empirical data. Experience from repair and restoration and corresponding structural damage from past events are used to develop the relationship. This empirical approach would be effective in regions with sufficient observation data. However, it would be difficult for regions with little seismic data when there are no adequate field observations for various types of structures from past earthquakes.

- Damage and functionality relationship can also be developed analytically by using statistics of structural damage repair and restoration for the regions with adequate observation data. Mackie (2004) investigated analytical damage and functionality relationship for typical bridge types in California, in which the functionality of a bridge was measured by its load carrying capacity. Sometimes, the transportation network is defined in terms of nodes and links, where nodes consist of locations where two (or more) highways intersect and links are highway segments which connect two nodes. In practice, several bridges may exist in a single transportation link, and damage to any bridge will to some degree have an impact on the service provided by the whole link. Chang (2000) developed a Link damage index (LDI) for converting bridge damage states to link damage states, which will be discussed later in details. The drawback of this approach is that it does not reflect the details of repair or road closure decisions.
- Expert opinion-based approach has been widely employed because it is easy to implement and effectively capture the subjective nature of bridge functionality which is based on closure and repair decisions. Padgett and DesRoches (2009) performed a web-based survey to collect expert opinions from experienced staffs in the departments of bridge engineering maintenance and operations of the Central and Southeastern United States (CSUS). 28 samples are collected from about 75% experts who responded to the survey. The damage and functionality relationship was developed

based on the collected sample. Obviously this approach is subjective and biased. What's more, it is limited due to the simplified assumption of several discrete levels traffic carrying capacity.

As introduced above, the LDI quantifies link damage states which translate these values into estimates of link traffic flow capacities. Although there may be different definition of LDI for each link, in this research, the LDI accepts the function given by Nobuhiko (2007), which is the square root of the sum of the squares of the BDI values assigned to all bridges within the link.

$$LDI = \sqrt{\sum_{j=1}^{N} \left(BDI_j\right)^2}$$

Where N = total number of bridges associated with the link; and BDI_j = bridge damage index for bridge *j*.

This LDI value increases at a decreasing rate as the number of damaged bridges in a given link increases. When a single bridge is damaged, the LDI value equals to the BDI value. The traffic capacity of a damaged bridge and the link is difficult to decide because many factors such as the remaining structural capacity of the bridge, the operating policies of local jurisdictions, and the actual situation at that time have be taken into consideration. If a single bridge is damaged, its residual traffic might be temporarily abandoned in the interest of safety. While if many bridges in a single network are damaged, local authorities might rely on the residual traffic capacities of damaged bridges in order to protect the network-wide level of service.

A reasonable correspondence between link damage index values, link damage states, and representative changes in traffic capacities is summarized in Table 2.4. In the post-earthquake situation, links were evaluated in terms of four qualitative damage states ranging from “no damage” to “major damage”.

Table 2.4 Changes in Link Capacity as Function of Link Damage State

Link Damage State	＞LDI lower bound	≤ LDI upper bound	Capacities (%)
No Damage	0.00	0.50	100
Minor Damage	0.50	1.00	100
Moderate Damage	1.00	1.50	75
Major Damage	1.50	∞	50

2.3.3.3 From Whose Point of View

To assess the financial impact of catastrophic risks on infrastructure, the economic value and functions of the systems need to be somehow quantified. This is by no means an easy task, since economic value and functionality of a system would differ from one party's perspective to another. For example, government agencies frequently rely on shadow pricing to evaluate the cost and benefits of public projects (Squire and Tak 1992). So the different standpoints must be incorporated in the vulnerability assessment.

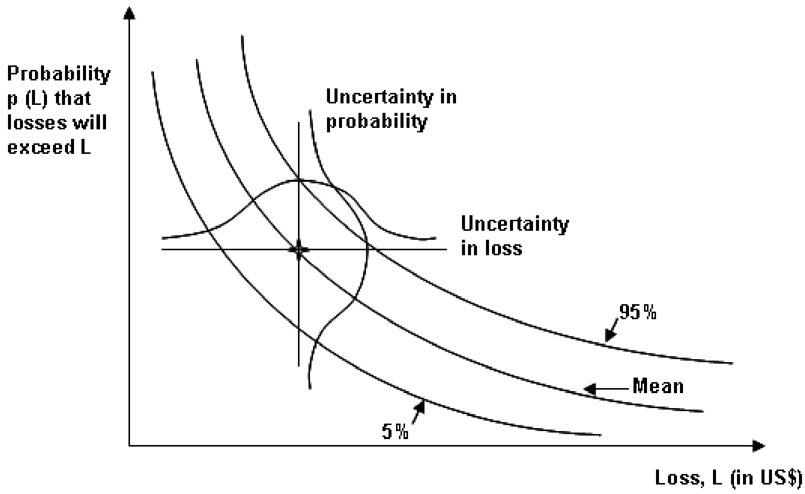
In investing in a PPP project, private sector aims to achieve return on their investment in generating sufficient future cash flows to cover initial capital expenditure and finance charges, thereby providing enough profit to invest in future projects and pay shareholder dividends. In contrast, the aim of the public sector is to ensure a level of service to the community which is timelier, more cost efficient and higher quality than if the public sector had retained responsibility. Given different objectives of the public and private sector, vulnerability of the same project may be different for various stakeholders.

From the public sector's point of view, the macro-impact such as the disruption of the service provided by the project, influence on the local economic and number of casualties may be more concerned. Also the public sector need worry about the financial stress especially the catastrophe has overwhelming impact of the region. Compared with the public sector, the private sector may focus on the micro-impact and the only concern is whether the investment is worthwhile.

Therefore, the private sector only concerns about the PPP infrastructure projects for concession period especially for payback period, however, the public sector is responsible for the projects during the whole life cycle. According to the risk allocation among the stakeholders of the project, the necessary costs brought by catastrophe events such as repair costs or rebuilt costs may be borne by public sector lonely or shared by both parties. In this case, vulnerability varies with all the above mentioned changes for different stakeholders.

2.3.4 Loss Estimation

Combined the hazard assessment with the vulnerability assessment, estimated loss can be easily obtained, and the accuracy of the loss estimation depends on the reliability of hazard risk and vulnerability assessment. The loss exceedance probability (EP) curve shown in Figure 2.7 provides a way of predicting this loss in a systematic manner. In this case, the severity measure of the horizontal axis is translated into losses L in dollars (based on functions, models and inputs from the hazard and vulnerability assessment modules); the vertical axis represents the probability that actual losses will exceed L in the horizontal axis. In view of the uncertainties associated with estimating both the probability of an event occurring and the magnitude of losses, Kunreuther (2001) highlighted the need to construct three (instead of one) exceedance probability curves - thereby defining a band that represents a selected confidence interval (illustrated as 90% in Figure 2.8).



(Source: Kunreuther (2001))

Figure 2.8 Example of Loss Exceedance Probability Curves

2.3.5 Catastrophic Risk Management Strategy

Since catastrophic events can be financially devastating for infrastructure projects, comprehensive risk management often involves efforts and resources of both the private and public sectors. It is important to realize that catastrophic risk cannot be totally eliminated and the probability of loss cannot be reduced to zero. The investment in loss control, loss financing, and risk reduction helps eliminate risk, and the marginal returns from each dollar in investment decline with the reduction of risk. How to minimize costs and maximize elimination of risk through risk management strategy becomes a big issue.

2.2.5.1 Loss Control

Loss control, also known as one type of risk mitigation, focuses on taking ex ante measures that can help minimize the level of vulnerability and reduce the chance of the business being interrupted. Loss control can be divided into two general categories: avoidance and resistance. Avoidance reduces the financial impact of a hazard by prohibiting expansion in at-risk areas. Resistance, in contrast, tries to reduce the effects of a hazard through safety precautions or rules/standards in at-risk areas. It's a kind of active action and technical knowledge such as structure engineering may be needed.

2.2.5.2 Risk Reduction

Risk reduction, also known as one type of risk mitigation, focuses on taking ex post measures that tries to reduce loss as efficiently as possible. When the catastrophe event occurs, minimizing the loss means maximizing NPV of the project at the same time. Different factors may have various impacts on NPV of earthquake occurrence. Through sensitivity analysis, it is possible to find out the most sensitive factor which may influence NPV mostly. Therefore the corresponding strategy which may allocate the limited resource to the most sensitive parameter may be arranged. If the loss is too devastating or the infrastructure assets locate on an active fault line, it can eliminate the risk by permanently closing the assets known as withdrawal. Withdrawal refers to the partial or complete abandonment of the infrastructure project that gives rise to a particular risk exposure, which becomes the last resort.

2.2.5.3 Risk Financing

Risk financing is the largest class of risk management mechanisms. Risk financing can be classified under two broad categories: pre-loss financing and post-loss financing. Pre-loss financing includes all mechanisms arranged in advance of a loss, and generally involves an ex ante cost; insurance/reinsurance, catastrophe bonds (cat bonds), contingent capital, and derivatives are all examples of pre-loss structures. Post-loss financing includes cash/reserve access, debt issuance, and equity issuance. Though post-loss financing does not involve an ex ante cost, if may feature an ex post cost in the form of a higher cost of capital, or the additional interruption costs due to no prompt recovery costs unavailable.

Cat bonds were developed in the mid-1990s to facilitate the direct transfer of catastrophe insurance risk from insurers, reinsurers and corporations (referred to as the cat bonds' "sponsors") to investors. They were designed to protect sponsoring companies from financial losses caused by large natural catastrophes by providing an alternative or supplement to traditional reinsurance. Since 1997, the first year in which multiple transactions occurred, a record total of $4.69 billion in new catastrophe bonds were issued in 2006, a 136% increase from 2005's record performance of $1.99 billion. New catastrophe bonds issued $2.5 billion for the first six months of 2010, which is 40% higher than the same period last year (Green 2010). Compared to the rest of the world, developing countries have relatively low insurance penetration. This research will discuss the possibility of application of cat bonds in these countries especially for infrastructure projects under PPP scheme. Under risk financing, there are two categories: risk retention and risk transfer.

1) Risk retention

Risk retention can be passive or active. Passive risk retention occurs when the stakeholder preserves more exposure than its financial capability because it has failed to properly identify the nature and magnitude of its risks. Active risk retention, in contrast, occurs when the stakeholder knowingly preserves certain risk exposures (i.e., classes and/or magnitudes), generally those that have the possibility of producing only small losses, and which appear on a very frequent, or statistically predictable, basis. In general, catastrophic risks are not considered to be good candidates for active retention as they occur infrequently (i.e., they are statistically unpredictable, particularly in the tail of the distribution) and have the potential of being very severe. However, as a part of catastrophic risk management strategy, active retention may be employed to be a supplementary to catastrophic risk financing instruments. For example, after allocating the total catastrophic risk among all the stakeholders, the respective stakeholder may choose to retain risk of a certain amount according to its financial capability.

Through ex ante contractual arrangement or ex post negotiation, the stakeholders of the infrastructure project may develop the appropriate risk retention strategy for themselves. With the total quantity of risk unchanged, what one party wins is the other party loses. It's difficult to develop a satisfying strategy for all the stakeholders because the risk cannot easily be divided equally. Given the importance of infrastructure, the government normally takes the most responsibility of the potential catastrophic risk. Even though the contractual arrangement doesn't state explicitly, the concessionaire may ask for financial aid from the government through negotiation once catastrophe occurs.

2) Risk transfer

Risk transfer shifts risks via the insurance/reinsurance mechanism. In exchange for a premium, part of their loss from a given set of exposures may be transferred to the insurance/reinsurance company. There are two main types: pro rata (re)insurance, in which premium and loss are shared on a proportional basis, and excess of loss (re)insurance, for which a premium is paid to cover losses above some threshold.

Hedging is often associated with unique or uninsurable risks which cannot be handled through a standard insurance arrangement. While risk transfer via insurance can lead to a net reduction of exposure, hedging simply shifts an exposure from one party to another party, and the exposure is still preserved by another party. Hedging is similar to an insurance contract. Certain hedging, transfer, and financing techniques between financial institutions and insurers/reinsurers have converged in recent years, meaning that a strict distinction of managing catastrophic exposures has become increasingly blurred.

2.4 Gaps in Current Catastrophe Research

2.4.1 Special Property of PPPs

Since PPP s are increasingly viewed necessary as a concerted effort to respond to catastrophic risks, this research would propose to start with analyzing infrastructure projects that are funded under a PPP scheme, especially those that are utilizing the BOT financing scheme. This proposition is founded on the following factors:

1) Contractual obligations of both the government and the concessionaire are generally well specified in the concession contract. The existence of these contract details provides a good basis for quantifying the expected risks and returns for each party. Moreover, in some cases, the level of tariffs that could be collected by the concessionaire is well defined (as in a Power Purchase Agreement). Clear projection of annual cash flows (or social benefits) will undoubtedly help to assess the impact of catastrophic risks.

2) The concession period defined in the contract serves a finite and realistic time for catastrophic risk assessment, rather than keeping the problem open-ended. On the other hand, the contract period (concession contract) is at least around 20 years, sometimes may exceed 30 years. In order to compensate for the largely unknown risks involved over such a long period, the private sector will inevitably demand high risk premiums, as will the financial institutions and members of supply chains which serve them. Substantial evidence shows that it is difficult to predict the extent of risk in such projects, of inappropriate risk distribution between the public and private sectors and of overly optimistic businesses cases and ending up with revenues less than investment costs.

3) The net cash flow pattern of a concessionary project is typified by a relatively long period of cash outflow before a net cash inflow can be realized. Most infrastructure projects provide low returns in the beginning of the operation period. If catastrophe happens during this period or even in the construction period, the private sectors may ask for more compensation of the recovery of the project and more financial stress will be faced by both parties.

4) Since the infrastructure projects may have social, cultural and ecological

impact on the region even the country, it cannot be easily abandoned even after being destroyed heavily. That is to say, sometimes the recovery works must be conducted regardless of huge costs. Public sector has social responsibility, while the private sector is profit driven, so the complex negotiation and necessary collaboration between public and private sectors are needed.

2.4.2 Force Majeure in PPP Contract

In a PPP contract, catastrophic risk has no clear definition and is mainly included in force majeure risk. The term "force majeure", a phrase originating in Napoleonic law, refers to certain circumstances and events which are recognized as being above and beyond the control of contracting parties and which could not reasonably have been foreseen or avoided by the due care of either of the parties (Powell 2001). Some unexpected circumstances that occur beyond the control of a project stakeholder and prevent stakeholder from fulfilling his obligations incorporated in the contract are usually included (Xenidis and Angelides 2005).

Traditionally, force majeure clauses have listed events of an extraordinary nature identified collectively as acts of God, in practice, the phrase "force majeure" may cover a much wider or narrower scope of circumstances depending upon the specific wording of the different contract clauses. Normally speaking, these “unexpected circumstances” should include events that are impossible to foresee at the point of signing the contract, such as acts of God, terrorism, rare events where their occurrence is predictable (public disorder, riots), embargoes, fires or explosions, wars, vandalism or sabotage, earthquakes, floods, civil unrest, strikes, etc. Catastrophic risk discussed in this research may be included in force majeure with some exceptions. War, public disorder, riots is categorized as political risks and will not be studied here as catastrophic risks. Force majeure risk is considered constant throughout the life of a PPP project. It begins when the decision to undertake the project is made (when the bidding and design phase starts) and lasts for the whole period of the project.

A force majeure event grants an extension to the completion date but does not normally provide the financial compensations due to damages resulting from the delay caused by the event to the contractors. The traditional arrangement industry-standard language goes like this: “The contractor will be entitled to extensions of time equal to delays on the Project’s critical path arising from unforeseeable causes beyond the contractor’s control and arising without the contractor’s fault or negligence” (Shumway, Richard et al. 2004). It is important to note that not every "force majeure event" excuses performance. Force majeure provisions only provide relief when there is a specific and direct connection between the event and the impact on the performing party (Gentile 2004).

For an infrastructure project under PPP schemes, such initiatives can be structured inherently as part of the concession contract, instead of transferring the risks to the insurance sector as a default solution. This may turn out to be more cost effective, since design can be customarily modified to mitigate the risks at the early stage of the project lifecycle. Depending on the insurance loading, the subjective loss of the insured and other insurance contractual details (e.g. deductibles and maximum payment limit), it is sometimes more effective to absorb rather than transferring the risks to the insurance sector (Hoshiya, Nakamura et al. 2004).

2.4.3 Summary

The importance of catastrophic risk analysis and management is highlighted by the potential of catastrophes in creating shocks to the existing social and economic systems and imposing significant financial losses. Relatively, more attention is given to damages of residential dwellings and commercial buildings, since these are primary premises where people live and work. On the other hand, infrastructure facilities and systems, such as highways, power plants and water treatment plants, are pillars supporting economic growth and sustaining the daily life of human being. It is therefore equally important to study the effects of catastrophic events on these facilities and systems.

The risk analysis and management process during the course of infrastructure project development typically does not include catastrophic risks. One reason for this is the assumption that catastrophic risks, as a form of force majeure risks, can be readily transferred to the insurance industry. However, this should not be taken lightly as a default option, since insurance cover:

- May not be available for certain types of catastrophes (e.g. terrorism) in some countries;
- Available only at a very high cost, particularly during the aftermath of an event; or
- Available but subject to various exclusions, thus rendering the purchase such coverage economically inefficient.

Furthermore, insurance density/penetration is low particularly in lower-income or less developed countries (Mechler 2004). As a consequence, the financing of recovery in developing countries often relies on government and multilateral agencies' initiatives. Incidentally, with a lack of public funds in these countries, infrastructure projects are sometimes financed using a PPP scheme (e.g. the BOT mode). In a typical PPP/BOT setting, both public and private sectors are locked into a long-term contractual relationship. The implications of catastrophic events leading to potential loss of functionality of these systems would therefore become even more complex.

This research aims to develop catastrophic risk management strategy for PPP infrastructure projects for government and concessionaire respectively.

Chapter 3 Research Methodology

Researchers are often confronted with an overwhelming number of research methods. It is regularly difficult to decide on the most suitable one. Research method selection is dependent on the circumstances and objectives of the research rather than deriving from philosophy (how we think about it) or methodology (how we study it) (Hammersley 1999). Selecting the most appropriate research method must be driven by the research question and current body of knowledge in the area researched (Wynekoop and Russo 1997).

Given the multiple research methods available, choosing the most appropriate research method is not an easy task. Careful selecting and applying the research methods as well as detailing their execution are necessary for achievement of research objectives. Research methods of this research are proposed based on the nature, aims and goals of the research as well as the data accessibility, and then are refined and finalized through practice at later stage.

3.1 Research Methodology Development

Literature review provides basis for the entire research methodology development. It is vital to conduct ongoing literature review throughout the entire research within the context of catastrophic risk management and PPP infrastructure projects. Literature review aims to build a theoretical foundation upon which the research methodology is based. In this research, comprehensive reviews are conducted on relevant literature on types of PPPs, project risks in general, types of catastrophic risks, earthquake risks, characteristics and risk allocation of PPPs. Moreover, development of the existing catastrophic risk model was introduced based on past literature. The gap between the two parts gives the reason for the initiate of this research. The sources of literatures cover a wide range of books, journal papers, government reports, international organization’s publications, latest information on the website and reports from insurance companies.

Research methodology is divided into quantitative and qualitative studies. They are by no means opposed research methods excluding each other, but that they can supplement each other. They combine the strong elements of the two research perspectives: a qualitative study on the nature of researchers' conceptions of research, followed by generating items from researchers' utterances to make up an inventory for a larger scale quantitative study. In order to develop catastrophic risk management strategies for infrastructure projects under PPP settings from various stakeholders' perspective, research methods including quantitative and qualitative study were proposed to be combined.

The finalized methodology includes case study (including scenario and real case), sensitivity analysis and Monte Carlo simulation. Figure 3.1 shows the logical framework of the overall methodology. In order to optimize the strategy, dynamic risk management is introduced to reduce the dynamic financial gap due to catastrophe events. If we assume that financial gap is fulfilled by reserve fund only, the maximum NPV with the minimum reserve fund will be proposed to be an optimal strategy. This selection procedure of optimal strategy can be easily realized in a Matlab program.

A scenario case study is carried out to output the various results under different mitigation scenarios. Comparative study and sensitivity analysis are conducted to suggest the optimal mitigation strategy for different project managers and examine variation of the incentive of dynamic risk management with changing variables.

At the same time, Monte Carlo simulation based on cash flow of a highway project will be used in the risk assessment module to simulate Net Present Value (NPV) under different situations. Comparative study and sensitivity analysis will be conducted based on the results from MATLAB program, and will provide suggestions on development of optimal risk management strategy for different stakeholder respectively. With cost-benefit analysis of different risk management measures, based on the respective dynamic financial demand for concessionaire, optimal catastrophic risk management strategies may be developed for concessionaire and government respectively.

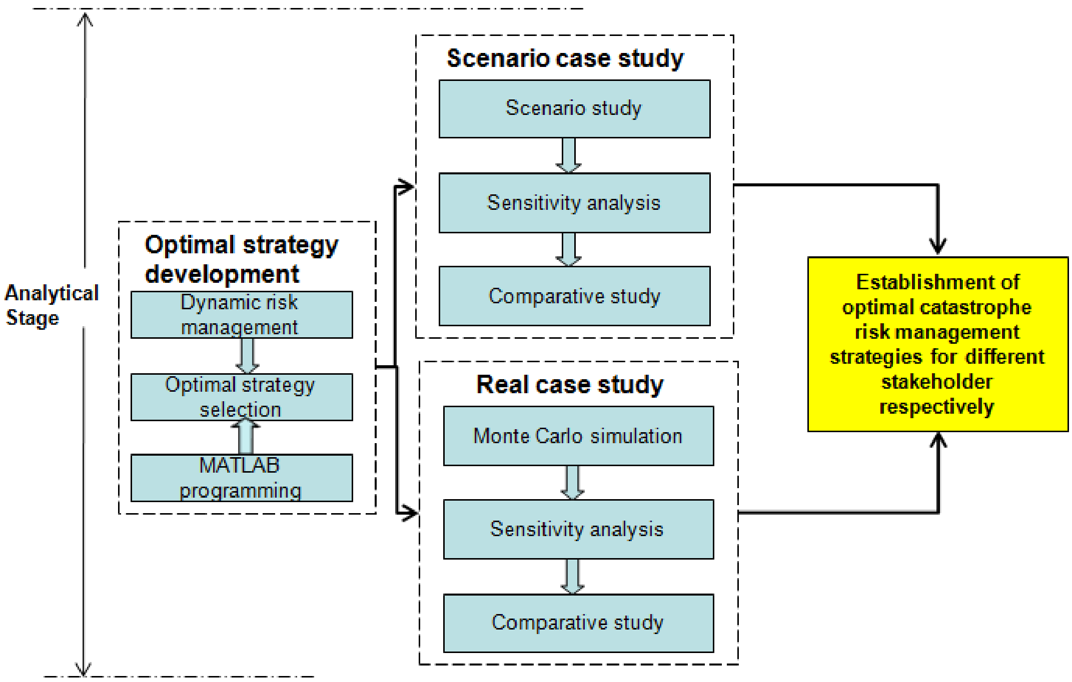


Figure 3.1 The Overall Research Methodology

3.2 Analytical Stage

In order to achieve the target of bridging the gap between the current research findings, an integral catastrophe risk model for infrastructure projects under PPP schemes including hazard module, vulnerability module and loss module will be set up. Catastrophic risk management strategy will be developed based on the result derived from catastrophe model. Case study, comparative study and sensitive analysis will help guide, verify and enrich the final strategy development.

3.2.1 Scenario Case Study

A scenario case study completely based on assumptions of different scenarios is conducted to compare the effects of 3 various mitigation strategies. Since dynamic risk management is introduced to improve efficiency of catastrophic risk management, scenario case study is also used to evaluate the merits of dynamic risk management. Two types of project managers who run after profit maximization and efficiency maximization are taken into account at the same time. Sensitivity analysis is conducted to show the relationship of different variables and value of dynamic risk management, hence provide suggestion to the two types of project managers on the adoption of dynamic risk management.

3.2.2 Real Case Study

Real case study is based on a real highway case which comes from a past case study that the author participated in. In the real case study, with a view to reflect the stochastic properties of occurrence of earthquake, MATLAB program based on cash flow model is introduced to simulate the impact of earthquake on the PPP infrastructure projects. Sensitivity analysis and comparative study will be utilized to analyze the results. Since this research is from management's perspective and the loss estimation is based on assumptions, the absolute number of the cash flow model will be meaningless, while the changing trend will be used to guide the development of optimal strategies for different stakeholders.

3.2.3 MATLAB Programming

MATLAB allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages, including C, C++, Java, and Fortran. MATLAB programming is applied in this research to integrate the temporal uncertainty of occurrence of catastrophe events with the cash flow of the infrastructure projects. Monte Carlo method, a class of computational algorithms that rely on repeated random sampling to compute their results, is utilized to simulate the catastrophic impact on cash flow of the project through MATLAB programming.

What's more, since MATLAB can read and output excel file, MATLAB programming is also used in the derivation of optimal risk management strategy based on dynamic risk management.

3.2.4 Sensitivity Analysis

Sensitivity analysis is normally used as one type of supplementary tools to further analyze the results from model. In this research, it is conducted to evaluate the robustness of the results to key assumptions of the developed catastrophe model. After obtaining the estimated losses, sensitivity analysis can be widely used to provide suggestions of different risk management measures. For example, sensitivity analysis can be used to guide the negotiation with banks on debt repayment plan. It can also be used to find the most sensitive impact factor to improve efficiency of risk management. In addition, sensitivity analysis can be conducted both before and after catastrophe events.

3.2.5 Dynamic Risk Management

Dynamic risk management incorporates the element of timing into risk management. In this research, dynamic risk management refers to dynamic risk financing and dynamic financial demand with more focus on the latter. Compared with traditional static financial demand, dynamic financial demand is more efficient and more acceptable. Together with cost benefit analysis, dynamic risk management can be used for selection of optimal risk management strategy including risk mitigation and risk financing.

Chapter 4 Catastrophic Risks in the Context of Transportation Infrastructure

4.1 Introduction

Transportation systems are spatially distributed systems whereby components of the system may be exposed to different ground motions due to the same earthquake event. Consideration of the spatial dependence of individual components, connectivity, and flow through the network are necessary elements in the development of an earthquake risk assessment model for such systems. Although many risk assessment methodologies for highway transportation systems have been developed, most of them are primarily in relation to bridge retrofit prioritization, emergency response and post-earthquake recovery period activities from the earthquake engineering's point of view (Gordon ; Kiremidjian, Moore et al. 2001). As for the whole transportation system, some studies related to post-disaster effects on transportation networks have largely focused on modeling and analyzing network performance (Nicholson and Zhen-Ping 1997; Chang and Nojima 2001; Sohn, Kim et al. 2003) and in the evaluation of the significance and reliability of transportation links in a larger network (Wakabayashi 1996; Karaouchi, Iida et al. 2001; Li and Tsukaguchi 2001; Sohn, Kim et al. 2003; Sakakibara, Kajitani et al. 2004).

These methodologies outline similar frameworks for assessing disruptions to transportation networks, distributed damage in the network, restricted access to the damaged sections, as well as economic losses due to reduced traffic flow. The general procedure for assessing the consequences of a seismic event includes defining the system and region of interest, simulating a deterministic ground motion or probabilistic hazard, assessing the performance of individual components (bridges), assigning associated levels of functionality to the bridges and roads, performing a network analysis and simulated traffic flow, and assessing the losses. While this approach has many potentially viable and beneficial applications, it relies heavily on the availability and reliability of incorporated tools and data. In this research, the simplified risk assessment model is based on the assumptions of cash flow model about the hazard impact and recovery plan combined with different mitigation measures. It does not aim to obtain the accurate loss due to earthquake, and we are looking at the results from sensitivity analysis which provides information for catastrophic risk management strategy instead.

4.2 Mitigation Measures in PPP Transportation Infrastructure

Transportation infrastructure systems are spatially distributed complex systems that serve as emergency routes for evacuation, rescue, and recovery in extreme events. Among the engineered components, bridges are the most vulnerable structural components under earthquake conditions. The system performance could suffer extensive damage and functionality loss, as evidenced in past earthquakes and bridge collapse events. In the 2008 Wenchuan earthquake, the damage to the highway and road system was extensive and severe. The China Transport Ministry (2002) reported that a total of 24 highways, 161 national and provincial main roads, and 8,618 countryside roads were affected by the earthquake.

Despite the unpredictable nature of disasters in terms of location, time, and magnitude, seismic retrofit appears to be one of the effective mitigation methods for highway bridges. For example, in the 1994 Northridge earthquake, the highway bridges that had been retrofitted survived the earthquake even though some were within 100 m of collapsed structures. On the other hand, retrofitting highway bridges can be costly in terms of monetary and manpower resources especially after the construction has started or even been completed, e.g. M-2 (Mitigation after construction period). Mitigation strategy conducted before the construction period, e.g. M-1 (Mitigation in the first beginning of the project) is relatively easy to realize because no business interruption will be involved. Things will become more complex for mitigation conducted within or after construction period. This naturally raises a research question: How should limited resources be allocated to candidate facilities for retrofit so that the total loss of the highway project caused by future earthquakes is minimized? Several challenges need to be addressed in order to answer the above question. First of all, individual bridges should be considered as a whole system instead of being treated separately. Federal Highway Administration seismic retrofit manual (Werner, Taylor et al. 1999) states that retrofit decisions are made according to seismic hazard and the importance of individual components. The importance is mainly judged by the daily traffic volume that a highway segment carries, and some other subjective judgments such as its connectivity to critical facilities. However, individual components in a transportation system are actually not independent of each other. Any change in one component of the system may cause redistribution of the traffic and thus affect the traffic on other remote components as well. Therefore, a rigorous retrofit decision should be made at a system level, where a spatially distributed transportation system may be modeled as a network and the interrelations between different components can be captured by network flow theories. Such system issues are not currently considered in seismic retrofit practice due primarily to the lack of adequate system-based evaluation and decision tools. Another challenge in retrofit decision making is to cope with uncertainties that may be caused by random disaster events and seismic performance of highway bridges (Fan, Liu et al. 2010). Integrated efforts are needed from both earthquake engineers and project-based analysts. In this research, probabilistic risk assessment of individual highway bridges will be integrated with various mitigation strategies to produce effective retrofit decisions from a project viewpoint.

4.2.1 Loss Estimation With and Without Mitigation Measures

Retrofit costs increase as more bridges in the network are retrofitted, but less repair cost and loss from business interruption can be expected. However, even with sufficient budget, it is not necessary to retrofit all the bridges in the network due to the principle of efficiency maximization. In some cases, no retrofit may be better than complete retrofit. A cost-benefit analysis will be carried out to assess the various retrofit strategies.

There are three kinds of cost or losses addressed by the current cost-benefit analysis: bridge repair/reconstruction cost after an earthquake event, economic loss due to business interruption of traffic flow, and retrofit cost. The repair/reconstruction cost of damaged bridges is the direct economic loss. The loss due to traffic flow interruption is assumed to represent the indirect economic loss due to the dysfunction of the network in this preliminary economic analysis.

4.2.1.1 Loss due to Business Interruption

In order to define the network performance as a whole after an earthquake, a comprehensive index of performance is introduced. Some researchers Like Shinozuka (2000) may use “Drivers’ delay” as the index. This is defined as the increase in total daily travel time for all travelers, including commuters and commercial vehicles, caused by earthquake induced delays. Essentially, it is the difference between the total daily travel time for all network travelers on the damaged network and that on the original undamaged network. “Drivers’ delay” aims to incorporate the economic loss of the whole network which may fall beyond the project. In this research, interruption of traffic flow is utilized to be the index because it is from the project’s perspective.

$$TR = \sum_{i=1}^{T} (tr)_i (tv)_i \tag{4-1}$$

$$BI = \left| \sum_{i=1}^{T} (tr)_i '(tv)_i ' - \sum_{i=1}^{T} (tr)_i (tv)_i \right| \tag{4-2}$$

Equation (4-1) delineates the calculation of the toll revenue (TR) in the project lifetime (T), where $(tr)_i$ is the toll rate of the respective vehicle in year i, and $(tv)_i$ is expected traffic volume in year i. Thus the product of the two yields the total toll revenue for all vehicles on the highway in year i. The summation over the whole project lifetime yields the total toll revenue of the highway project. Equation (4-2) describes the calculation of business interruption (BI) due to earthquake occurrence. The notation in equation (4-2) is the same as in equation (4-1) with the exception that the primed variables denote the situation after earthquake occurrence, and the unprimed variables refer to the original free flow without earthquake events. Note that the toll revenue after earthquake events should be less than that of the original situation. Therefore an absolute value will be adopted for calculation of BI.

4.2.1.2 Repair Cost

Bridge repair costs are assumed to be proportional to the bridge's replacement value, depending on its damage state. The replacement value is estimated to be the product of the deck area and a unit replacement value. Unit replacement values will vary depending on the bridge's structural type, material and other factors. (Zhou, Murachi et al. 2004) The repair costs cannot be obtained before the earthquake occurrence, however some suggestions on the repair cost factors corresponding to different damage states are recommended by HAZUS99-2 (1999).

4.2.1.3 Retrofit Cost

Depending on the retrofit measure and bridge type, the retrofit cost per unit deck area is variable. Previous studies have shown that the single span bridges are highly resistant to seismic loading (Choi 2002), and therefore are not considered here. Four different bridge types are introduced here as an illustration, including multiple span continuous steel girder (MSC steel), multiple span simply supported steel girder (MSSS steel), multiple span continuous concrete girder (MSC concrete), and multiple span simply supported concrete girder (MSSSS concrete) bridges. All four classes are typically zero skew three span highway overpass bridges supported on multi-column bents. The non-seismic detailing considered is common of Central and eastern United States bridge inventories, such as having approximately 1% longitudinal reinforcement in poorly confined reinforced concrete columns, short seat widths and vulnerable high-type steel fixed and rocker bearings in the steel bridges (Nielson and DesRoches 2007; Padgett 2007). Past studies have illustrated that these bridges types are susceptible to damage to fixed and expansion bearings leading to potential span unseating, excessive ductility demands on non-seismically detailed columns, pounding between adjacent spans and between the deck and abutment, among other issues that may lead to potential inhibition of post-event bridge functionality and the need for repair or replacement (Padgett 2007).

In order to address the potential vulnerabilities of the multi-span bridges, five different retrofit measures are considered: steel column jackets, elastomeric isolation bearings, steel restrainer cables, seat extenders, and transverse shear keys. The combined used of seat extenders and shear keys, or restrainer cables and shear keys is also considered (Padgett, Dennemann et al. 2010).

4.2.2 Cost and Benefit Analysis

The benefit from retrofit is the sum of reduced repair/rebuilt costs for damaged bridges and avoided loss due to business interruption brought by traffic interruption, which is simplified as decreased amount of toll revenue in this research. If the ratio of the expected benefit to the expected retrofit cost is greater than 1, the measure is considered to be cost effective. The expected annual benefits of retrofit measures can be expressed as

$$B = \sum_{i=1}^{T}\Big(L\big(S_0|Q_i\big) - L\big(S_R|Q_i\big)\Big) + \sum_{i=1}^{T}\Big(L\big(D_0|Q_i\big) - L\big(D_R|Q_i\big)\Big) \qquad (4\text{-}3)$$

where T = project life;

L = estimated loss;

S_0 = system performance without retrofit;

S_R = system performance with retrofit;

D_0 = components' physical damage without retrofit;

D_R = components' physical damage with retrofit;

Q_i = earthquake occur in year i.

by modifying the formula in Chang (2000).

In this research, system performance is denoted by business interruption, and components' physical damage is defined as repair cost of bridges. Therefore, the first item in Equation (4-3) is the reduced loss due to traffic flow interruption. When the damaged bridges are gradually repaired, the system performance will get recovered. It should be noted that the traffic flow will not return to the original status before earthquake at once. There will be temporal postpone which will be elaborated in Chapter 7.

The second item in equation (4-3) is another benefit gained from retrofitted bridge components: reduced repair cost. The retrofitted bridges have enhanced fragility curves and will experience less severe physical damage, leading to lower expected repair costs given future earthquake events. The difference between the expected repair cost before and after retrofit is the reduced repair cost.

The expected retrofit cost depends on the assumed retrofit status of the bridges. Different degree of retrofit may have distinct performance. For infrastructure systems, some mitigations that may not be cost-effective from the perspective of the utility may be very cost-effective if societal impacts are considered. Cost-benefit analysis conducted by Zhou and Murachi et al. (2004) shows that retrofit status more than 50% shows a higher cost-effectiveness factor as large as 3.0. In this research, only 100% retrofit will be discussed for illustration.

4.3 Quantitative Analysis of Seismic Risk Assessment

Quantitative analysis of seismic risk assessment aims to integrate the impact of seismic risk with PPP cash flows. The basic cash flow model of a PPP infrastructure project usually captures the following characteristic components:

- Toll Revenue, TR (usually comes from user charges, tariffs specified in a Power Purchase Agreement)
- Initial engineering and construction costs, CAPEX
- Annual operating and maintenance costs, OM
- Major replacement and/or expansion costs, RE
- Debt drawdown, DB
- Interest and principal payments of debt, PI
- Taxes, TX

The impact of seismic risk can be superimposed onto the cash flow model and modeled as potential disruptions to the realization of this set of cash flows. In addition to the potential loss of revenues (TR) and any savings gained from non-occurring cost items during the period of disruption, there will also be recovery cost (RC) incurred during the recovery period (e.g. rebuilt costs). Savings gained from non-occurring cost items which are supposed to be incurred in the first place, such as cost and maintenance expenses (OM) that are not required to be carried while the infrastructure is being re-built.

NPV of the project is calculated based on the cash flow to the firm named as SPV in PPPs. The impact of earthquake, from the project's (concessionaire) viewpoint, can be quantified as follows:

NPV of the project from concessionaire's perspective without earthquake (NPV^0) =

$$DB+\sum_{t=0}^{a}\frac{-CAPEX_t}{\left(1+WACC\right)^t}+\sum_{t=a+1}^{T}\frac{\left(TR-OM-RE-PI-TX\right)_t}{\left(1+WACC\right)^t} \tag{4-4}$$

NPV of the project from concessionaire's perspective with earthquake (NPV*) =

$$DB+\sum_{t=0}^{a}\frac{-CAPEX_t}{\left(1+WACC\right)^t}+\sum_{t=a+1}^{T}\frac{\left(TR^*-OM^*-RE^*-PI^*-TX^*\right)_t}{\left(1+WACC\right)^t}-\sum_{t=b}^{b+c}\frac{RC_t}{\left(1+WACC\right)^t} \tag{4-5}$$

where t denotes the timing of the cash flow components;

$t = a$ marks the end of construction period;

$t = b$ denotes the year when earthquake strikes;

c denotes the duration of recovery period;

$t = T$ marks the end of the concession period;

r_e is required rate of return-on-equity;

* denotes the variable with seismic impact;

WACC is the weighted average cost of capital, assuming an optimal capital structure for the company.

So, the general financial impact (*FI*) due to earthquake can be denoted as

$$FI = NPV^0 - NPV^* \tag{4-6}$$

which is regarded as the basis of layered catastrophic risk financing.

Several points should be clarified further:

1. Obviously, different magnitudes of earthquakes will result in varying degree of damages to the structure. This may in fact lead to different recovery periods, and each scenario would bear a different impact on the cash flows of the project combined with the different vulnerability.

2. In Equation (4-5), it is assumed that the private concessionaire will shoulder the full cost of recovery *RC*. In practice, this is subject to the contractual terms, and the public sector will normally be obliged to share the burden. Infrastructure assets are closely linked to social and economic welfare, thus public sector may support a speedy recovery of the facility affected. Also, it has been assumed that the recovery period coincides with the duration of losing the usual revenue/cost items. Sensitivity analysis regarding adjustment of such items will be conducted to simulate the actual situation in chapter 7.

3. Equation (4-4) and (4-5) are set up from concessionaire's viewpoint. Similar equations can be derived from the other stakeholders' viewpoint. For example, an additional component to capture the economic value of the infrastructure component of the infrastructure facility (or the loss of it after an event) may be included from public sector's perspective (Ergonul 2005). Equity drawdown, dividend and preference shares redeemed will be taken into consideration for equity cash flow calculation.

4. One should realize that Equations mentioned above is deterministic in which the probability of earthquake occurrence is not reflected directly. The temporal uncertainty of earthquake occurrence can be modeled in a decision tree analysis or influence diagram with the annual cash flow components as the input, which may be easily realized through Monte Carlo simulation. This is illustrated in the influence diagram shown in Figure 4.1, which provides more details than the one appeared in Condomin et al. (2006).

5. In the following Figure 4.1, the "Earthquake" variable is a binary random variable whose value is 1 with a probability of occurrence derived from, say, the Poisson model, and 0 otherwise. The "Impact" variable would be equivalent to the term in Equation (4-6). This is related to the extent of damage, which in turn is related to spatial and magnitude uncertainty. For a simplified model, a specific magnitude may be assumed and the extent of damage/impact

can be narrowed to a few discrete scenarios. More sophisticated engineering models would link the "Impact" variable. In addition, the effects of Bayesian updating can be introduced (i.e. the future outlook of earthquake occurrence is constantly updated depending on what has happened this year). This can be achieved by introducing additional links among the "Earthquake" variables from one year to another. Alternatively, the temporal uncertainty of earthquake occurrence can be easily modeled through some kinds of simulations. Choice of models for damage state combined with the temporal uncertainty will decide the actual seismic impact on cash flow items, and it is based on assumptions in this research.

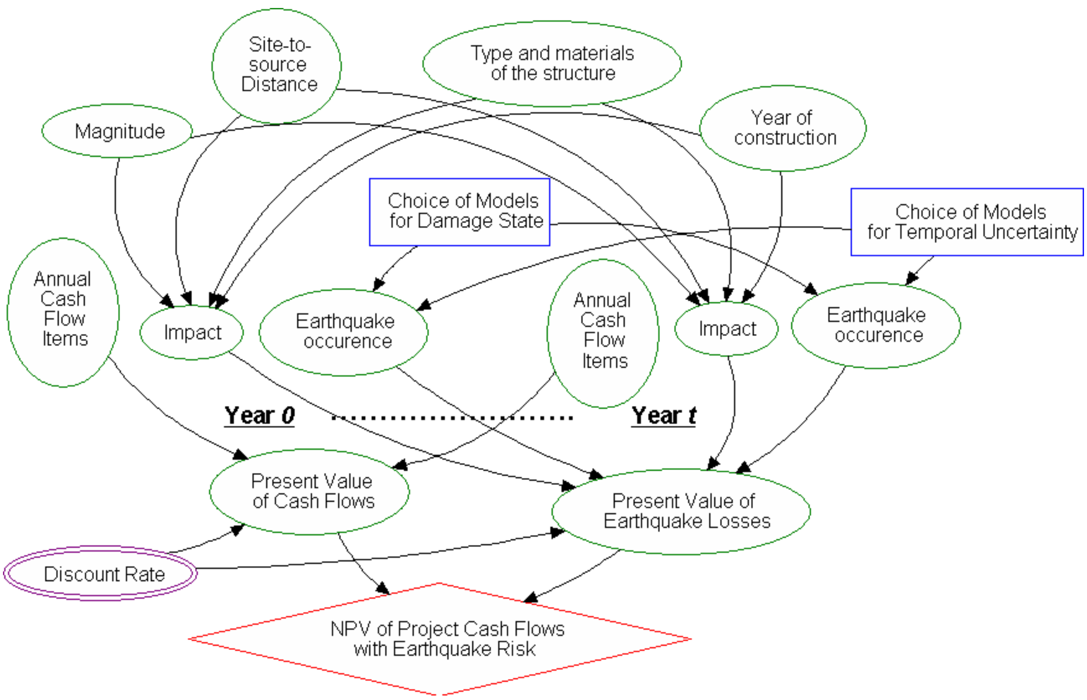


Figure 4.1 Influence Diagram for Analysing Financial Impact due to Earthquake

4.4 Summary

Present efforts mainly focus on buildings as the risk object, whereas models and data are more developed only for certain regions such as U.S., Europe, Japan and Australia. The exposure of the larger part of Asia is less understood, and the impact of catastrophic risk on infrastructure requires further quantification.

Incidentally, this larger part of Asia is mostly represented by emerging economies, whereby the PPP/BOT model is regularly explored as a potential project delivery mechanism. A pro forma cash flow model, set up according to the details of the concession contract, would form a useful basis for quantifying catastrophic risks and the associated financial impact for the project.

Chapter 5 Risk Financing Strategy for PPP Infrastructure Projects

Risk financing, the single largest class of risk management mechanisms, includes ex ante measures centering on risk retention and risk transfer, as well as ex post measures. Pre-loss or anticipatory financing includes all techniques/mechanisms arranged in advance of a loss. Some ex ante measure such as contractual arrangement does not need extra costs, while most other pre-loss financing measures generally involves an ex ante cost such as contingent credit, catastrophe bond and catastrophe insurance, etc. Post-loss financing, or financing arranged in response to a loss event, includes debt issuance, taxation, donor, and development bank etc. Though post-loss financing does not involve an ex ante cost, it may feature an ex post cost in the form of a higher cost of capital.

Figure 5.1 shows the layered catastrophic risk financing for the project. The lower layer is normally shared by the public sector including concessionaire, contractor, and supplier etc through contractual arrangement and reserve fund. The middle layer will resort to the financial instrument such as catastrophe insurance and catastrophe bond, etc. Normally such products are subsidized by government due to the special attributes of the PPP infrastructure facilities. The upper layer is absorbed by government since the loss level exceeds far beyond what the private sector can accept. Details of each layer are elaborated in each section as below.

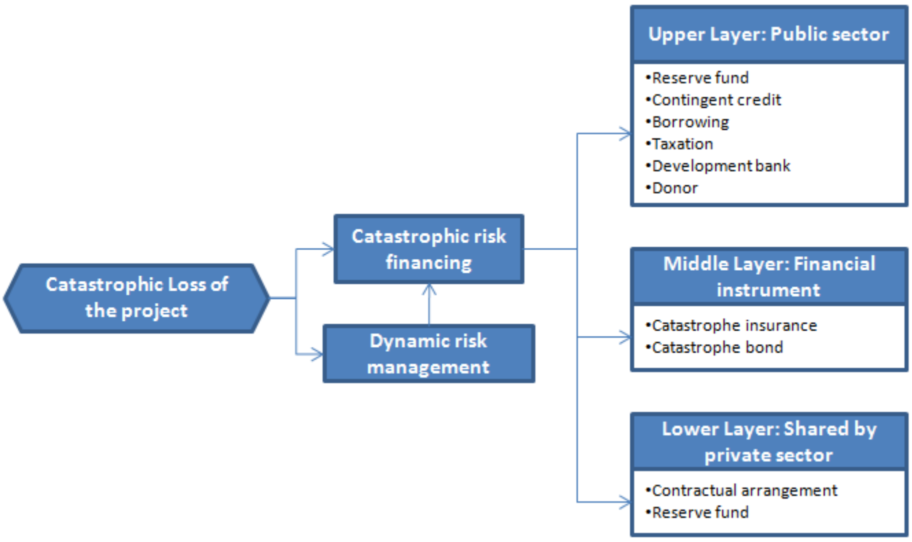


Figure 5.1 Layered catastrophic risk financing for the project

5.1 Risk Retention (Ex ante)

Risk retention, the first risk financing technique, can be passive or active. Passive risk retention occurs when the project preserves more exposure than it wants because it has failed to properly identify the nature and magnitude of its risks. Active risk retention is made before catastrophe events and the retained amount should be reasonable and acceptable.

5.1.1 Government

With increasing losses due to catastrophe events, Government becomes more and more vulnerable to natural disasters. The usual approach could simply be "wait and see", with the intention of arranging a loan after the occurrence of a disaster to finance reconstruction. While this is likely to be a reasonable strategy for much reconstruction, despite the potentially higher post-disaster cost of borrowing (Ozcan 2005), it is not appropriate for the financing of immediate post-disaster liquidity needs, such as the reconstruction of key public infrastructure such as bridges or hospital or the financial compensation of affected households, since arranging a reasonably priced loan in the aftermath of a disaster takes time (Ghesquiere and Mahul 2010).

Another approach would be to pre-fund a budget allocation or reserve fund, with government either borrowing or accumulating tax revenues to hold in liquid assets to act as a quick disbursement facility. For countries with large economies relative to the potential size of catastrophe loss exposure, a broad tax base and spatially well-diversified economic activities, it may make sense to retain some catastrophic risk while transferring to the reinsurance market the peak risk accumulations.

The amount of the total country risk retentions, however, should be subject to several important considerations. The first one is the country's ability to absorb the loss while avoiding long-lasting negative implications on its economic growth and fiscal performance, including its overall debt-borrowing capacity. While some states have access to substantial sovereign wealth funds which can be disbursed quickly in the aftermath of a disaster (Kern 2007), for many others there are significant political economy constraints on the size of such a fund in the short or medium term, limiting their ability to fully pre-fund post-disaster liquidity needs. Obviously, countries with larger economies that are not spatially concentrated in disaster-prone areas are in the position to be able to retain more risk. Although it is impossible to come up with a practical universal "benchmark" estimate for risk retention that would be suitable for all country situations, the experience shows that any loss in excess of 2% of the country's GDP can be quite disruptive, if not catastrophic (Gurenko 2004).

Another important consideration in determining the amount of retention is the rate of the country's economic growth, which decides its opportunity cost of capital. We can check the return of some other instruments (e.g. cat bond) with protection equivalent to the reserve fund in the cat bond market. If the rate of economic growth is more than the yield on cat bonds, the larger the difference, the more a country would be inclined to resort to risk transfer. Alternatively, a country with poor economic growth prospects may find it more advantageous to retain more risk. The country's ultimate risk retention decisions based on this approach, however, would still be subject to the fiscal and economic constraint respectively.

A more sophisticated explanation of countries' risk-retention decisions is based on the application of the modern portfolio optimization theory (Gurenko and Lester 2003). Using this approach, a country is viewed as a portfolio optimizer with the portfolio containing investments in the country's economic proxy index, as characterized by the country's main economic indicators, and catastrophe bonds, aggregately amounting to the country's total risk exposure to natural disasters. Each bond represents a unique layer of the country's catastrophic risk with different risk frequency/severity characteristics and the respective pricing for such a layer. The country's overall risk retention is then determined by the catastrophe bonds that are still left outside the government's portfolio after the portfolio has been optimized.

As Figure 5.2 shows, the risk financing strategy for government subject to restrictions on their budget allocation or reserve fund should include both risk retention through reserve fund and contingent credit and risk transfer through reinsurance and other instruments (Ghesquiere and Mahul 2010). The underlying theoretical model suggests a risk layering approach with reserve fund financing small losses and contingent credit and reinsurance providing additional financial capacity for moderate and devastating losses.

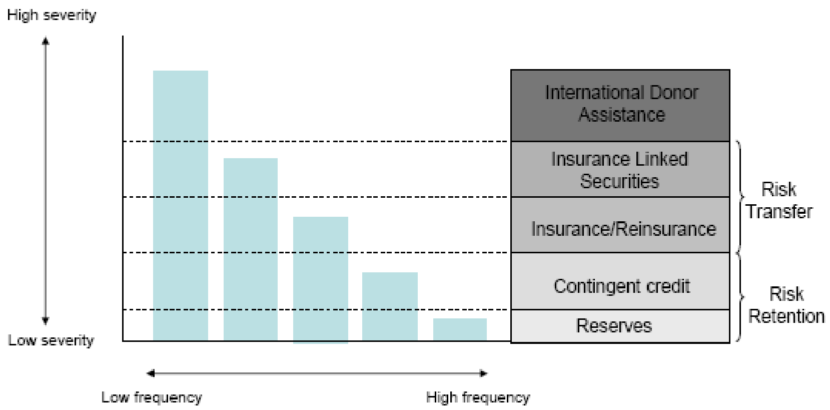


Figure 5.2 Risk Layering and Disaster Risk Financing Strategy

A government could arrange a line of credit in advance, to be drawn down in the event of a disaster. As for a commitment loan, the credit contract between lender and government would specify how the interest rate would be determined, maximum drawdown amount, the maturity of the loan, repayment schedule and how the loan could be put to use (Greenbaum and Thakor 2007). The contract could also specify that a loan could only be disbursed given the occurrence of a disaster. This could have either a hard trigger, as for reinsurance, or a soft trigger, such as the declaration of state of emergency by the government. Contingent credit with a soft trigger is similar to relationship banking since, although a government could trigger drawdown at any time, this would be costly and would harm their reputation with lenders (Boot 2000); by improperly declaring an emergency, government would essentially be swapping “relationship capital” for financial capital (Boot, Greenbaum et al. 1993). Compared with other instruments, contingent credit may be subject to fewer political economy constraints and enjoy more liquidity flexibility before the catastrophe events.

5.1.2 Concessionaire

5.1.2.1 Dynamic Liquidity Gap

Although losses due to catastrophic events may occur in a very short time, maintenance and reconstruction operation can spread over several years. That is to say, losses may be immediate, but the resulting financing needs can spread over a very long period. In order to develop more efficient catastrophic risk financing strategy for infrastructure projects, time variable need to be incorporated into the analysis. Identification of dynamic financial gaps between potential losses and the internal financial capacity is necessary for developing catastrophic risk financing framework for PPP infrastructure projects exposed to adverse natural events.

Dynamic liquidity gap is defined as the potential lack of funds for financing public expenditures at different periods after the occurrence of a natural disaster (e.g., short term, medium term, long term). With thorough analysis of potential liquidity gaps, an optimal catastrophic risk financing strategy including a combination of ex-ante risk financing instrument (including reserves, risk allocations, insurance, cat bond) and ex post vehicles (including negotiation with government and banks etc.) need to be developed to cover such gaps.

Dynamic financial needs come from recovery operation post disaster – recovery/maintenance period and reconstruction period. Recovery operation is crucial to limit secondary losses and ensure that reconstruction can start at earliest. It includes the removal of debris and conduct maintenance. Reconstruction operation centers on rebuilding the infrastructure assets damaged by a disaster. According to different magnitudes of catastrophe events, the damage of infrastructure assets may vary from minor to major extent. For minor damage, maintenance is enough and rebuilt is needless; both maintenance and rebuilt are necessary for medium damage; maintenance is useless and rebuilt is necessary for major damage.

The use of scenario analysis coupled with risk models can also help concessionaires better understand their potential needs over time. Table 5.1 provides an illustration of the difference in timing of financing needs resulting from recovery and reconstruction operations for a moderate damage.

Table 5.1 Estimated Timing of Financial Needs due to a Catastrophe Event

	Short term (1-3 months)	Medium term (3-9 months)	Long term (over 9 months)
Recovery operation			
Removal of debris			
Maintenance			
Reconstruction operation			
Rebuild			

An optimal risk financing strategy will ensure that funds are available at the appropriate time in a post disaster situation. A variety of instrument can be considered in the establishment of a risk financing strategy. These can be classified as ex-ante risk financing instruments such as the building of financial reserves, insurance, cat bond and/or other financial instruments, and post-disaster risk financing instruments including negotiation with other stakeholders involved in the project, etc. One should note that the risk financing strategy is established from the project's perspective which is not on behalf of concessionaire only, so that cat bond and contingent credit which are initiated by government and donor which normally goes to government will be also involved here to provide coverage for the catastrophic losses.

Table 5.2 provides a classification of risk financing instruments based on the availability of funds in the short-term, medium-term and long-term period following a catastrophe. The timing on the availability of fund is based on the experience of recent operations (e.g., Turkey, Mexico, Mongolia, and Colombia) and can vary depending on the economic and financial characteristics of a country (Ghesquiere and Mahul 2007). Projects which would rely solely on ex-post negotiation would face serious challenges in the financing of its recovery and reconstruction operations. Conversely, projects relying solely on reserves and insurance may be very well positioned to finance post disaster operations.

Table 5.2 Availability of Financial Instruments over Time

	Short term (1-3 months)	Medium term (3-9 months)	Long term (over 9 months)
Ex-ante financing			
Reserve fund			
Contingent credit			
Insurance			
Cat bond			
Ex-post financing			
Negotiation with banks			
Negotiation with government			
Donor assistance			

An efficient risk financing strategy should be designed based on the cost-benefit analysis of each financing instrument available in each phase of the post disaster operations. Ex-post disaster sources of funds will generally be cheaper than ex-ante instrument. Unfortunately, and as shown in Table 5.2, resources available through ex-post instruments are generally limited in the immediate aftermath of a disaster. What's more important, negotiation goes against what has been stipulated in the contract beforehand, which will result in inefficiency and negative attitude towards risk management. Government assistance should be the last resort of concessionaire depending on various contract terms. For an extreme devastating catastrophe event which may have stated in the concession agreement, it is reasonable to ask assistance from government, while for some catastrophe losses which are not so severe and have been allocated to respective party, post-disaster negotiation with government may imply one type of default by concessionaire. Therefore, the ex-post financing instrument is not advocated for establishment of an efficient risk management system for infrastructure projects.

5.1.2.2 Optimize Risk Financing Strategy

A first step in building an efficient risk financing strategy will consist in comparing estimated resource needs with estimated resource available in each phase of the post disaster operation. Figures on both sides of this equation will depend on the characteristics, and in particular the magnitude, of a potential disaster. Catastrophic risk modeling techniques and scenario analysis can provide estimates of potential needs that can be used to guide the project managers. Table 5.3 shows such exercise for a PPP infrastructure project exposed to a catastrophe event of medium size. For illustrative purpose, the matrix of resource availability is built for a 1-in-100 year event to assess the potential deficit in the various phases of the post disaster operations. A more complete exercise would include similar analysis for various return periods ranging from 20 to 500 years or more depending on the importance of the target.

We should realize that capacity of a project to absorb catastrophic risk may be limited especially when faced by a major disaster. Although a practicable and efficient risk management strategy should be established as required by the government when submitting the bidding documents, government assistance will still be the last resort to mobilize with disaster of greater magnitude.

Table 5.3 Resources Availability Post Disaster in Case of A One In Hundred Year Event (illustrative example)

US$ millions	Short term (1-3 months)	Medium term (3-9 months)	Long term (over 9 months)
Ex-ante financing			
Reserve fund	2		
Contingent credit			
Insurance		10	
Cat bond			
Ex-post financing			
Negotiation with banks			
Negotiation with government			2
Donor assistance			
Estimated total available	2	10	5
Estimated needs	6	30	17
Financial gap (surplus)	-2	-10	-10

When comparing estimated resource needs with estimated resource available in each phase of the post disaster operation, it is easy to find out the difference between resources needed and available at a specific time in the aftermath of a potential disaster event. Table 5.4 illustrates a more complete exercise where the analysis is done for various return periods. Such analysis can help project managers assess where the estimated liquidity demand would exceed the financial resources available at a given point in time after the occurrence of a disaster.

In this example, the short term resource gap is estimated at US$2 million, the medium term resource gap is estimated at US$10 million and the long term resource gap is estimated at US$10 million in the case of a 1-in-100 year catastrophe event.

Table 5.4 Matrix of Project Financial Vulnerability (illustrative example)

Dynamic liquidity gap (US$ million)			
Return period (years) of the catastrophic event	20	100	500
Short term (1-3 months)	-	2	20
Medium term (3-9 months)	-	10	50
Long term (over 9 months)	5	10	100

The understanding of potential liquidity gap based on timing at which resources will be needed can greatly influence the design/improvement of a catastrophic risk financing strategy aimed at reducing funding gap at a given period of potential post catastrophe events. One approach is to start with the most frequent events and gradually build up the financial capacity through risk management and financing strategy to an acceptable return period. The project managers will decide this return period based on the scenarios and internal financial capacity of the project.

Dynamic reserve fund may be consumed when catastrophe events occur. In order to ensure the implement of the optimal strategy, one important thing which must be secured is timely complement of reserve fund once there are catastrophe events. Without this premise, dynamic reserve fund cannot be realized. The financial complement may be accomplished by financial instrument such as insurance or cat bond if any. Financial strategies can easily be devised to limit the risk of liquidity gap post disaster. These strategies can be highly effective in ensuring that resources are available to finance post disaster operation when needed. A good understanding of the timing in the needs for resources can help optimize such strategy.

5.1.2.3 Layered Risk-transfer Portfolio

An example of a layered risk-transfer portfolio is illustrated in Figure 5.3. In this case, risk exposure of the project will be derived from the combination of catastrophic impact and physical vulnerability. After the risk exposure is combined with financial vulnerability of the project, dynamic liquidity gap can be developed.

This gap may result in resource deficit during recovery and reconstruction operation.

In Figure 5.3, the box with border in double line shows the risk financing strategy developed. The value of lower threshold and upper threshold can be set based on estimated losses due to catastrophe events of different frequency. For example, the lower threshold x will refer to loss from a catastrophe event of more frequency (e.g., a 1-in-10 year event), and the upper threshold y will refer to loss from an event of less frequency (e.g., a 1-in-200 year event). The estimated losses can be derived from catastrophe model based on historical data and simulation. Besides estimated losses, project's internal financial capacity is the other important consideration to decide the two thresholds.

As Figure 5.3 shows, in the lower layer, if losses are no more than x, the risk will be shared among those stakeholders (such as decreasing the dividend, extending the repayment period, decreasing the interest rate, postponing the delivery date, etc.) as contractual terms stated. Since factors, such as scope changes, poor contract documentation, unforeseen ground conditions, and contractual ambiguities are contributors of disputes (Love, Davis et al. 2011), clear documentation which identifies and allocates catastrophic risk properly are necessary to avoid the potential dispute as well as eliminate the default risk and secure recovery work. In the middle layer, if losses are no more than y and more than x, insurance and cat bond (other financial instruments may be involved) will be utilized to transfer risk. The upper layer covers losses which are more than y. Negotiation with other stakeholders such as banks and government will be helpful, and donor will provide assistance in the case of devastating disaster because infrastructure as pillar of the country is important for the national economy.

When examining the flow chart carefully, it is easy to find out that the three layers roughly coincide with the three types of liquidity gap. The lower layer is usually used to fill up short term liquidity gap. Medium term liquidity gap is mostly bridged through the middle layer. Long term liquidity gap is normally financed by the upper layer. It should be noted that financing of liquidity gap is connected to the three layers, but each type of liquidity gap is not strictly limited to the respective layer. For example, the short term liquidity gap is mainly financed by reserve fund and contractual arrangement, at the same time, insurance and cat bond may also work as complement. In the same way, insurance and cat bond play an important role for serving the medium term liquidity gap, however, when there is sufficient reserve fund or through reasonable contractual arrangement, medium term liquidity gap can also be filled up by the lower layer.

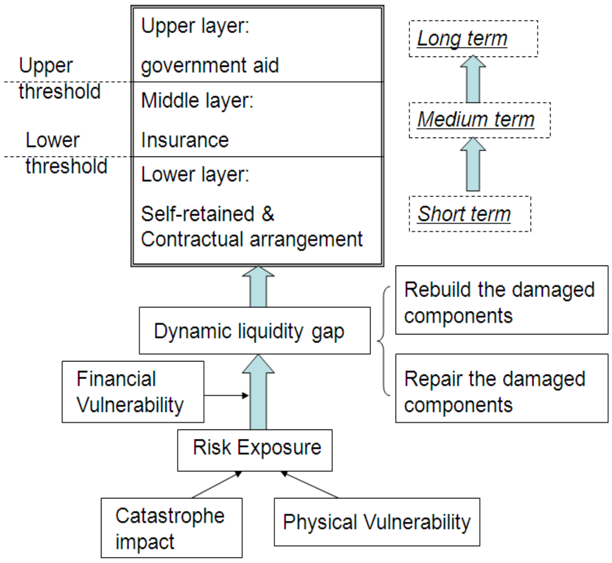


Figure 5.3 Layered Risk-Transfer Portfolio For Concessionaire

5.1.3 Derivation of EP Curve for Different Layers

One of the popular ways to determine what impact a catastrophic loss would have on the infrastructure projects is to construct an exceedance probability (EP) curve. For a given asset at risk, an EP curve is a graphical representation of the probability that a certain level of loss will be exceeded within a given time period. Special attention is paid to the “right-hand tail” of this curve, where the largest losses are situated. The catastrophic risk management is a multi-faceted approach that requires input from various stakeholders including private and public sectors.

It would be more useful for different stakeholders to make decision and develop strategy when EP curves are drawn separately for different layers as Figure 5.4 shows.

The three EP curves, derived from the traditional EP curve on the left hand, allocate quantified risk among respective layers. EP curves can be utilized to determine how much loss the respective layers would like to undertake, so that their total loss are unlikely to be greater than a pre-specified amount. Using these metrics, it is possible to make rational, informed decisions on how to price risk and determine how much coverage is needed based on an acceptable level of risk. Therefore, it will provide guide to develop efficient risk allocation scheme accordingly.

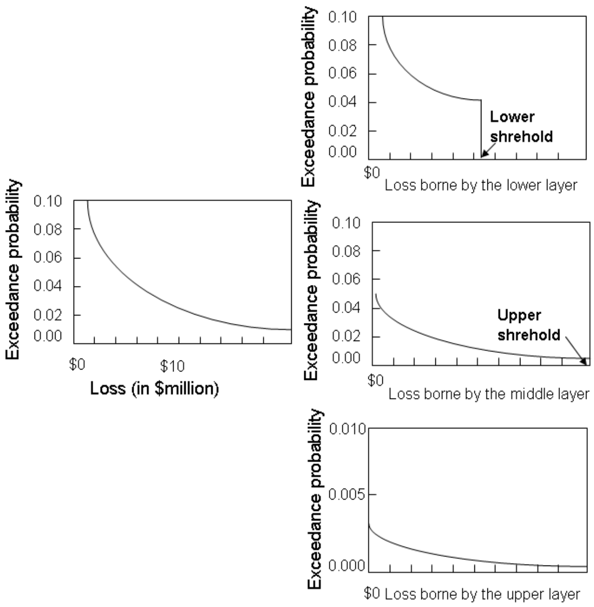


Figure 5.4 Exceedance Probability Curves for Total Portfolio and Different Layers

EP curves are derived from a catastrophe model. They may vary with some conditions vary. Suppose a specific mitigation measure is adopted on the infrastructure assets in seismically active area. One can then determine the impact that a loss-reduction measure will have on economic losses for earthquakes of different magnitudes and intensities by constructing two EP curves: one with and one without mitigation measure. Naturally, the EP curve with mitigation conducted lies below the EP curve without mitigation measures, as shown in Figure 5.5. This would provide incentive for insurance industry to encourage mitigation. The proper design of such incentive schemes is quite important for the implementation of mitigation measure if there are no compulsory requirements.

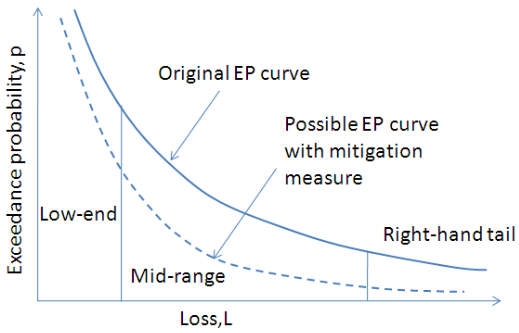


Figure 5.5 Exceedance Probability Curves with Mitigation Measure

5.1.4 Risk Allocation Mechanism

As is known, an equitable risk allocation mechanism among different parties is crucial to the successful implementation of the PPP projects. (Chan, Yeung et al. 2011) According to layered EP curves, risk can be assigned among all the involved stakeholders of an infrastructure project. Since catastrophic risk may bring disastrous losses to a project, all the parties involved will be impacted more or less, so the risk should be assumed by a suitable party who is in the best position to absorb or handle. Generally speaking, consideration should be paid to three critical factors: the ability to influence or control the risky outcomes; the ability to bear adversarial consequence resulting from the risk; and the incentive to bear the risk. These considerations lead to various principles of allocating risks as listed in Kerf (1998).

Li, et al (2005) has proposed a classification approach on the basis of three levels of risk factors for PPP/PFI projects. The three levels comprise: macro level risks; meso level risks and micro level risks. Catastrophic risk is categorized as force majeure at macro level risks which are sourced exogenously. According to Bing's questionnaire results, force majeure as macro level risk falls into the shared risk category (range: 61-77%) option. It is generally recognized that force majeure risk could be severe, but has a low probability of occurrence. The nature of this risk factor is such that public and private sectors may be not able to deal with it alone. Hence, a shared mechanism would appear to be the best option. In order to achieve value for money objectives in public project and service delivery development, the public and private sector partners need to reach a mutually acceptable risk allocation scheme before the contract is awarded (Bing 2005).

Al-Bahar and Grandall (1990) developed a systematic risk management approach for construction projects with the principle of risk sharing in PPP/PFI supported by Grant (1996) and HM Treasury (2000). Similarly, an adjusted risk allocation process for catastrophic risk is put forward as Figure 5.6 shows. In the proposed framework, the public sector identifies the potential catastrophic risk, sets out the risk relevant to each stage of the project, estimates the likelihood of occurrence for each risk event and evaluates the financial consequences. The private sector participants then receive tender documents which are complete with the risk factors, matrix or preliminary allocation framework. They will analyze the risk themselves, including risk pricing and the cost of managing the risk. If the bidding price is not acceptable by public client, negotiation may be necessary for risk reallocation. The government also has the option to award bidding with the best risk management strategy. The principle of risk allocation is that risk should be allocated to one who is able to control the risk and bear the risk at the lowest cost. Appropriate risk allocation can secure active risk management, while an inappropriate risk allocation may lead to passive risk retain which may result in abandon of the project. For example, if a risk is more controllable by party A, then party B will have greater tendency to allocate the risk to party A. If a certain risk event is uncontrollable by party A, with the increasing possibility of taking the risk, party A's tendency of risk handling changes from actively transferring the risk to passively retaining the risk. In contrast, if a risk is controllable and certainly allocated to party A, party A tends to take the initiative to reduce the impact caused by the risk event rather than retain the risk.

Catastrophic risk is allocated through contractual clauses when the contract is awarded. However, there may be different interpretations of risk allocation between the two parties. Disagreements may result from the absence of related contract clauses, unclear stipulations, or queries about the fairness of risk allocation. Since a clear, reasonable and appropriate risk allocation scheme is the premise of successful risk management, the government must clear contractual requirements, focus on key performance specifications to promote performance and minimize potential disputes due to catastrophe events as a guiding role. At the same time, the project manager requires expert analysis of all of the attendant catastrophic risk and then a structuring of the contractual arrangements prior to competitive tendering that allocates risk burdens among all the other stakeholders (i.e. bank, sponsor and contractor etc.) appropriately. Successful contract management which incorporates catastrophic risk management rests on prudent monitoring risk, an analysis of their changing impact on the project and the formulation of dynamic risk management plans.

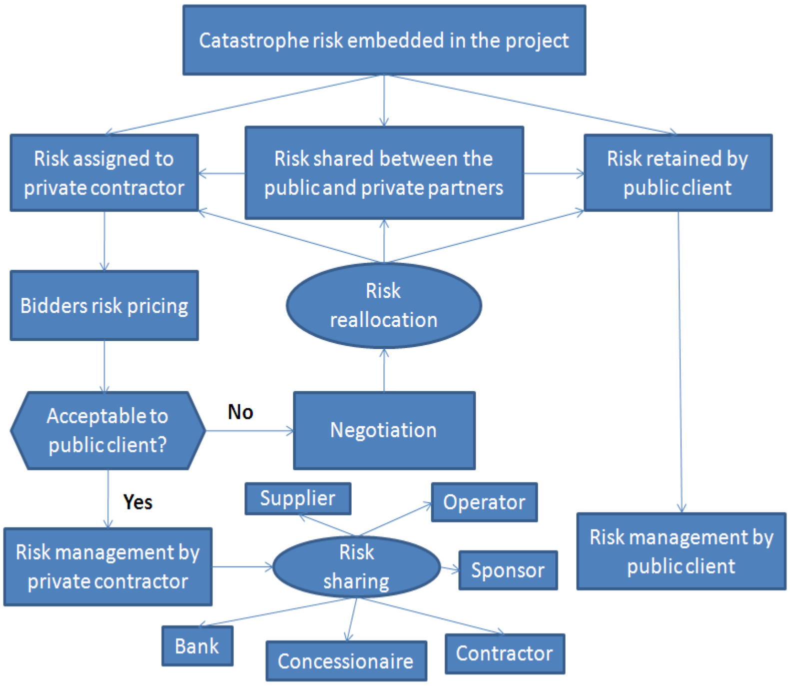


Figure 5.6 Catastrophic Risk Allocation Process in PPP Contract Procurement

5.2 Risk Transfer (Ex ante)

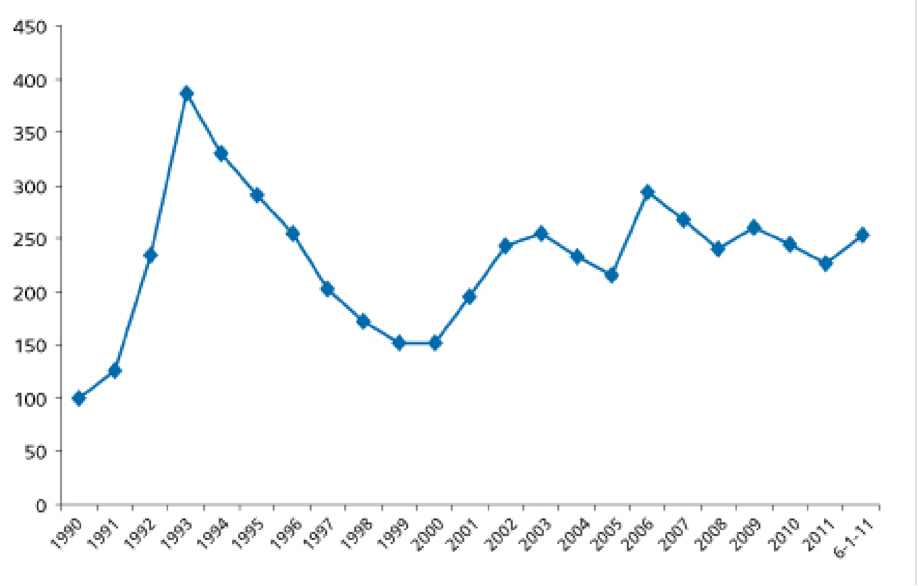
Risk transfer, a second form of risk financing, means the switch of risk responsibility between contracting parties in a project. Risk can be shifted to another party via some mechanisms such as insurance, cat bond, etc. Insurance means that parts of the financial losses resulting from risk events are compensated by insurance companies. It is one of the most important risk transfer instruments. However, it may not be available sometimes. Even though it is available, it may not be affordable for an infrastructure project. In this case, government involvement may be necessary given its public attribute.

5.2.1 Government Concern with Catastrophic Events

Government worries about catastrophe events because they trigger obligations to maintain the daily life of its citizens, so it is important to secure the normal function of the infrastructure assets which provide fundamental support for people's everyday life. Besides sudden funding requirements for emergency humanitarian aid, catastrophe events generate additional funding requirements to repair/reconstruct the built infrastructure assets and continue with disrupted infrastructure projects in progress.

A relatively risk-averse government may also wish to protect its infrastructure assets of wholly-owned features (including the PPP projects whose ownership will be transferred back to government after concession period) such as roads, schools, dams, electric utilities, and the telecommunications infrastructure, rather than self-insuring as most governments do. The government may in particular wish to assure liquidity immediately after a catastrophe event, given that it rationally anticipates that all liquid resources will be devoted to humanitarian aid and infrastructure assets, to assure that these existing assets can be recovered and ongoing projects can be completed in a timely manner and without extraordinary costs caused by interruption. Such possibility of either sudden or unexpected financial distress due to catastrophe, may lead to higher expected costs to complete such projects. Introduction of risk transfer instruments which provide funds to help aid the recovery and rebuilt process can greatly reduce such costs. The most basic risk-transfer instrument is insurance, where the policyholder pays a small premium in return for claim payments from the insurer should they suffer losses from a disaster.

Market-based insurance solutions for governments have experienced low appeal in the past because of the pronounced volatility of the global reinsurance market as Figure 5.7 shows, the lack of volatility hedging instruments, and the short-term nature of reinsurance contracts (Loh 2005). As a result, when and if countries do decide to act, most of them are better off opting for catastrophe insurance pools, which act as efficient intermediaries between the ultimate consumer and reinsurance markets. Due to the reinsurance pricing volatility, the pools need to accumulate sufficient funds to be able to smooth the domestic cost of risk transfer by varying the level of local risk retention.



(Source: Guy Carpenter & Company, LLC (2011))

Figure 5.7 Guy Carpenter Global Property Catastrophe ROL Index

5.2.1.1 Catastrophe Insurance

Private insurance industry is limited in its ability to finance catastrophic risk. Insurance is best suited to cope with independent non-correlated risk. The law of large numbers is the mainstay of insurance. The larger the pool of independent risks in an insurance pool, the lower the variability of risk. Private insurance passes through this reduced cost of risk to its policyholders. However, catastrophic risk is a highly correlated risk. Once catastrophe happens, a large area may suffer great damage. Almost all the people and buildings in the area will be impacted without exception. The pooling of correlated risk increases the variability of risk which implies the exact opposite of the law of large numbers. As a result, the natural advantage of private insurance is lost. Although private insurance has developed techniques to cope with correlated risk, the costs of the private solutions are expensive.

What's more, the private insurance normally disregards the infrastructure assets which are considered as public assets. As a result, if the government wants an insurance program to cope with catastrophic risk especially for infrastructure assets, some form of government involvement is needed to control the costs, or at least keep the cost manageable.

Government natural hazard insurance programs take two forms: government acting as insurer and government acting as reinsurer. Government as insurer means that government assumes direct liability for losses without sharing by private insurance sector. Spanish program and National Flood Insurance Program in United States follow such rules. The program is meant to supplement gaps in private insurance. Government as reinsurer means that government provides financial support to the private insurance market. Private insurance industry may be required to retain some risk (Japan) or can voluntarily retain risk (France). Both approaches tend to rely on private sector to provide necessary administrative support (Office 2007). Some commission fee need to be paid for providing such service. These programs were created because homeowner coverage for catastrophic events is often not available from private insurers at prices deemed affordable by insurance regulators. Large losses associated with natural catastrophes are some of the biggest exposures that insurers face. Particularly in catastrophe-prone locations, government insurance programs have tended not to charge premiums that reflect the actual risks that homeowners face, resulting in financial deficits. After a resource depleting disaster, the programs have post-funded themselves through, among other sources, payments from insurance companies and policyholders and appropriations from state and federal taxpayers.

As figures in Table 5.5 shows, to date, 13 government sponsored national catastrophic risk management programs have been established and operated successfully in 25 countries, once 16 countries of Caribbean region participating in the CCRIF and take into consideration. Each of these programs emerged following highly devastating natural disasters to address the subsequent inability of the local insurance market to provide affordable catastrophe insurance coverage of a specified peril (Gurenko, Itigin et al. 2008).

Table 5.5 Government Sponsored Catastrophe Insurance Programs

Country	Institution	Cover	Type
Algeria	CCR	EQ	PPP
France	NatCat/CCR	EQ/FL/WS/LS/S	PPP
Caribbean region	CCRIF	EQ/WS	PPP
Japan	JERe	EQ	PPP
New Zealand	EQC	EQ	PPP
Norway	Norsk Naturskedepool	WS/FL	PPP
Spain	Consorcio	EQ/FL/WS/LS	PPP
Taiwan	TREIP	EQ	PPP
Turkey	TCIP	EQ	PPP
US (CA)	CEA	EQ	PPP
US	FEMA	FL	PPP
US (FL)	Citizens	WS/FL	Public
US (FL)	FHCF	WS	Public

Notes: EQ-earthquake; FL- flood; WS – windstorm; LS – landslide; S – subsidence; PPP – public private partnership.

When looking at Table 5.5, it is easy to find out that countries exposed with low levels of risk tend to have broader based programs, while countries exposed with high level of risk tend to have programs that focus on the particular risk. All of these government sponsored catastrophe insurance programs listed in Table 5.5 mainly cover residential buildings, while public infrastructure assets are not taken into consideration in such schemes. There is still a lot of work to do to incorporate infrastructure assets in the national catastrophe insurance programs. The following suggestions will be given according to lessons drawn from some of the government sponsored insurance program.

- Participation. Catastrophe insurance will be compulsory for all the infrastructure assets including built assets and ongoing projects within the sovereign domain.
- Risks covered. The program should provide earthquake (and earthquake initiated hazards such tsunami, landslides and fire) coverage at the earliest opportunity, as fast as a program can be practicably created. Flood, wind and

other natural hazard covers are dependent on the development of technical data, and will be added in a timely manner on a schedule to be specified by the government.

- Policy terms and conditions. Coverage will be provided for structural damage. Business interruption is not incorporated in the scheme due to huge moral hazard.
- Risk rating. The premium should be based on the respective risk. Risk-based premiums create the proper incentives for the policyholders to take actions to mitigate the underlying risks, and try to avoid location-based risks if possible.
- Risk underwriting. The compulsory insurance policies will be issued by participating insurance companies and backed by the government. The program will act as a national aggregator of catastrophic risk acquired from the sales of compulsory insurance policies. All aspects of the program's management and insurance operations will be outsourced to the private sector. The program will be managed by a professional insurance services company hired through an open tender.
- Claims settlement. Property damages in the aftermath of natural disasters will be adjusted by participating insurance companies.
- The role of government. The key elements of government participation include introduction of special catastrophe insurance legislation, enforcement of the compulsory insurance requirement as well as provision of a backstop contingent capital facility to the program to ensure its solvency in case of highly unlikely catastrophic events.
- Initial reserves. Previous experience in setting up insurance pools shows that there is a need for initial capital in the pool to make it financially sustainable in the long run. The lack of sufficient risk seed capital exposes the pool to reinsurance price volatility, thus affecting the stability of the insurance

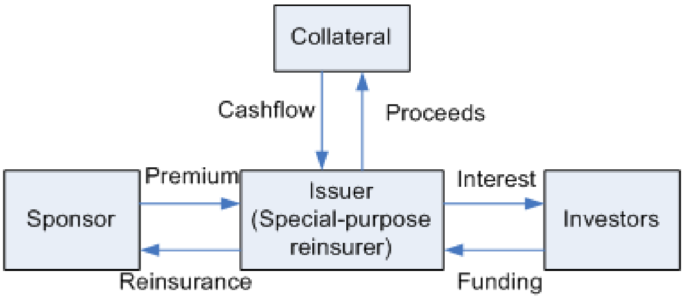
premiums. The CCRIF has been seeking donor contributions to finance the Facility's initial reserves and its operating expenditures for the first years of operation.

- Need for transparency. The catastrophe reinsurance market includes a very limited number of players, making this market opaque accompanied with information asymmetric. This lack of transparency is to the detriment of the client countries. The CCRIF has developed country-specific catastrophe risk models to allow for the pricing of catastrophe insurance products. The CCRIF has also explored several avenues for the transfer of risk, including the role of the World Bank Treasury as a financial intermediary.
- Critical business volume. A minimum amount of business is required to access the catastrophe insurance market on competitive terms. As of August 2011, there are 16 participating countries in the CCRIF.

5.2.1.2 Catastrophe Bond

Unless the government has large reserves to cover all the losses, besides insurance, it may also want to purchase some type of risk-transfer instrument that can take the form of an insurance-linked security, more commonly known as catastrophe bond, in case of unavailability and/or high premium of insurance.

Catastrophe bond (cat bond) is one of the most popular financial instruments for catastrophic risk transfer. The standard structure of cat bond is shown in Figure 5.8. Sponsor establishes special purpose reinsurer (SPR) as issuer of bond and as source of reinsurance protection. Issuer sells bond to investors, and proceeds are invested in collateral account for further reinvestment. Sponsor pays premium to issuers which together with bond proceeds investment are source of interest paid to investors. If a named qualifying event occurs, the collateral account withholds interest and/or principal payments temporarily or permanently and paid to sponsor. At maturity, remaining principal or if there is no event, 100% of principal is paid to investors. There are two classes of cat bond: indemnity cat bond and index cat bond. Indemnity bond base contract threshold payouts on the issuer's own loss experience. Index-based catastrophe bond use indices including parametric trigger, industry-loss trigger and model-loss trigger.



(Source: Lane Financial LLC)

Figure 5.8 Basic Catastrophe Bond Structure

A cat bond requires the investor to provide money upfront that will be used by the project if some type of triggering event occurs. In exchange for a high return on investment, the investor faces the possibility of losing either a portion or its entire principal investment. The amount paid to the issuer depends on how the cat bond is constructed and the nature of the disaster. Notably, the issuer does not face any credit risk from the cat bond: the money to pay for the losses is already in hand.

Catastrophe bonds can be divided to following four types of triggers underlying the bond structure.

- Indemnity trigger - payouts are based payouts are based on the actual losses of the sponsor.
- Pure parametric trigger - payouts are triggered by actual reported physical events (e.g., wind speed of hurricane, magnitude of earthquake, etc.).
- Industry loss index trigger - payouts are triggered by an estimate of industry losses.
- Modeled loss trigger - payouts are determined by inputting parameters of the

catastrophe events into a predetermined and fixed model to calculate losses.

Investors have stepped away from indemnity catastrophe bonds and gravitating toward non-indemnity bonds (industry loss index, parametric and modeled loss catastrophe bonds) due to unexpected basis risk. Basis risk, in the context of catastrophe bonds, generally reflects the possibility that a catastrophe bond may not be partially or fully triggered (for covered perils) even when the sponsor of the catastrophe bond has suffered a loss. In this case, many of the cat bonds issued today are tied to a disaster-severity index (e.g., covering damage from a certain earthquake magnitude event within a specified region) rather than to actual losses. Since these parameters are normally independent of actual losses, payments can be made immediately after the disaster occurs.

However, it must be noted that some risks such as tail risk, basis risk, model risk, and moral risk are inevitably remained in the cat bonds. What’s more, the issuers of CAT bonds often state that this securitization is very costly, and investors are reluctant to purchase catastrophe-linked securities despite the offered attractive premiums, which are sometimes more than 500 basis points over the LIBOR (Froot 2000). The lack of liquidity and relative novelty may have substantially contributed to this high premium demand. The highly risk-averse behavior raises the question whether the problem is about the current offerings or whether there are some psychological barriers associated with the risks of catastrophe-linked securities (Croson and Kunreuther 2000). The ambiguity aversion of the investors is one of the behavioral barriers that remarkably increase the cost of catastrophe-linked securitizations. The investors demand higher spreads if there is significant ambiguity associated with the risk, which is often the case with the natural hazards. Further, investors may overweight small probabilities (i.e., statistically rare events like catastrophes). Several studies showed that for two alternative investments having the same expected loss values, preference is given to a sure small loss rather than a very small chance of a relatively large loss (Rode, Fischhoff et al. 2000). Typically, investors are reluctant to invest the effort and time required to understand the potential risks of the new securities.

In addition to psychological barriers, cat bonds also have prohibitively high premiums. Contrary to the reality, cat bonds are often considered as only weakly correlated with market risk implying that the price of such securities should include only small risk premiums. But, as market data show, cat bonds which have been issued offered a substantial premium above the risk free rate (Bantwal and Kunreuther 2000), probably to attract investors to this new kind of investment. Furthermore, for the few deals that have taken place, transaction costs obviously have been quite high.

After weighting the strength and weakness of cat bonds, one can expect, however, that the cost of issuance will significantly decrease as the market gets more experienced in this field and the degree of standardization of such products increases (Nell and Richter 2004). And with the costs cutting down, cat bonds will become more and more popular.

The notion of securitizing catastrophic risks became prominent in the aftermath of Hurricane Andrew (Froot 1999). Giant insurance companies such as AIG, Hannover Re, St. Paul Re, and USAA completed the first experimental transactions in the mid-1990s. An immediate huge market then followed: $1–2 billion of issuance per year for the 1998-2001 period, and more than $2 billion per year following the September 11, 2001 terrorist attack and approximately $4 billion on an annual basis in 2006 following Hurricane Katrina. This market continued to grow rapidly through 2007 because a number of insurers sought diversification of coverage through the market (Freeman and Pflug 2000). In 2010, cat bond issuance touched $5bn, its third-highest annual total, according to data from Swiss Re. And the catastrophe bond market could witness $6bn of new bond issues in 2011 according to a report by Willis Capital Markets & Advisory (WCMA) (Willis 2011).

A number of countries such as Mexico, USA, California and Japan etc. have employed catastrophe bonds and insurance-linked securities as ways to protect themselves against the costs of a major natural disaster. If we check out "Catastrophe Bond & Insurance-Linked Securities Deal Directory", there are two cat bonds transactions with government involved as of August, 2011 as Table 5.6 shows (2011).

Table 5.6 Latest Catastrophe Bond and Insurance-Linked Security Transactions

Cedent	Placement Agent	$	Coverage Details	Date
USAA SPV: Residential Reinsurance 2011 Ltd.	Goldman Sachs and Swiss Re Capital Markets are acting as joint structuring agents and joint book runners. AIR Worldwide will be performing risk modelling and reset duties.	$250m	Residential Re 2011 will provide USAA (and certain subsidiaries) with cover for a portion of their U.S. hurricane, earthquake, severe thunderstorm, winter storm, and wildfire exposure over a four year term with maturity expected in June 2015.	May '11
California Earthquake Authority SPV: Embarcadero Re Ltd.	Deutsche Bank Securities are sole structuring agent and bookrunner. AIR Worldwide are providing risk modelling services.	$150m	Embarcadero Re Ltd. is designed to provide the CEA with indemnified risk transfer for a layer of their state of California earthquake risks via a reinsurance agreement on an annual aggregate basis over a three-year risk period. It covers only earthquake shake risks, not other perils often associated with quakes such as tsunami or fire following. Only residential property is covered through this deal as the CEA does not provide commercial insurance. The deal is expected to close in August 2011 and mature in August 2014.	Aug '11

Cat bonds have been utilized by a number of countries such as California, Mexico and USA etc. to transfer catastrophic risk, and some more countries are very interested of issuance of cat bonds. According to the news (2011), in May 2011, Ministry of Finance Division officials suggested that China should try to issue catastrophe bonds to transfer catastrophic risk, ease the financial burden, and promoting the re/insurance and capital market development. The Financial Secretary recommended using the state owned insurance agency as a sponsor of a catastrophe bond pilot scheme. The frequent typhoons in eastern coastal areas should be regarded as the first priority, and Midwest earthquake, snow, floods, droughts and other natural disasters then would be considered to be covered by the scheme. Given the popularity of cat bonds among governments, infrastructure assets are never involved in any of the existing cat bonds schemes.

If we examine closely infrastructure projects, we will find that the government is the owner of these projects (after concession period for PPP infrastructure projects), and the only buyer of cat risk protection. It may be hard to find a third party which has an obvious insurable interest in such projects. The government can thus be regarded as having 100% market share in insuring its infrastructure. Therefore, it is easy to conclude that government may have much more interest in issuing cat bond for infrastructure assets compared with insurers and reinsurers and private sectors.

The 100% market share would seem to offer an opportunity to design a countrywide cat bond with low basis risk, as catastrophe-related damage to the entire country would correlate well with catastrophe-linked damage to countrywide projects. A portfolio of similar projects (e.g., a highway system) spread evenly nationwide could thus be protected by a country-level index instrument. Geographical dispersion of a highway system prevents the asset from being totally destroyed by a local phenomenon (such as a flood or earthquake). It becomes a form of built-in diversification and resistance to catastrophic damages from geographically concentrated risks from an individual project's perspective. For some countries such as China, which incorporate such extremely large and diverse geographic scope, it may be difficult to define appropriate triggers for such catastrophe-related instruments on a national scale. What's more, the infrastructure projects, even though geographically widespread, are not sufficiently uniformly subjected to or affected by disaster for national coverage to be a good proxy for project coverage. Thus, the geographical dispersion makes it a challenge to design an instrument to protect the asset without introducing massive basis risk.

Ideally, however, financial instruments to protect specific infrastructure projects would be designed project by project to incorporate customization both at the geographic level (insuring against the appropriate hazards) and at the project level (generating the appropriate cash flows for reconstruction). Such project-by-project design is relatively simple to achieve for a project of limited geographical area such as a dam or a power station. At the same time, it would be very difficult to develop such project-based model for an infrastructure asset that, by its very nature, is geographically dispersed such as an electrical grid or a railway system. Such projects may be too widespread for general project coverage, yet not uniform enough for country-level coverage. In this case, some customized catastrophe model may be designed to calculate the losses of such infrastructure projects in order to decide premium of cat bond more accurately.

5.2.1.3 Other Financial Instruments

Given an estimate of financial vulnerability of the project, appropriate financing strategy consisting of different financing instruments need be developed to transfer risk. Catastrophic risk financing instruments can ensure availability of funds during the aftermath of catastrophic events and sustain the operations of the facility or system.

Besides cat bond, there are many other types of catastrophe derivatives such as catastrophe-related exchange-traded derivatives and over-the-counter (OTC) derivatives, etc. Naturally, derivatives also have certain costs/disadvantages, and some of them would be 1) coverage of non-standard risks through the exchange-traded market is very limited; 2) liquidity for contracts on non-standard risks is minimal and bid-offer spreads may be very large, adding to the cost of risk management; 3) basis risks can be significant, resulting in imperfect risk hedges; 4) credit risks for certain OTC transactions can be large (Banks 2005). In this research, only cat bond is discussed, and other types of derivatives may be involved in future study.

5.2.1.4 Catastrophic Risk Financing Mix

Two important alternatives for covering catastrophic risks discussed in this research are catastrophe insurance or buying index-linked coverage (cat bond). Evidence shows that combining the two hedging tools might extend the possibility set and by that means lead to efficiency gains (Nell and Richter 2004).

Clearly, the demand for indexed cat bonds can only be explained by imperfections in the reinsurance market, since these bonds always result in a basis risk for the cedant. Doherty and Richter (2002), introduced a model to formally address the attractiveness of a joint use of insurance and index-linked coverage. Insurance can be used to insure the basis risk, which means the policy holder can purchase a separate policy, called gap insurance, to cover the difference between the index-linked coverage and the actual loss.

It is shown that there are strong interdependencies, because both means influence each other heavily with respect to their efficiency. Index-linked coverage causes a structural as well as a quantitative effect on the demand for insurance. Insurance coverage for large losses will be substituted by index-linked coverage, since both effects point in the same direction. However, for small losses the result is ambiguous, since the negative quantitative effect on the demand for insurance may be dominated by the positive structural effect (Nell and Richter 2004).

The design of two different catastrophic risk financing mix is to fill in the financial gap of infrastructure projects due to catastrophe events efficiently. The interaction of them is complicated. The coverage of the two different instruments is one of the most important considerations, but it is not the only concern. Moreover, many other factors such as the transaction costs, moral hazard and default risk would be important to be taken into account.

The mixture can be priced the same as insurance, with greater profits for the insurer and resulting protection for the infrastructure assets, or the mixture can be priced lower than insurance, providing the infrastructure assets with lower costs of protection and the insurers with profits similar to or greater than for insurance.

5.2.2 Concessionaire Concern with Catastrophic Events

Except for the contractual arrangement which may ask for sharing risk among the stakeholders involved in the project, the natural reaction for the project manager is to utilize insurance. However, the growing scope of impact means that there is simply not enough insurance-based capital to provide coverage for all of those seeking protection and it may be not cost effective. Accordingly, alternative solutions must be factored into the process, including ex ante measures such as loss control/mitigation, loss financing via capital markets securitizations (only cat bond is involved in this research for illustration), and ex post measures such as ask for government/public funding (and/or donor if necessary).

As for infrastructure projects, risk transfer is challenging for project managers and other stakeholders involved. It is not only due to the difficulty of the quantification of the exposed risk but also the restrictions of the various risk financing instruments.

5.2.2.1 Catastrophe Insurance

Insurance cannot reduce the level of death, injuries, damage and financial losses, but it does provide readily available cash to cope with these at a time of extreme stress, and by just doing this can significantly cut down the recovery period and thereby reduce disruption of normal operation.

By arranging such ex ante sources of risk financing as insurance, PPP infrastructure projects will be able to access liquidity immediately following natural disasters. In addition, such insurance arrangements are likely to result in considerate improvements in projects' overall risk management, subsequent reductions in their financial vulnerabilities to natural disasters in the long run and improved prospects for investment.

Yet, despite clear advantages of insurance as a source of disaster funding, countries remain to be severely underinsured especially for PPP infrastructure projects. It's estimated that there was over $250 billion of economic loss world-wide associated with catastrophes in 2010—only $38 billion of it insured (Penland 2011).

As mentioned in last section, government will be actively involved in catastrophe insurance provided for PPP infrastructure built assets and ongoing projects. What's more, it should be compulsory for such projects to be insured so that all the infrastructure assets can be covered.

In general the availability of insurance does not reduce the damage losses from disasters, its primary contribution being to reduce the financial stress associated with coping with these losses and to facilitate the recovery and rebuilt from disasters. Indeed instead of acting as an incentive to disaster reduction it can be a disincentive as the ready availability of insurance can lessen the pressure on the project to take effective mitigation measures (Walker 1995).

Direct incentives to mitigation through insurance systems are commonly advocated as a significant tool for mitigation of disasters. One form of direct incentive is the use of risk rated premiums which take into account the standard of construction relevant to the risk at the location of the property. This is a more complex form of the schemes described above, but because it does not preclude insurance cover, it can be used in association with compulsory schemes. An example is the new Turkish Catastrophe Insurance Pool (TCIP) which is a compulsory scheme with differential premium rates, depending on construction standard and zone, for the same level of cover. The primary purpose is probably to encourage new construction to be built to the highest standards, but it may also provide some incentive for retrofitting to meet the higher standards, and therefore lower premiums. However there seems to be a general reluctance of homeowners to bear the upfront cost of retrofitting with the promise of eventually recovering it from the reduction in premiums. To overcome the latter problem the California Earthquake Authority (CEA), which runs the Californian earthquake insurance scheme for dwellings and also has risk rated premiums, provides a grant towards the cost of retrofitting. However it is understood that even with this additional incentive there has not been a great deal of retrofitting.

Greater success appears to have been made in Florida where by State law insurance companies are required to provide hurricane wind cover as part of standard home insurance. The premiums have to be approved by the Insurance Commissioner, and must incorporate differential premiums reflecting the use of different forms of risk reduction including shutters.

Traditional seismic design philosophy puts little emphasis on design solutions that go beyond legal and code-imposed requirements. However, as insurance cost can be a significant component of life-cycle costs for the facilities in hazard-prone areas (e.g., California, Indonesia, etc.), seismic design philosophy must be changed to consider optimal level of design variables that minimize not only the first (i.e., construction) cost, but also the total life-cycle cost including insurance cost (Damnjanovic, Aslan et al. 2010).

When integrate mitigation measures with insurance, one who purchases insurance would like to be rewarded with a premium reduction to reflect the lower risk of losses from investing in a mitigation measure. To see the difference between these two policy instruments, suppose that there is a probability p that an earthquake will occur next year and will cause damage to an unmitigated power plant of L. If a mitigation measure is put in place, then suppose the damage is reduced to L’<L.

If an insurance policy with premiums based on risk had been purchased to cover the entire loss should a disaster occur, then the concessionaire (owner of the infrastructure assets within the contract period) would expect to pay pL for coverage prior to mitigation and pL’ should mitigation be instituted. To be simplified, the probability of an earthquake and the damage to the assets are assumed to remain constant over time. The discounted insurance premium savings (I*) from mitigation over the life of the project is

$$I^* = \sum_{t=1}^{T} p(L - L') \Big/ (1+d)^t$$

The discount rate d may refer to social discount rate (SDR). Based on the formula above, the concessionaire would always voluntarily invest in mitigation if I*>C. In other words, the discounted premium reduction exceeds the upfront cost of mitigation.

In reality concessionaires with budget constraints are likely to be reluctant to incur the upfront costs associated with protective measure because they may not afford these expenditures given the huge expenses of construction costs in the beginning of the project. Concessionaire may also have little interest in investing in protection if they believe that they will only be financially responsible for a small portion of their losses should a disaster occur, either because of prohibitive premium or anticipation of liberal assistance from public sector or other organization even though the clauses already have distinctly stated the obligation and right.

5.2.2.2 Government Aid

Early in the bidding stage, the concessionaire already designed and submitted the risk management proposal consisting of risk allocation and risk transfer schemes. In the concession agreement, it should clearly allocate the respective responsibility among public and private sectors. The concessionaire will have a comprehensive understanding of the retained catastrophic risk. After assigning the specified part of catastrophic risk to the government, the retained risk embedded in the project should be allocated and shared properly among all the other stakeholders such as sponsor, bank, contractor, supplier, etc to make sure that the recovery will be carried out immediately and the corresponding interruption costs are minimized. Given the financial constraints of private sector and public attribute of PPP infrastructure assets, catastrophic risk will be transferred to government when it is above the financial capability which cannot be borne by private sector.

5.3 Risk Financing (Ex Post)

Ex post risk financing belongs to passive risk management which is not advocated by proper governance and management of catastrophic risk, hence, it is introduced shortly as below.

5.3.1 Government

If necessary, Government will have to resort to internal borrowing or development bank or other types of institution. Alternatively, government may impose taxes on the region that have not been damaged by the catastrophe events. During the major catastrophe events, government normally will receive donor from inside and outside the country. All these measures may help relieve the financial stress due to catastrophes; however, such measures are more passive action and cannot be relied by the government.

5.3.2 Concessionaire

After catastrophe occurs, concessionaire may negotiate for more than contract stated on financial items. For a mature and well developed risk management system, catastrophic risk should be distributed among all the stakeholders according to pre-arrangement listed in the contract. However, there are always some sketchy stipulations about certain items. Besides, there exist no clauses in the contract to allocate such risks, and the two contracting parties have no consensus as to risk responsibility. In addition, there are always some unexpected or extreme situations. In this case, concessionaire may negotiate with other stakeholders (mainly the government) for more compensation.

For the concessionaire, it should be last resort for project to seek help from bank, government or other stakeholder involved in the project. Although such negotiation is kind of passive risk management, it can help deal with the financial crisis and get recovered sooner.

The project may negotiate with the bank to postpone or to suspend the debt repayment, or even ask for more loans. If negotiation is successful, the project may have more liquid fund to cover the repair and rebuilt costs. Bank may be willing to make some concession to some extent because the debt will not be repaid if the project goes bankruptcy.

It is important to note that national or municipal authorities generally have to face obligations of infrastructure assets even though it is not owned by government for the moment (for example, PPP projects during the concession period). The project may negotiate with government for financial assistance. If the project needs to pay any tax, the project may ask to be waived or decreased; or the project may ask for subsidy for maintenance/rebuilt costs; or the project may ask for extension of concession period. Normally speaking, government will subsidize the project because the project belongs to public assets in the long run.

In an emergency situation, the disbursement of basic needs is paramount, while in a recovery situation, the disbursement of funds to rebuild infrastructure assets is a principle critical success factor. This disbursement requires speed and flexibility - two important pillars of effective financial management within a recovery situation. Speed is essential in project preparation to ensure rapid budget approval and subsequently efficient procurement procedures. Flexibility is critical as the demands of the recovery are dynamic such that mechanisms for fast-tracking funding must be in place as this will ensure rapid reallocation of funds when and where required. How to balance speed and flexibility of disbursement while maintaining procedural obligations to ensure accountability is a challenging task, and project managers need to manage and balance the priorities of funds available for catastrophe events with the needs and realities on the ground.

5.4 Summary

Concessionaire will identify the dynamic financial gap due to catastrophic risk. All the embedded catastrophic risks have to be allocated among all the stakeholders. Government will take the largest part given the public attribute of the infrastructure assets. Concessionaire will take the second largest part. All the other stakeholders share the remaining catastrophic risk which is far less than the risk retained by government and concessionaire.

Concessionaire takes the initiate to manage and allocate all the risks in the PPP infrastructure projects during the concession period. Concessionaire will allocate all the risks to all the other stakeholders through contractual arrangement. The clear terms will help eliminate possible dispute and default and secure recovery works after catastrophe events. Therefore, it is strongly recommended that careful examination on contractual terms for all the stakeholders should be carried out, since it is almost zero cost needed and have great benefits. After contractual arrangement, concessionaire will choose to self-retain a small part of risk and transfer the other part to insurance industry by paying premium.

Government always takes the largest part of the risks of PPP infrastructure projects especially when contractual terms are ambiguity and hard to clearly identify the responsibility. Given the low frequency and high severity of the catastrophe events, reserve fund of government is obviously not enough for the sudden requirements. In this case, government may wish to transfer its aggregate catastrophe risks of all the PPP infrastructure projects to capital market through cat bond and some other financial instruments. An optimal risk financing strategy should be a mixture consisting of different measures not a single instrument.

Chapter 6 Risk Mitigation Strategy for PPP Infrastructure Projects

Figure 1.2 displays the process towards developing an effective risk management strategy. The process typically starts with risk identification, followed by risk assessment, together with vulnerability assessment, leads to loss assessment. As shown in the downstream of Figure 1.2, risk management strategies including risk mitigation and risk financing will be developed for infrastructure projects from concessionaire's and government's perspective. This chapter will discuss risk mitigation strategy including loss control and risk reduction in details.

6.1 Loss Control (Ex Ante)

6.1.1 Avoidance

Avoidance means the rejection or change of an alternative to remove potential catastrophic risk. If necessary, it should be stipulated that all the construction projects especially the infrastructure projects should avoid construction in high vulnerable areas by government. Take China for example, four types of construction plants are classified according to respective vulnerability to earthquake in "Code For Seismic Design Of Buildings". Favorable area means stable bed rock, hard soil, open, flat, thick, and well-distributed secondary hard soil, etc. Unfavorable area refers to soft and liquefiable soil, spur with outstanding strip, high and isolated hill, steep hill, river bank, edge of side slope, obviously various-distributed soil layer, moldable yellow soil of high water content, the earth's surface with structural crack, etc. Area with potential landslide, collapse, land subsidence, ground fracturing, rock and mud slides, dislocation of earth surface if earthquake happens is classified as dangerous area. Area which belongs to none of the 3 types listed above is counted as regular area (2010). It is stated that infrastructure projects should be reinforced or relocated if they are built in dangerous area in “Construction Design Criteria Of Seismic Reinforcement”. (2010)

It is well known that all the construction projects had better avoid the locations highly vulnerable to catastrophe events. However, compared with other kinds of construction, the location of infrastructure projects are much more limited due to their special property. For example, highway as one type of transportation infrastructure which connects different cities, contributes a lot to local and regional economic growth. Even though some destination of a highway is noticeably vulnerable to earthquake, this highway project cannot be forbidden easily.

Different stakeholders may have various measures to avoid catastrophe related risk, and some of the measures are presented from government and concessionaire’s perspectives as follows.

- Government

Given the special properties of the infrastructure projects, the concessionaire may totally give up and ask for help of government when catastrophe event occurs however it is stated by the contract. In this case, the financial distress faced by the government will be larger more than expected. In order to avoid such risks, government needs to be cautious from the first beginning stage of the project. The government should be careful in site selection which should try to avoid construction in or near active fault line if possible. In order to make sure that concessionaire thinks highly of catastrophic risk management, the government must examine closely during evaluation of bid, and increase weights on catastrophic risk management especially. Only the bidders who have complete and reasonable planning of catastrophic risk management will be considered. During evaluation of bid, efficiency and practicability of proposal on catastrophic risk management should be two of the most important considerations. What’s more, a prudent selection of concessionaire during evaluation of bid can largely avoid potential moral risk after occurrence of catastrophe events. Successful project design relies on a comprehensive overview of all the risks and the design of contractual arrangements prior to competitive tendering that allocate risk burdens in terms of specified service obligations, the payment mechanism, and specific contractual provisions adjusting the risk allocation implicit in the initial structure (Grimsey and Lewis 2002).

- Concessionaire

Specific design types and structural material characteristics can significantly help in reducing the cost of mitigating structural losses from earthquakes. The impact of structural response and damage potential parameters is almost as important as the hazard parameter (Damnjanovic, Aslan et al. 2010). This is an important implication for concessionaire to select an appropriate structural designer, who should exercise special attention during evaluating designs and developing specifications. Besides structural designer, in order to reduce derivative risk due to catastrophe events, concessionaire also needs to manage relationship with other stakeholders. For example, a stable and trustable relationship with contractors/subcontractors of good reputation accompanied with contractual arrangement is necessary to secure an immediate repair and/or reconstruction work. Concessionaire should try to avoid sign contract with contractors/subcontractors of bad reputation in order to avoid potential default risk or increased interruption costs due to no prompt recovery work available after catastrophe events.

6.1.2 Resistance

An upfront investment on mitigation can reduce losses of infrastructure from a future disaster or catastrophic accident. There are a number of benefits that accrue from mitigation, which may justify the investment cost. In this research, earthquake will be used as an example to illustrate these points, however, the concepts are very general and apply to protective measures against other types of catastrophe events. The following aspects will gain benefits from mitigation measures.

- Direct losses are reduced. This refers to physical damage to a structure or its infrastructure caused by the disaster as well as the loss of lives or injures that might have been avoided had a mitigation measure been put in place. For example, bracing the cripple wall and bolting the structure to the foundation to reduce damage and save lives following the earthquake.
- Indirect losses which mean the longer-term losses brought by regional and social impact due to catastrophe events are reduced. For example, many local firms will suffer from business interruption if the power station is damaged. The interprovincial transaction volume of local farm products will be decreased when the transportation link is cut after earthquake occurs. The potential losses would not be incurred if the structure had been retrofitted so as to withstand damage from the earthquake. By investing in mitigation measures to reduce the risks associated with infrastructure damage one can avoid the consequences of a disruption in electricity and provision of water (Kunreuther 2002).
- National economic losses are reduced. The country's economy is not isolated; on the contrary, it is based on its composition. Once earthquake occurs, the whole country will also be impacted as long as a small part in the country is involved.
- Financial costs from catastrophic events are reduced. One of the less appreciated benefits of mitigation is the reduction in catastrophic losses from a disaster, and hence a reduction in the costs incurred by the public sector for financial protection. So far national catastrophe insurance schemes as a developing scheme is not mature enough to take infrastructure assets into account. Hence, when the catastrophe event occurs, the country has nothing to

do but to employ the national reserve fund, borrow from international financial institutions, world organization or other country, donation from world-wide individuals, firms and organizations, etc. Take Wenchuan Earthquake as an example, according to China Transport Ministry reported by Xinhua (2008) and Li Xin (2002), many infrastructure assets were damaged and even destroyed after the earthquake. Several major highways and expressways in southwestern Sichuan and northwestern Shanxi provinces were closed according to the Ministry of Transport. State Grid reported that six transformer sub-stations shut down and five power plants were disconnected from the power grid after the earthquake. The Sichuan province's transportation capacity has been severely impaired. A total of 180 trains had been left stranded due to multiple landslides and collapses along railway lines near the provincial capital Chengdu. All trains running near quake-hit areas have been ordered to halt in open areas, and trains heading for quake-hit areas are awaiting orders to turn back. All the infrastructure assets destroyed by the earthquake were maintained and rebuilt based on Chinese government’s reserve fund and donation from people, firms, organizations of the country and all over the world. For instance, the disaster relief fund from the central budget rose to 3.41 billion yuan, 3.175 billion yuan (454 million U.S. dollars) in cash and goods for earthquake relief from donors at home and abroad were received as of 4 p.m. 17 May 2008, according to the Ministry of Civil Affairs (MCA). Domestic donations reached 2.59 billion yuan, while 19 foreign governments and four international organizations contributed 580 million yuan in cash and goods. Local governments, domestic companies and social institutions had donated 1.63 billion yuan to the affected areas. If there were protective measures in place, the potential losses will be reduced accordingly.

6.1.2.1 Regulatory Stipulation

Many countries have stipulation regarding seismic precaution of buildings. Take China as an example, according to national regulations, safety and seismic precaution appraisal and necessary reinforcement of built infrastructure assets should be conducted if no seismic precaution was taken into consideration, or it cannot meet the new upgraded seismic precaution requirements, or the location of assets was disaster area (2010).

To determine whether a particular mitigation measure is cost-effective, one computes the expected benefits over the life of the project with its expected cost. Since a mitigation measure is conducted against potential catastrophe events, the benefits may be potential savings, which may be reflected through difference of NPVs with and without mitigation. To be more precise, suppose NPV with a particular mitigation measure and all the other elements unchanged is NPV*, and original NPV without mitigation measures is NPV0, then expected benefits (B*)

$$B^* = NPV^0 - NPV^*$$

Assume that the cost of mitigation (C) is incurred in period 0 and that there are no ongoing expenses associated with the measure over time. In other words, if an infrastructure asset is retrofitted to withstand shaking from a severe earthquake, there will be no maintenance or other costs after the measure is put in place. In this case, the benefit of investing in mitigation is simply (B*-C). Whenever there is a positive benefit, then the measure will be deemed cost-effective. Alternatively, a cost benefit ratio $\sigma = B^*/C$ is introduced to evaluate the efficiency of mitigation. σ is a measure of the financial return for each dollar invested in the seismic retrofit under consideration. σ greater than one indicates a positive return on investment, and the retrofit with the largest σ has a larger expected savings in losses over the remaining life, per dollar invested in mitigation. It is noted that a σ less than one may still be favorable in certain cases due to non-monetary benefits of retrofit and social responsibility, such as loss of life avoided.

6.1.2.2 Different Perspective of Stakeholders

Although the actual contractual arrangement varies from project to project, one common key issue for all parties concerned – government, shareholders, lenders, contractors, suppliers, and operators, is to assess the risks and uncertainties inherent in the project from their respective standpoint. Regarding mitigation measurement, different stakeholders may have various perspectives.

- Once catastrophe events occur, the regional and even national economy will suffer huge losses. The damage to infrastructure assets may bring much more losses than its own damages due to its fundamental support to the whole society. For example, the break of power supply may bring about longer time business interruption for most local manufacturers. The stronger the infrastructure assets are, the less the potential loss will be. Therefore, the government always looks forward to stronger ability of catastrophe resistance of infrastructure assets. Retrofit can reinforce the capability in resisting disaster. The government will always support the decision of structural consolidation of PPP infrastructure projects. There are two ways which can be utilized to encourage adoption of cost-effective mitigation measures. One is to integrate mitigation with premium deduction, and the other one is to have banks provide loans of discounted rate that could be tied to the mitigation measures. For government, it would be ideal if the infrastructure projects can be retrofitted to resist the most severe catastrophe events under PPP schemes. In this case, the government needs not to worry about catastrophe events because the owner of the project has been transferred to special purpose vehicle (SPV) during the concession period.

- For concessionaire, there are two types of project managers. One runs for profit maximization, and the other one runs for efficiency maximization. The project managers of the first type care about profit too much, which means that NPV may be one of the most important considerations. In this case, they don't worry about costs of mitigation. If mitigation can increase NPV of project in the end, they will conduct mitigation. Compared with the former project managers, the project managers of the latter will take financial demand/reserve fund as one more factor into consideration. It is easy to find out that mitigation will influence the setting of reserve fund although how much the influence will be is hard to quantify. Only when the increased amount of NPV is more than increased amount of reserve fund, the mitigation measure will be deemed as efficient for the project managers and then be put into effect.

- For sponsors/shareholders, return on equity should be one of the most important factors which may influence their decision. In the short term, mitigation will incur extra capital investment which may result in objection to conduct mitigation. In this case, research of return on equity should be conducted to help make decision. In the long run, mitigation can decrease the potential financial losses due to catastrophe events which may secure the dividend to some extent. Further research should be conducted to incorporate the underlying benefits in order to decide the strength and weakness of mitigation.
- For banks, two of the most important concerns are return on investment and solvency. According to the first criterion, when the project has enough proof to prove that it's profitable, banks will lend money; otherwise the loan will not be permitted. However, mitigation may decrease the possibility of insolvency due to occurrence of catastrophe events. That is to say, financiers also have incentives to make sure that services are supplied on time and to the requisite standard when the revenue stream that is generated represents the main source for repaying debt. In this case, bank may re-consider the decision of mitigation based on evaluation of solvency.

- For operators, mitigation may reduce the degree of physical damages and decrease the possibility of being destroyed due to catastrophe events. What's more, the costs incurred by mitigation have no direct relationship with them. Hence, they will advocate the mitigation decision without doubt.
- For suppliers and contractors/sub-contractors, it seems that mitigation has no direct relationship with their contract. Therefore, they don't care about mitigation at all.

More discussion will be explored in this research below, using a simplified model, from concessionaire's and sponsor's perspective respectively.

6.1.3 Model of Mitigation Decision-making

As one of the most important loss control measures, mitigation can avoid a lot of costs and bring a multitude of benefits by avoiding the unnecessary income loss because of project interruption, reducing the potential losses due to catastrophe events, and decreasing the premiums if any. Based on the tradeoff between costs and benefits of mitigation, different stakeholders may make various decisions from different perspectives. A simplified model will be used shown as below to illustrate the process, and suggest how to make decision on whether and when to conduct mitigation measures and repair. The concept origins from David Croson and Andreas Richter who discuss repair strategy with different occurrences of catastrophe events. This research extends the similar concept to explore the various mitigation strategies with different possibilities of catastrophe occurrence.

6.1.3.1 Project Description

The project is divided into 2 periods: construction period (period 1) and operation period (period 2). The construction costs (c) are launched to start the project, which means that the necessary expenses are incurred at the beginning of the project. It is assumed that the project currently under consideration is worth continuing regardless of possible damage and losses. The benefit of the project (b) is realized at the end of period 2. Suppose that the risk faced by the project is catastrophic: Once the catastrophe event occurs, the total value of the project is destroyed. The occurrence probability of a catastrophic event is p in each period. Mitigation costs (m) which may be incurred in any period are assumed to be the same. It is assumed that m is incurred at the beginning of respective period. Repair costs (r) are invested by the end of the period in which the disaster occurs. Suppose that the mitigation measure can make the project withstand the catastrophe event for one time. No repair costs are needed given that a mitigation measure is put in place if catastrophe event once happens. When facing with hit by the second catastrophe event, repair work is still necessary for project recovery.

δ denotes the discounting factor, for equity owner, it should be $\delta = 1/(1+r_e)$;and for concessionaire, it should be $\delta = 1/(1+WACC)$.

σ denotes the cost-benefit ratio of mitigation measure, and $\tilde{r}$ denotes the repair cost after taking into account mitigation effect.

Structural consolidation can strengthen the ability of the infrastructure assets to resist catastrophe events, however, whether to retrofit or not, when to retrofit and the degree of retrofit remains to be a question. Among all the determinants, cost is one of the most important one. Although there are many variations in practice, three potential options are proposed for a new infrastructure project in this research. The first option “M-0” does not take any structural consolidation into consideration in the whole project life. That is to say, the original design of the project remains unchanged, and no extra costs are needed. The second option “M-1” aims to conduct structural consolidation in the first beginning of the project. That is to say, extra costs need to be incurred in order to strengthen structural resistance to earthquake. In this case, a huge cash outflow happens in the beginning of the project; hence making cash flow look like having a heavy head. It is easily to make an illusion that construction costs are increased suddenly. In the circumstances, NPV may be much lower compared with that of original design without structural consolidation. Thereby the investors may hesitate or even give up the previous decision of consolidation. In order to prompt consolidation and improve NPV, compromised options are proposed accordingly. To avoid the centralized costs in the earlier stage which may lead to negative NPV, structural consolidation can be arranged after construction period (named as “M-2”) or even after cash flow breaks even. In this case study, option “M-2” introduced in this simplified example refers to mitigate after construction period.

In case of catastrophe events, the decision whether and when to repair depends on many factors such as the current damage state, risk preference of project manager, financial constraint/funds availability, mitigation strategy, various outcomes of the first period and project status quo etc. It is assumed that all the infrastructure projects are necessary for economic development, they can be withdrawn for the moment if the project manager decides to let it fail but a new project which replaces the old ones will restart immediately. For simplification, the potential new project is supposed to have the same value (denoted by NV in the following calculation) as the old one without taking inflation into consideration. In order to incorporate the different repair situation, 4 scenarios are given as below.

Scenario 1 (F,F)

Scenario 1 refers to the situation that the project will be withdrawn and restart once there is earthquake occurrence in period 1, period 2 or in both periods. Sometimes the catastrophe events may be devastating and the reserve fund is not enough for repair work; or the project manager may be too conservative and reluctant to incur any further expenses besides construction costs and mitigation costs if any. When operation is interrupted by catastrophe events and huge repair costs are necessary for resuming project, project manager will let the project fail and choose to restart. Given the assumption, net values of 3 mitigation strategies under different occurrence of catastrophic events are given in Table 6.1.

Table 6.1 NPVs for Different Mitigation Strategies of Scenario 1

		No event	Event (only) in period 1	Event (only) in period 2	Event in both periods
Probability		(1-p)^2	p(1-p)	p(1-p)	p^2
Mitigation Strategy	M-0	$-c+b\delta^2$	$-c+NV^{M-0}\delta$	$-c+NV^{M-0}\delta^2$	$-c+NV^{M-0}\delta$
	M-1	$-c-m+b\delta^2$	$-c-m+NV^{M-1}\delta$	$-c-m+NV^{M-1}\delta^2$	$-c-m+NV^{M-1}\delta$
	M-2	$-c-m\delta+b\delta^2$	$-c+NV^{M-2}\delta$	$-c-m\delta+NV^{M-2}\delta^2$	$-c+NV^{M-2}\delta$

The net present values of each strategy M-0, M-1 and M-2 are given in the following equations after taking the four possibility of catastrophe occurrence into consideration.

$$NPV^{M-0} = (-c+b\delta^2+b\delta^2p^2-2b\delta^2p) \Big/ (1+p^2\delta^2-p\delta^2-p\delta)$$

$$NPV^{M-1} = (-c-m+b\delta^2+b\delta^2p^2-2b\delta^2p) \Big/ (1+p^2\delta^2-p\delta-p\delta^2)$$

$$NPV^{M-2} = (-c-m+b\delta^2+b\delta^2p^2+m\delta p-2b\delta^2p) \Big/ (1+p^2\delta^2-p\delta-p\delta^2)$$

Scenario 2 (R,R)

Scenario 2 refers to the situation that repair work will always be carried out no matter which kind of catastrophe events occur. If the project is irreplaceable for the local economic development, or if there is enough reserve fund, or if the project manager is risk seeking, too confident on future benefits of the project, repair costs will be invested without hesitation for such decision maker no matter what happens. Given the assumption, net values of 3 strategies under different occurrence of catastrophe are given in Table 6.2 and σ denotes cost-benefit ratio of mitigation measure.

Table 6.2 NPVs for Different Mitigation Strategies of Scenario 2

		No event	Event (only) in period 1	Event (only) in period 2	Event in both periods
Probability		$(1-p)^2$	$p(1-p)$	$p(1-p)$	p^2
Mitigation Strategy	M-0	$-c+b\delta^2$	$-c-r\delta+b\delta^2$	$-c-r\delta^2+b\delta^2$	$-c-r\delta-r\delta^2+b\delta^2$
	M-1	$-c-m+b\delta^2$	$-c-m-\tilde{r}\delta+b\delta^2$	$-c-m-\tilde{r}\delta^2+b\delta^2$	$-c-m-\tilde{r}\delta-\tilde{r}\delta^2+b\delta^2$
	M-2	$-c-m\delta+b\delta^2$	$-c-r\delta-m\delta+b\delta^2$	$-c-m\delta-\tilde{r}\delta^2+b\delta^2$	$-c-m\delta-r\delta-\tilde{r}\delta^2+b\delta^2$

The net present values of each strategy M-0, M-1 and M-2 are given in the following equations after taking the four possibility of catastrophe occurrence into consideration.

$$\tilde{r} = r - m\sigma$$

$$NPV^{M-0} = -r\delta p - r\delta^2 p + b\delta^2 - c$$

$$NPV^{M-1} = -c - m + b\delta^2 - \tilde{r}p\delta - \tilde{r}p\delta^2$$

$$NPV^{M-2} = -r\delta p - c - m\delta + b\delta^2 - \tilde{r}\delta^2 p$$

In reality, most project managers will act as a rational decision maker who is neither conservative nor risk-loving. A rational project manager will make flexible decision which can change with the financial constraint and current damage state. In this case, there are 2 other scenarios listed as below.

Scenario 3 (R,F)

Scenario 3 refers to the situation that the repair work will be conducted only if catastrophe event occurs in period 1, otherwise the old project will be aborted and a new project will start. The project may have some reserve fund only available in period 1; or a project manager may be risk-seeking in period 1 and conservative in period 2; or the losses due to the catastrophe events in period 2 are devastating. In this case, repair work will be carried out only in period 1; if a catastrophe event occurs in period 2, the project will be allowed to fail and restart. Since the project will be given up once catastrophe events happen in period 2, mitigation as one kind of protective measures against catastrophe strike should be meaningless to conduct in the beginning of period 2. Therefore, M-2 will not apply under this scenario.

Table 6.3 NPVs for Different Mitigation Strategies of Scenario 3

		No event	Event (only) in period 1	Event (only) in period 2	Event in both periods
Probability		$(1-p)^2$	p(1-p)	p(1-p)	p^2
Mitigation Strategy	M-0	$-c+b\delta^2$	$-c-r\delta+b\delta^2$	$-c+NV^{M-0}\delta^2$	$-c-r\delta+NV^{M-0}\delta^2$
	M-1	$-c-m+b\delta^2$	$-c-m-\tilde{r}\delta+b\delta^2$	$-c-m+NV^{M-1}\delta^2$	$-c-m-\tilde{r}\delta+NV^{M-1}\delta^2$

The net present values of each strategy M-0 and M-1 are given in the following equations after taking the four possibility of catastrophe occurrence into consideration.

$$NPV^{M-0} = (-r\delta p - b\delta^2 p + b\delta^2 - c) \big/ (1 - p\delta^2)$$

$$NPV^{M-1} = (-\tilde{r}\delta p - b\delta^2 p + b\delta^2 - c - m) \big/ (1 - p\delta^2)$$

Scenario 4 (F,R)

Scenario 4 refers to the situation that the repair work will be conducted only if the catastrophe event occurs in period 2, and the project will be abandoned when catastrophe event occurs in period 1. Sometimes the project manager is not able to conduct repair work in period 1 because of financial constraint. Heavy cash outflow of construction costs in the beginning of the project may be one of the most important reasons of financial shortage in period 1. In this case, a project manager may be conservative in the construction period, and risk-seeking in the operation period. So repair work will be conducted only in period 2, if a catastrophe event occurs in period 1, the project will be allowed to fail and restart. Under this scenario, mitigation should not be conducted in the first beginning of the project since the project will be given up once catastrophe events happen in period 1. M-1 strategy will not apply.

Table 6.4 NPVs for Different Mitigation Strategies of Scenario 4

		No event	Event (only) in period 1	Event (only) in period 2	Event in both periods
Probability		$(1-p)^2$	$p(1-p)$	$p(1-p)$	p^2
Mitigation Strategy	M-0	$-c+b\delta^2$	$-c+NV^{M-0}\delta$	$-c-r\delta^2+b\delta^2$	$-c+NV^{M-0}\delta$
	M-2	$-c-m\delta+b\delta^2$	$-c+NV^{M-2}\delta$	$-c-m\delta-\tilde{r}\delta^2+b\delta^2$	$-c+NV^{M-2}\delta$

The net present values of each strategy M-0 and M-2 are given in the following equations after taking the four possibility of catastrophe occurrence into consideration.

$$NPV^{M-0} = (r\delta^2 p^2 - r\delta^2 p - b\delta^2 p + b\delta^2 - c) \Big/ (1-p\delta)$$

$$NPV^{M-2} = (m\delta p - b\delta^2 p - \tilde{r}\delta^2 p + b\delta^2 - c - m\delta + \tilde{r}\delta^2 p^2) \Big/ (1-p\delta)$$

6.1.3.2 Numerical Illustration of the Model

The model developed above can be applied to concessionaire and equity owner when there is no debt drawdown in the project. In this case, the only difference should be discount rate which is rate on equity for sponsor and WACC for concessionaire. A numerical example is shown as below to give a better understanding on the mitigation strategy selection. We use WACC in this numerical example to explore the impact of different mitigation strategy on NPV for concessionaire. It is noted that the unit of the parameters is omitted for this example, however it is easy to understand that all the NPVs should have monetary unit.

Example 1:

$WACC = 0.1$ $c = 10$ $r = 5$ $m = 0.1$ $p = 0.01$ $b = 30$ $\tilde{r} = 3.5$

Based on the assumptions above, we can get the NPVs under different scenarios.

Table 6.5 NPV of Various Mitigation Strategies

	Scenario	F,F	R,R	R,F	F,R
Mitigation strategy	M-0	14.551	14.707	14.621	14.638
	M-1	14.450	14.633	14.534	-
	M-2	14.460	14.628	-	14.559

As it is illustrated above, one of the most important factors which may influence the strategy selection is financial constraint. Financial constraint occurs when a catastrophe event happens and a shortage of capital forces the project manager to let the project fail in a case where repair work would otherwise be the preferred solution. In this research, reserve fund, denoted by R_f, are the funds earmarked for the mitigation, repair and rebuilt costs related to catastrophe events. The financial demand derived from catastrophe events is denoted by F_d. As discussed in chapter 5, in practice, financial demand will not be covered by reserve fund alone, since there will be risk allocation and some risk financing instruments which help to allocate and transfer such risk. Here in a simplified example, we assume that there are no other financing instruments available and the corresponding financial demand must be fulfilled by reserve fund of concessionaire alone. In this case, in order to meet all the possibilities of financial requirement, the financial demand should be the maximum financial requirement among those of 4 possibilities (no earthquake, earthquake in period 1, earthquake in period 2, earthquake in both periods). Take strategy "M-0 & F,R" as an example, $F_d^{M-0\&(F,R)} = \max\left[0, c*\delta, r*\delta^2, c*\delta + r*\delta^2\right]$. For example 1, financial demand for strategy "M-0 & F,R" should be maximum value of [0,10/1.1,5/1.21,(10/1.1+5/1.21)] which should be equal to 13.223. Different mitigation strategies and repair options will have various F_d as Table 6.6 shows below. Although the financial demand may be fulfilled by various risk financing strategy including reserve fund, risk allocation among stakeholders, insurance, etc., we assume that reserve fund is the only source in this case. The purposed mitigation strategy can only be realized when $R_f > F_d$ if no other fund is available. In order to meet the financial requirements of all the mitigation strategies and repair options, R_f must be no less than the maximum F_d. In this case, R_f can cover all the possible financial gaps during the project life. The selection of mitigation strategy and repair options will not be restricted by financial constraint. The project can be secured to last for the project life no matter what happens. For each mitigation strategy without financial constraint, the equation will apply: $R_f^i = \max\left[F_d^{F,F}, F_d^{R,R}, F_d^{R,F}, F_d^{F,R}\right], i = M-0, M-1, M-2$.

Table 6.6 Financial Demand due to Catastrophe Events for the Project

	Scenario	F,F	R,R	R,F	F,R
Mitigation strategy	M-0	17.355	8.678	12.810	13.223
	M-1	17.455	6.174	11.546	-
	M-2	17.446	7.529	-	12.074

If all the financial gaps can be fulfilled and there is no financial constraint, the maximum NPV can be obtained from strategy “M-0 & R-R”, which means that no mitigation is needed and the project will be always repaired once there are catastrophe events. The traditional practice is to select the strategy of maximum NPV as the best strategy. For those project managers who prefer to pursue profit maximization (maximum present value), “M-0 & R-R” should be regarded as the best strategy. In this case, no mitigation will be conducted at all and repair will always be done no matter what happens.

However, the most efficient strategy may not be the strategy which has the largest NPV because it may have the largest financial demand and therefore have to prepare a huge reserve fund at the same time with no other financing instrument available. If we have a double check of the selected strategy, it is easy to find out that the financial demand of this strategy is 2r, which is also the largest one among all the financial demands. The premise of the strategy is that reserve fund should be no less than 2r when reserve fund is the only source of financial gap. In reality, such a huge amount of reserve fund is difficult to be realized. Reserve fund of the project may not be enough to cover the financial gap due to financial constraint. Even though the project doesn't have financial constraint, the existence of such a huge amount of fund may be regarded as idle fund, which is a kind of resource waste. For those project managers who run after efficiency maximization, the concept of opportunity value of reserve fund need to be introduced. Opportunity value of reserve fund (OVRF) is the net present value reduced related to the next-best strategy with smaller reserve fund available to the project manager who has picked among several mutually exclusive strategies. Opportunity value of reserve fund demand (OVRF) can be measured as shown in the following equation.

$$OVRF = NPV_i^m - NPV_j^n, i, j \in \left[(F,F),(R,R),(F,R),(R,F)\right], m,n \in \left[(M-0),(M-1),(M-2)\right]$$

The difference of F_d is denoted as DF.

In order to find the most efficient strategy, we need make comparison between OVRF and F_d. Tradeoff between the decrease of R_f and OVRF need to be studied. The first step is to pick out the largest *NPV* among the various *NPVs* for the same F_d. The smaller ones will be deleted and the larger one will be remained for further comparison. The second step starts from the strategy with minimum F_d. Suppose reserve fund can meet the basic financial requirement, and set it to be equal to the minimum financial requirement. With R_f of the first strategy increases, *NPV* should increase accordingly. Otherwise the second strategy should be eliminated. If *NPV* decreases with R_f, comparison between DF and OVRF will be made. When the absolute value of OVRF is larger than that of DF, the opportunity value of DF is larger than its cost. In other words, the potential benefits of increased reserve fund are more than its costs. In this case, the larger *NPV* is proved to be more efficient and the respective strategy should be selected. For example, from F_d = 6.174 to F_d = 8.678, *NPV* changes from 14.633 to 14.707. The difference of the former (2.503) is more than the difference of the latter (0.074), so the strategy “M-0 & R,R” should not be selected although it has the larger net value.

Flow chart of MATLAB programming as illustrated in Figure 6.1 can be utilized to realize the process described above easily. As Figure 6.1 shows, comparison will start from the minimum reserve fund. Only if the increased amount of NPV is more than that of reserve fund, will the larger NPV be the better strategy. When all the numbers have been compared, the optimal NPV and corresponding reserve fund will be outputted. When taking catastrophe risk management into account, the best strategy determined by this method mentioned above is regarded as “an optimal strategy”. In this example, the optimal strategy is “M-1 & R,R”, which is to conduct mitigation in the first beginning and repair all the way.

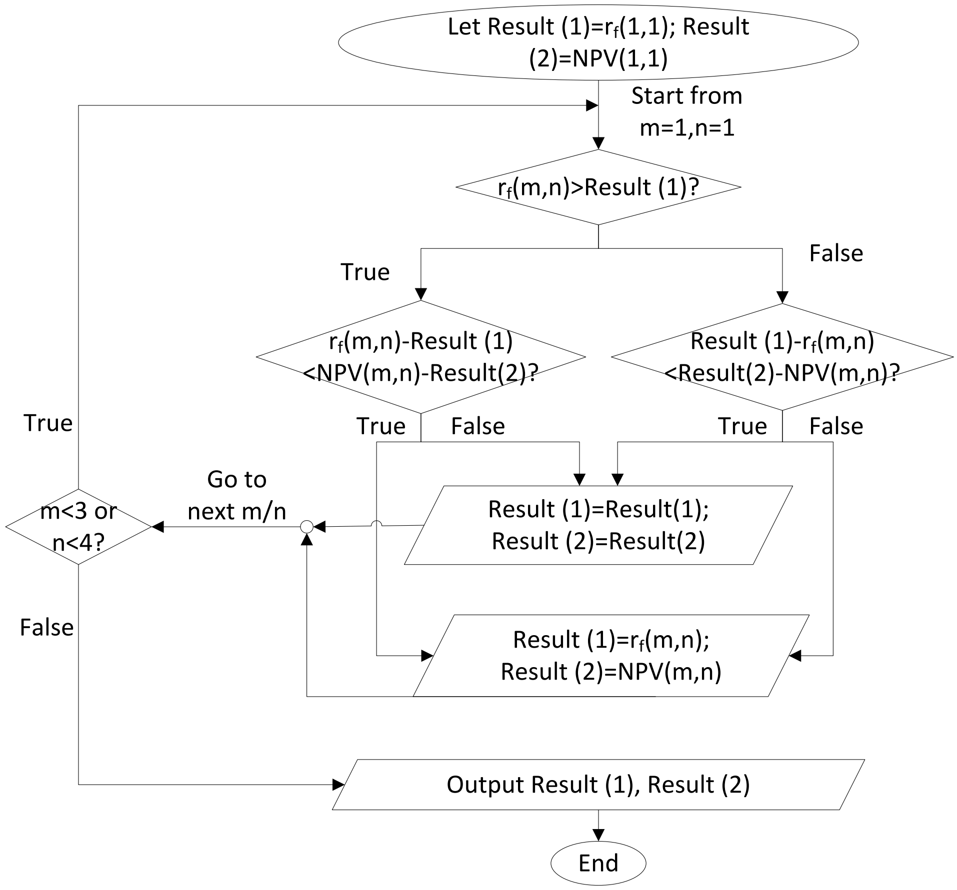


Figure 6.1 Flow Chart of the Programming of Optimal Strategy Selection

6.1.3.3 Dynamic Risk Management

In this case, we assume that all the financial demand has to be covered by reserve fund with no other financial instruments available. If the project manager runs after the most efficient strategy, it is important to reexamine the setting of reserve fund. It is noted that the amount of R_f may decrease with time goes by and will become 0 under the worst scenario, and it will never be consumed at one time. Therefore, dynamic reserve fund may be developed to cover the requirement of dynamic financial gap. For each mitigation strategy with various repair scenarios, dynamic reserve fund can be easily quantified as *max* $[F_d^1, F_d^2, F_d^3, \ldots F_d^t]$ (t = project life). Under these circumstances, the maximum financial demand per year can be satisfied, hence the strategy selection will not be restricted by financial constraint. Dynamic reserve fund can largely reduce the amount of financial requirement even for the same strategy. Take strategy “M-0 & F,R” as an example, $F_d^{M-0\&(F,R)} = \max\left[0, c*\delta, r*\delta^2, \max(c*\delta, r*\delta^2)\right]$. For example 1, financial demand for strategy “M-0 & F,R” should be maximum value of [0,10/1.1,5/1.21,max(10/1.1,5/1.21)] which should be equal to 9.091.

The reduction of reserve fund makes some strategies previously restricted by financial constraint become practical. Dynamic reserve fund management plays significant role in strategy’s selection; however, its value is difficult to be quantified. In this research, the expected value of dynamic reserve fund management (EVDM) can be measured as the reduction of reserve fund for the maximum net value obtained under the same condition divided by the maximum net value. The larger EVDM means dynamic reserve fund management is more efficient and productive. EVDM is an important parameter which indicates the necessity of dynamic risk management.

$$EVDM = \left(R_f^{static} - R_f^{dynamic}\right) \Big/ NPV_{MAX}$$

At first glance, EVDM may be mistakenly deemed as a parameter for project manager who runs after efficiency maximization. However, after careful examination, it is not difficult to find that EVDM is actually more useful for project manager who runs after profit maximization. When the project manager does not have financial constraint, he or she may focus on profit maximization. In this case, achieved maximum NPV may be the only thing which may be taken into consideration. Although the project manager need not worry about the capital, it would be better if the same NPV can be obtained through less reserve fund given other conditions unchanged. In this case, EVDM is introduced as an important parameter to help make decision for project manager who runs after profit maximization.

When the project has financial stress, the project manager may be more cautious of how every dollar is spent and runs after efficiency maximization. In this case, reserve fund of optimal NPV which includes repair costs and mitigation costs prepared for catastrophe events must be no more than that of maximum NPV. The reserve fund difference (RFD) between static risk management and dynamic risk management of optimal NPV will show the efficiency of dynamic risk management.

For example 1, the maximum NPV of the project can be realized with reserve fund reduced approximately half from 8.678 to 4.545, EVDM is 0.281, and RFD is 4.233.

Table 6.7 Comparison of Static and Dynamic Reserve Fund

Mitigation strategy \ Scenario		F,F	R,R	R,F	F,R
M-0	Static	17.355	8.678	12.810	13.223
	Dynamic	9.091	4.545	8.264	9.091
M-1	Static	17.455	8.778	12.910	-
	Dynamic	9.091	4.545	8.264	-
M-2	Static	17.446	8.769	-	13.314
	Dynamic	9.091	4.636	-	9.091

In the same way as described above, we can easily find the optimal strategy "M-1 & R,R". In this case, mitigation needs to be conducted in the first beginning of the project and repair work will be conducted all the way once the catastrophe events happen.

With dynamic reserve fund management, the realized optimal NPV can change from 14.638 to 14.633, while the reserve fund decreases from 9.091 to 3.182. It is easy to find out that dynamic risk management can help make more efficient strategy.

The decision may change with variables in given assumption. A series of comparative static analysis will be used to show the effects of important variables.

Probability of catastrophe occurrence

We now consider how the strategy selection depends on probability of the disaster occurrence in any given period. The severity of the disaster is assumed to be constant, although its probability changes. Based on the given value of parameters in the example 2, the relationship between the maximum NPV, optimal NPV with static reserve fund, optimal NPV with dynamic reserve fund and the probability variation is shown in Figure 6.2.

Example 2:

$WACC = 0.1$ $c = 10$ $r = 5$ $m = 0.1$ $b = 30$ $\tilde{r} = 3.5$ p varies from 0 to 1

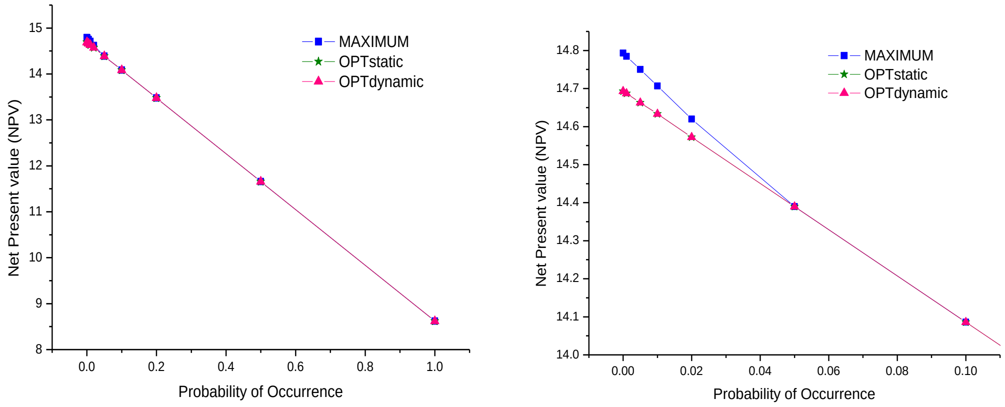


Figure 6.2 NPVs for Different Probability of Occurrence

In Figure 6.2 and all the other figures in this section, "MAXIMUM" denotes the strategy selected by project managers who run after profit maximization, "OPTstatic" and "OPTdynamic" denote the strategy selected by the project managers who run after efficiency maximization with static reserve fund and dynamic reserve fund respectively. From Figure 6.2, it is easy to find out that the NPV of the project will decrease when the probability of the catastrophe events increases. Since catastrophe is characterized as high severity and low frequency risk, the density of low probability is much more than that of high probability in example 2. Furthermore, the right-hand figure zooms in the variation of probability from 0 to 0.1. The gap between maximum NPV and optimal NPV is the largest when probability of occurrence is zero. The larger the probability, the smaller the gap between maximum NPV and optimal NPV, in other words, optimal NPV will become much closer with maximum NPV with occurrence probability increases. When the probability reaches around 0.05, the three types of NPV become equal, which means that the project managers who run after profit maximization and efficiency maximization will select the same strategy as the best strategy.

In this case, the best strategy which runs after profit maximization is “M-0 & R,R” when probability of occurrence is less than 0.05, and changes to “M-1 & R,R” when probability of occurrence rises to no less than 0.05. Whether to conduct mitigation depends on tradeoff between its benefit and costs. When catastrophe events have small probability of occurrence, the benefit of mitigation has relatively smaller weight compared with its costs, therefore decision maker may choose no mitigation as the best strategy. With the probability of occurrence increases, the advantage of mitigation will overweigh its costs. Hence, mitigation in the beginning of the project will become the best strategy. However the probability of occurrence changes, the best strategy remains unchanged to be repair anyway. That is to say, decision maker who runs after profit maximization should always conduct repair work once there are catastrophe events.

The optimal strategy for project managers who run after efficiency maximization remains to be strategy “M-1 & R,R” when probability of occurrence varies from 0 to 1. In other words, no matter how the probability changes, the optimal strategy will always be mitigation in the first beginning and conduct repair work all the way.

Probability variation itself will not influence reserve fund directly. However, reserve fund will change with different strategies which may vary with probability. The relationship of reserve fund and probability is shown in Figure 6.3. In Figure 6.3 and all the other figures in this section, “MAXstatic” and “MAXdynamic” denotes the strategy selected by the project managers who run after profit maximization with static reserve fund and dynamic reserve fund respectively. The huge difference between the upper two red lines and the lower two green lines tells that dynamic reserve fund management with a relatively smaller amount of fund can thus accomplish the same benefit with other conditions unchanged. The gap between red lines and green lines is the amount which can be saved through dynamic reserve fund management.

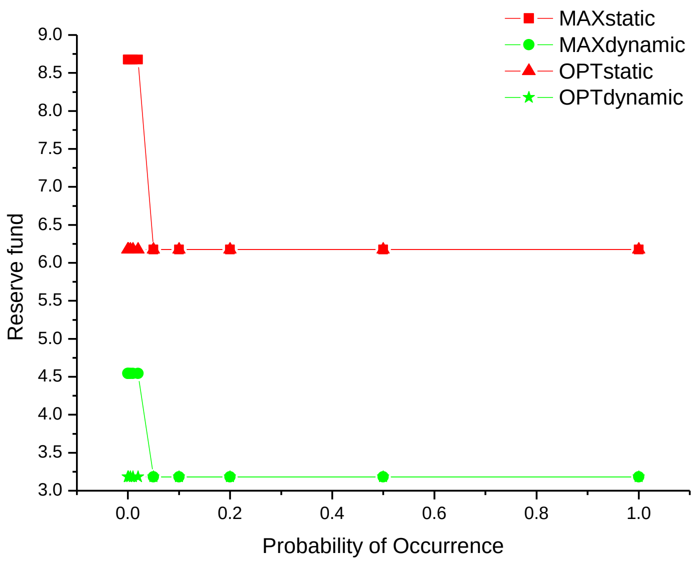


Figure 6.3 Reserve Fund for Different Probability of Occurrence

As Figure 6.4 shows, EVDM behaves like a concave and increase with non-zero probability increases. For project manager who runs after profit maximization, dynamic reserve fund management will be more worthwhile when the probability of occurrence is higher. Hence, for the same infrastructure projects, dynamic reserve fund management will be of more importance in the catastrophe prone area. Since RFD remains the same however probability varies, it is indicated that change of probability will not influence the decision of project manager who runs after efficiency maximization. In a word, dynamic risk management will be more attractive for project managers who run after project maximization in the more vulnerable area, while the incentive for project managers who run after efficiency maximization has no relationship with variation of occurrence probability.

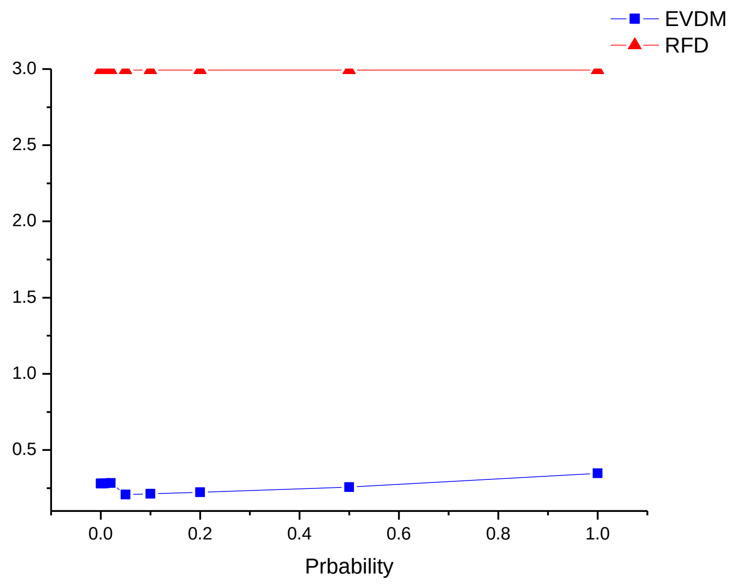


Figure 6.4 EVDM and RFD under Different Probability of Occurrence

Potential project revenue

We now consider how the strategy selection depends on potential project revenue in any given period. With other parameters unchanged, potential revenue varies from 50% to 150% of original assumption as shown in x axis (variation range from -50% to +50%, 100% refers to the base case of Example 1). Based on the given value of parameters in example 3, the relationship between the maximum NPV, optimal NPV with static reserve fund, optimal NPV with dynamic reserve fund and benefit variation is shown in Figure 6.5.

Example 3:

$WACC = 0.1$ $c = 10$ $r = 5$ $m = 0.1$ $p = 0.01$ $\tilde{r} = 3.5$ b varies from 50% to 150% of original assumption 30

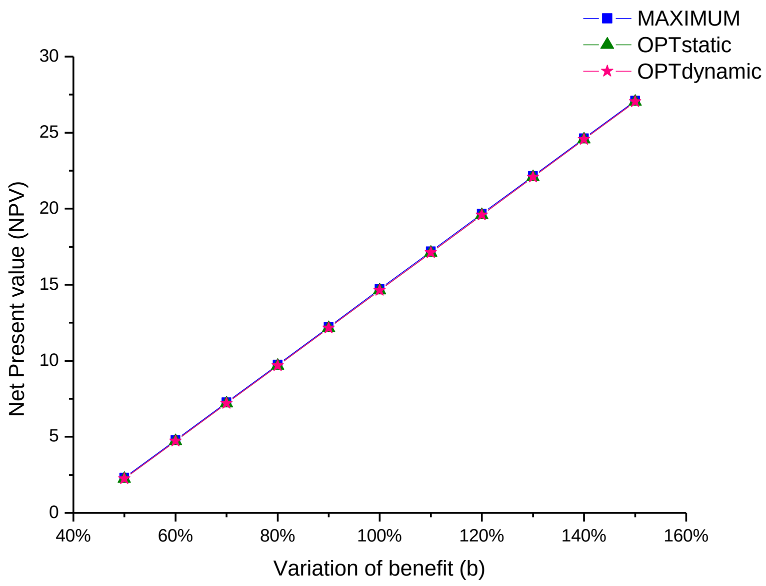


Figure 6.5 NPVs for Different Project Revenue

However benefit changes, the maximum NPV can be obtained through “M-0 & R,R” and the optimal strategy is “M-1 & R,R”. The selection of strategy will not be influenced by variation of benefit. From Figure 6.5, it is obvious to observe that NPVs under 3 conditions almost coincide when benefit variation range is from -50% to +50%. It is easy to find out that NPVs increase with benefit increases. Optimal NPVs remain unchanged for static reserve fund and dynamic reserve fund. Little difference which always exists with benefit changes can be observed between maximum NPVs and optimal NPVs. Therefore, no matter how benefit changes, the decision of project managers who run after efficiency maximization will remain the same for dynamic and static reserve fund.

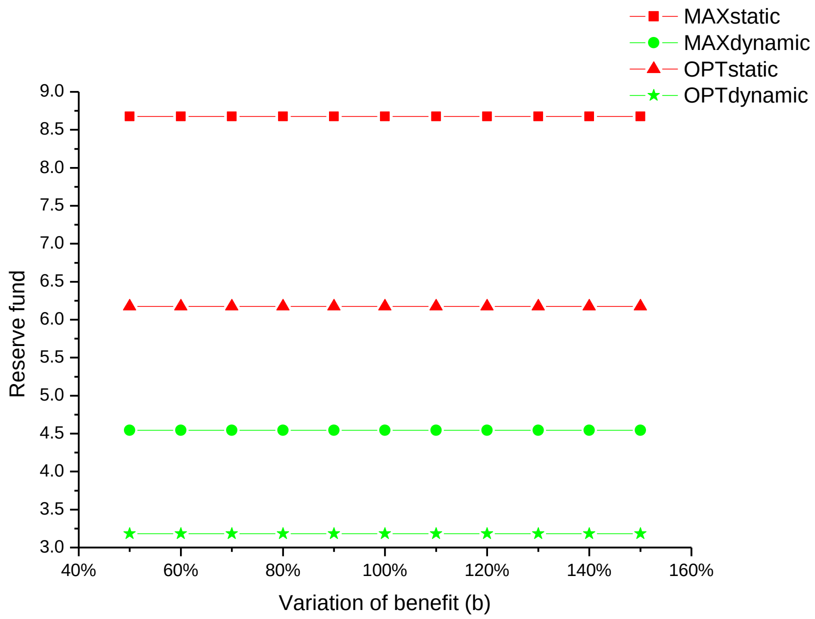


Figure 6.6 Reserve Fund for Different Project Revenue

Static reserve fund remains unchanged to be 8.678 and 6.174 for maximum NPV and optimal NPV respectively. Dynamic reserve fund remains unchanged to be 4.545 and 3.182 for maximum NPV and optimal strategy respectively as Figure 6.6 shows. The difference between dynamic reserve fund and static reserve fund of maximum NPV is fixed, therefore, EVDM will change with maximum NPV changes when benefit varies as Figure 6.7 shows. It should be noted that EVDM first decreases quickly to around 0.5 and, in addition, does not react in a highly sensitive manner to small changes in benefit. The absolute quantity of earnings which can be gained from dynamic reserve fund management remains unchanged with benefit varies, however, the relative quantity (EVDM) decreases when benefit increases because denominators (maximum NPVs) keep growing. That is to say, compared with the project which has lower benefits, for the project with higher benefits, dynamic reserve fund management will appear to be less effective. Therefore, for the project with relatively smaller size, dynamic reserve fund management should be more attractive. RFD remains unchanged however benefit varies. In this case, the incentive to carry out dynamic risk management of project manager who runs after efficiency maximization will not be influenced by benefit variation.

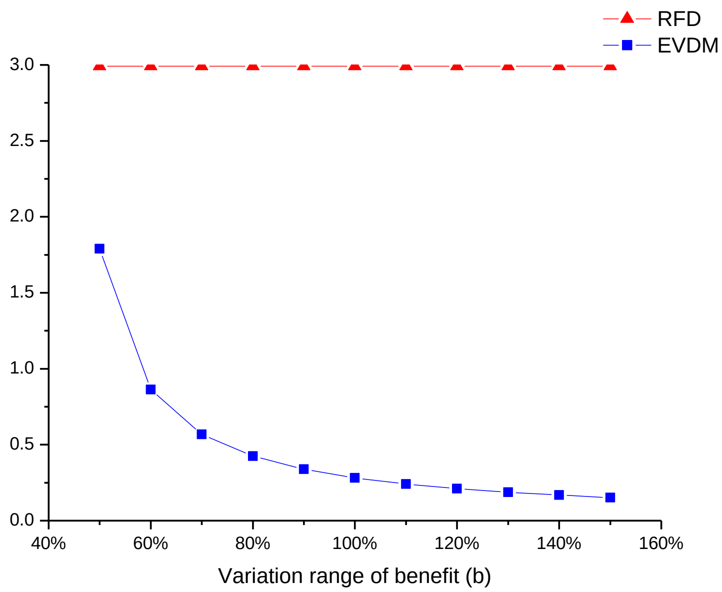


Figure 6.7 RFD and EVDM for Different Project Revenue

Mitigation costs

We now consider how the strategy selection depends on mitigation costs in any given period. With other parameters unchanged, mitigation costs vary from 50% to 150% of original assumption (variation range from -50% to +50%). Based on the given value of parameters in example 4, the relationship between the maximum NPV, optimal NPV with static reserve fund, optimal NPV with dynamic reserve fund and variation of mitigation costs is shown in Figure 6.8.

Example 4:

$WACC = 0.1$ $c = 10$ $r = 5$ $p = 0.01$ $b = 30$ $\tilde{r} = 3.5$ m varies from 50% to 150% of original assumption 0.1

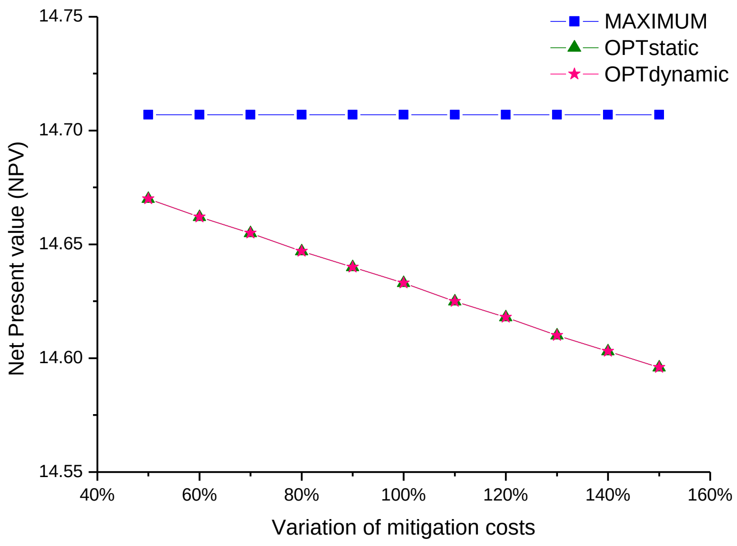


Figure 6.8 NPVs for Different Mitigation Costs

From Figure 6.8, it is obvious to observe that the maximum NPVs remain the same however mitigation costs vary. It is in accordance with intuition that since there is no mitigation involved in the strategy of maximum NPV "M-0 & R,R", the maximum NPVs will not be influenced by mitigation costs. Optimal NPVs with dynamic and static reserve fund coincide in this case. The descending line shows an inverse relationship between mitigation costs and optimal NPVs. Therefore, for the project managers who run after optimal NPVs, they will consider mitigation measurement seriously given the impact of mitigation costs since the optimal strategy is "M-1 & R,R".

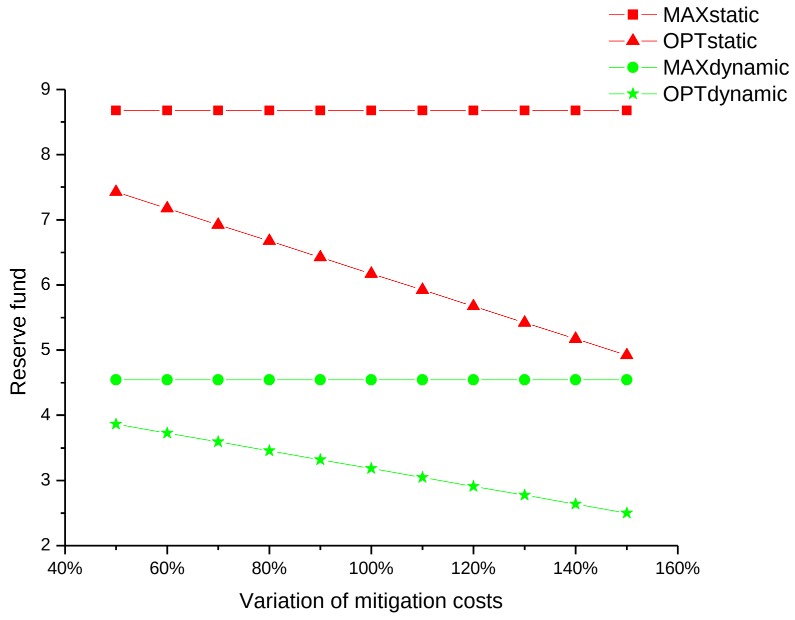


Figure 6.9 Reserve Fund for Different Mitigation Costs

Reserve fund remains unchanged for maximum NPV, 8.678 for static and 4.545 for dynamic respectively. With mitigation costs increase, reserve fund for optimal NPV decrease accordingly. This relationship provides guidance for project managers who face with various mitigation strategies. Since save of reserve fund as the virtue of mitigation is not as apparent as its shortcoming of the huge capital investment in earlier stage, project managers with financial constraint must weigh up the pros and cons of mitigation.

EVDM always remains to be 0.281 with mitigation costs vary. Given the maximum NPV unchanged, the absolute value which can be saved through dynamic risk management is fixed. In other words, change of mitigation costs will not influence the efficiency of dynamic risk management. In this case, the attraction of dynamic risk management will remain the same for project managers who run after profit maximization however mitigation costs change. RFD decreases with mitigation costs increase. That is to say, when mitigation costs grow, project manager who runs after efficiency maximization will be less motivated by dynamic risk management. In a word, the incentive for dynamic risk management remains the same for project managers who run after profit maximization and decrease with mitigation costs increase for project managers who run after efficiency maximization.

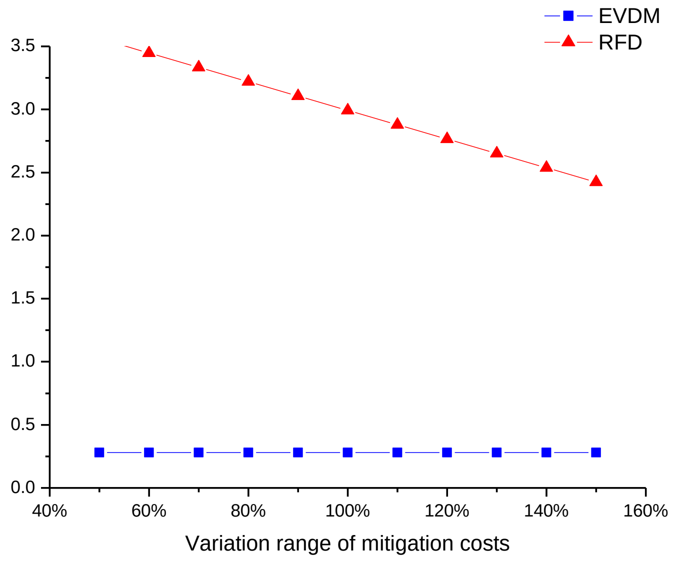


Figure 6.10 EVDM and RFD for Different Mitigation Costs

Discount rate

We now consider how the strategy selection depends on discount rate in any given period. With other parameters unchanged, mitigation costs vary from 50% to 150% of original assumption (variation range from -50% to +50%). Based on the given value of parameters in example 5, the relationship between the maximum NPV, optimal NPV with static reserve fund, optimal NPV with dynamic reserve fund and variation of mitigation costs is shown in Figure 6.11.

Example 5:

$WACC = 0.1 \quad c = 10 \quad r = 5 \quad m = 0.1 \quad b = 30 \quad p = 0.01 \quad \tilde{r} = 3.5$

WACC starts from 0.1 and varies from -50% to +50% of original assumption 0.1

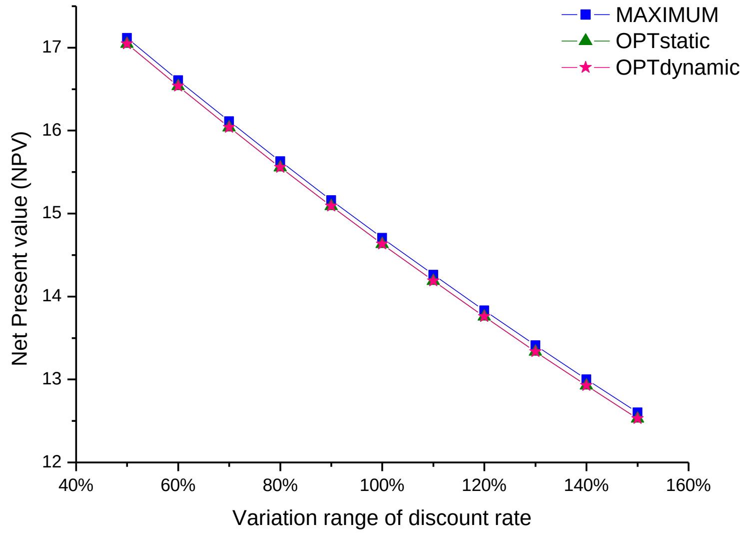


Figure 6.11 NPVs for Different Discount Rate

From Figure 6.11, it is easy to observe that both maximum NPV and optimal NPV decline with increase of discount rate which is used as a discounted rate. Optimal NPV of static reserve fund and dynamic reserve fund always coincide. It is easy to understand that the more you discounted, the less the present value is. In this example, variation of expected return rate will not influence the strategy selection for two types of project managers. The selected strategy remains to be “M-0 & R,R” for project managers who run after profit maximization and “M-1 & R,R” for project managers who run after efficiency maximization.

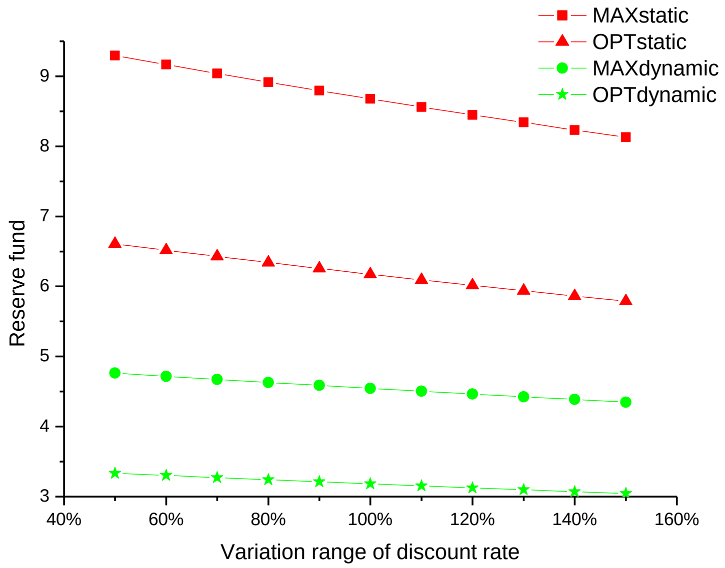


Figure 6.12 Reserve Fund for Different Discount Rate

Figure 6.12 shows that reserve fund for two types of project managers declines with discount rate increases. The decreasing amount of static reserve fund is more than that of dynamic reserve fund. That is to say, the variation of discount rate will have more influence on static reserve fund. Project managers who adopt static reserve fund need pay more attention to discount rate than those who adopt dynamic reserve fund.

From Figure 6.13, it is easy to find that EVDM slightly increases and almost remains the same with discount rate increases. In this case, project managers who run after profit maximization may not be obviously motivated by dynamic risk management when discount rate varies. RFD decreases with discount rate increases. That is to say, project manager who runs after efficiency maximization will be less motivated by dynamic risk management when discount rate increases.

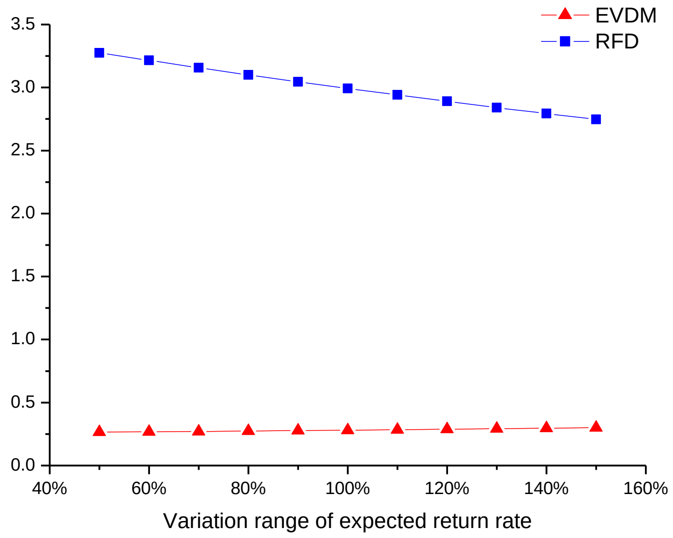


Figure 6.13 EVDM and RFD for Different Discount Rate

Repair costs

We now consider how the strategy selection depends on repair costs in any given period. With other parameters unchanged, repair costs vary from 50% to 150% of original assumption (variation range from -50% to +50%). Based on the given value of parameters in example 6, the relationship between the maximum NPV, optimal NPV with static reserve fund, optimal NPV with dynamic reserve fund and variation of mitigation costs is shown in Figure 6.14.

Example 6:

$WACC = 0.1$ $c = 10$ $r = 5$ $m = 0.1$ $b = 30$ $p = 0.01$ $\tilde{r} = 3.5$

$\tilde{r}$ starts from 5 and varies from -50% to +50% of original assumption 5

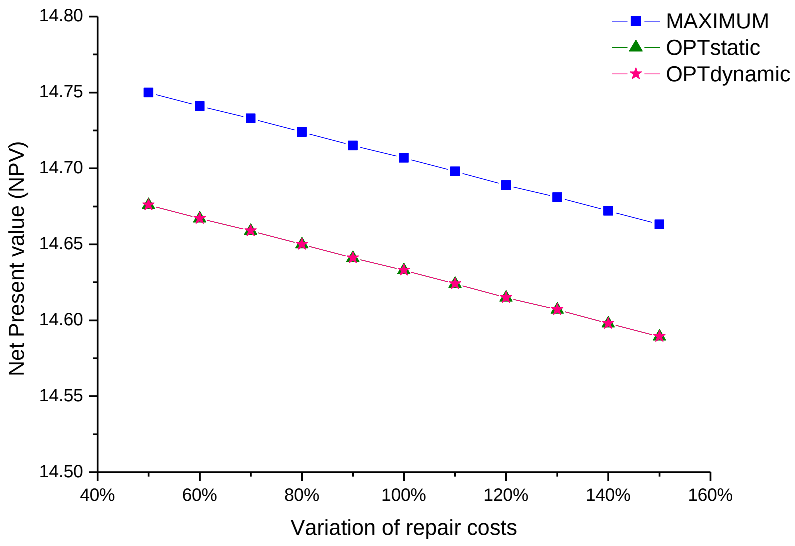


Figure 6.14 NPVs for Different Repair Costs

No matter how repair costs vary, the selected strategy remains to be "M-0 & R,R" for project managers who run after profit maximization and "M-1 & R,R" for project managers who run after efficiency maximization. From Figure 6.14, it is easy to observe that both maximum NPV and optimal NPV decline with repair costs increase. It is easy to understand that the more repair costs are, the more the project will pay and the less the project will gain in the end. Since the decreasing ratio of the three lines remain almost the same, the variation of repair costs will lead to the same variation range of all the NPVs. That is to say, NPV for project managers who run after profit maximization and efficiency maximization will be influenced by variation of repair costs at the same time, and the changing extent is almost the same. Optimal NPV of static reserve fund and dynamic reserve fund coincide in this case, although their reserve fund should be definitely different.

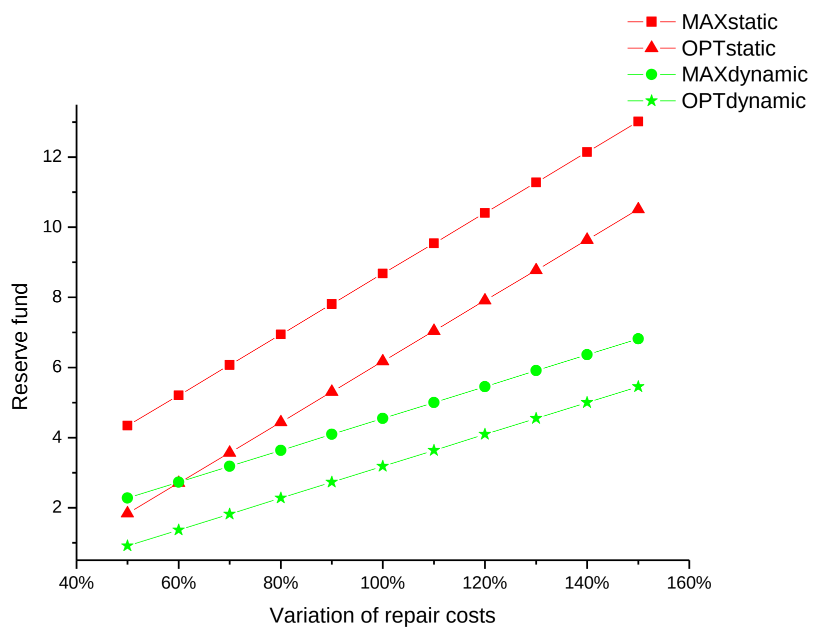


Figure 6.15 Reserve Fund for Different Repair Costs

From Figure 6.15, it is easy to find out that reserve fund will increase with repair costs increase and the increasing amount of static reserve fund is more than that of dynamic reserve fund. It is consistent with common sense since reserve fund will surely increase with expenditure increases. The red line is much steeper than green line. That is to say, when repair costs increase, increasing demand of static reserve fund will be more than that of dynamic reserve fund. Project managers who adopt static reserve fund should pay more attention to variation of repair costs.

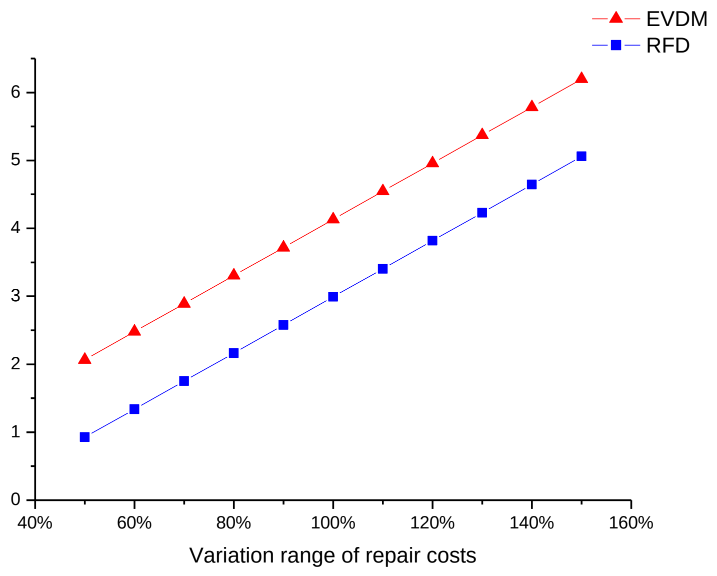


Figure 6.16 EVDM and RFD for Different Repair Costs

From Figure 6.16, it is easy to find that both EVDM and RFD increase with repair costs increase. Therefore, for two types of project managers, the incentive to conduct dynamic reserve fund management increases with repair costs increase.

Cost-benefit ratio of mitigation measure

We now consider how the strategy selection depends on cost-benefit ratio of mitigation measure in any given period. The benefit of mitigation can be measured as saving of potential repair costs in this research. However, there may be indirect benefits which cannot be quantified easily such as decrease of interruption costs. Therefore, the number of cost-benefit ratio as shown below is exaggerated to some extent in order to incorporate the potential benefit brought by mitigation.

Example 7:

$WACC = 0.1$ $c = 10$ $r = 5$ $m = 0.1$ $b = 30$ $p = 0.01$ $\sigma = (r - \tilde{r})/m$

σ varies from 0 to 50

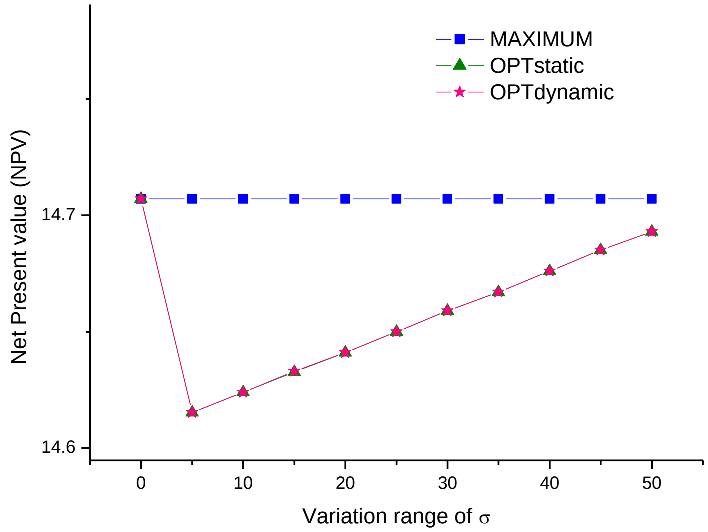


Figure 6.17 NPVs for Different Cost-benefit Ratio of Mitigation

From Figure 6.17, it is easy to find out that optimal NPV of static reserve fund and dynamic reserve fund is exactly the same, and the maximum NPV remains unchanged no matter how σ changes. Project managers who run after profit maximization will have constant NPV because the best strategy selected is "M-0 & R,R" with no mitigation involved at all. When σ is equal to 0, the mitigation has no benefit, the optimal strategy should be "M-0 & R,R"--no mitigation and repair all the way. With σ increases from 5 to 50, the optimal strategy is "M-1 & R,R", and its NPV increases from 14.615 to 14.693. That is to say, once the benefit of mitigation is more than 0, the optimal strategy should be to conduct mitigation, and the higher cost benefit ratio, the larger NPV of optimal strategy. It is easy to imply that when σ is divided into infinite small intervals, NPV will rise smoothly with σ increases.

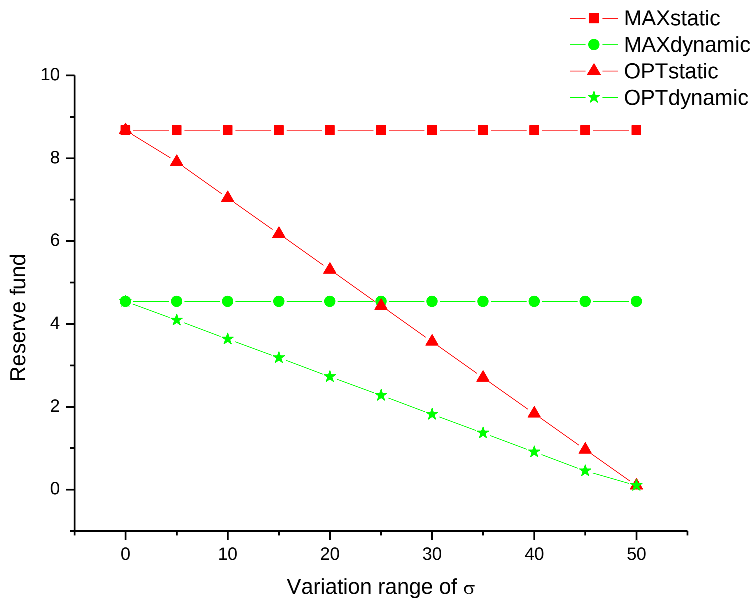


Figure 6.18 Reserve Fund for Different Cost-benefit Ratio

Figure 6.18 shows the required reserve fund of the maximum NPV and NPV of optimal strategy for both static and dynamic reserve fund respectively. Obviously we can observe that static reserve fund for maximum NPV and optimal NPV remains unchanged, while dynamic reserve fund will decrease with σ increases. It is easy to understand that the best strategy for project managers who run after profit maximization, "M-0 & R,R" does not take mitigation into account at all, so reserve fund will be unchanged.

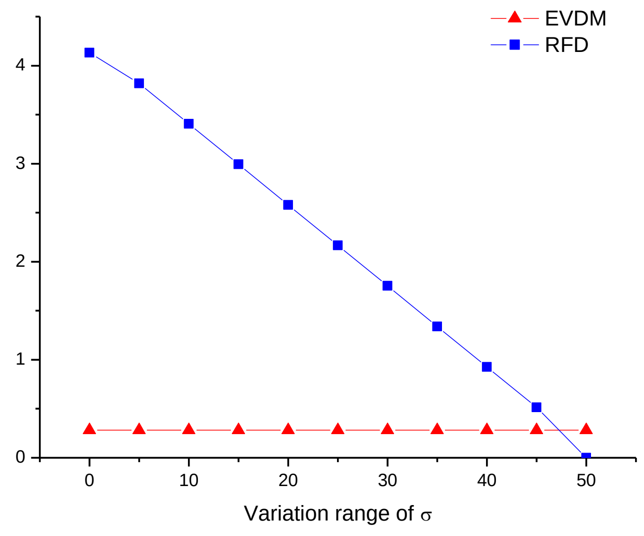


Figure 6.19 EVDM and RFD for Different Project Managers

EVDM remains unchanged to be 0.281 in this example, and RFD decreases with σ decreases. That is to say, for project managers who run after profit maximization, the efficiency of mitigation measure will not impact the decision of dynamic reserve fund management. However, with the efficiency of mitigation measure increases, project managers who run after efficiency maximization will be less motivated by dynamic risk management.

Table 6.8 summarizes the relationship of two important parameters EVDM and RFD with the different variables based on Example 1 to Example 7. From Table 6.8, it is easy to find out that when occurrence probability (p) and repair cost (r) increase, the incentive for project managers who run after profit maximization to carry out dynamic risk management will increase, while such incentive will decrease when project revenue (b) increase. The incentive for project managers who run after efficiency maximization will decrease when mitigation cost (m), expected return on equity (r_e), and cost-benefit ratio of mitigation (σ) increase, while such incentive will increase with repair cost (r) increases. It is inferred that incentive to adopt dynamic risk management will increase with potential cost increases for two types of project managers.

In practice, most of project managers run after efficiency maximization even though there are enough funds available. In this research, all the discussion later regarding on project managers means project managers who run after efficiency maximization.

If we take a look at the 3 variables of occurrence probability of catastrophe events, repair cost and benefit which influence EVDM, it is easy to find out that change of the 3 variables indicates the potential loss due to catastrophe events. With the potential loss increases, the necessity of dynamic risk management increases.

In the same way, 4 variables including mitigation cost, discount rate (WACC), repair cost and cost-benefit ratio of mitigation which influence RFD are examined carefully. It is easy to find out that the change of 4 variables will result in the same changing trend of reserve fund. That is to say, any increase of mitigation cost, WACC and cost-benefit ratio of mitigation, as well as any decrease of repair cost will lead to decrease of reserve fund, which means that the efficiency of dynamic risk management will be decreased.

Table 6.8 Incentive of Dynamic Risk Management for Different Scenarios

	p (0-1)	b (-50% to +50%)	m (-50% to +50%)	WACC (-50% to +50%)	r (-50% to +50%)	σ (0 to 50)
EVDM	↑	↓	—	—	↑	—
RFD	—	—	↓	↓	↑	↓

6.2 Risk Reduction (Ex Post)

Risk reduction explores the ex post non-financial risk management measures to reduce catastrophic risk. It belongs to passive risk management which is not advocated in developing risk management strategy, hence, it is introduced in short as below.

6.2.1 Negotiation—For Concessionaire

Concessionaire may negotiate with the other stakeholders for more than contract stated on non-financial items. Government is always easier to be negotiated compared with other stakeholders given the special attributes of PPP infrastructure projects.

Concessionaire may ask government for extension of concession period since the revenues in the future are expected to reimburse the catastrophic loss. For highway projects, concessionaire may ask government to raise tariff so that more revenues can be achieved to offset the financial losses due to catastrophic events.

Concessionaire may ask debt holder to postpone or extend debt repayment schedule in case of catastrophes. Such negotiation is better to be acceptable than negotiation on the financial items because it does not incur more costs for concessionaire, and will not lead to decrease of repayment amount directly for debt holder.

Concessionaire may ask contractor to expedite the repair work in order to reduce repair period. When repair period is reduced, the infrastructure can be restored sooner so that financial losses can be recovered with continued revenues. Obviously, such negotiation is difficult to implement if the construction site is still threatened by secondary hazard.

In addition to negotiation, given limited resources, concessionaire may improve efficiency of resource allocation to reduce as more financial losses as possible. For example, concessionaire may put more efforts in recovery work of bridge which connects the whole transportation system instead of focus on the restore of lane.

6.2.2 Withdrawal—For Government

The PPP infrastructure project cannot be withdrawn easily because it is fundamental for regional economic development whose value is far more than that of the project value itself. Take China as an example, according to national regulations, safety and seismic precaution appraisal of built infrastructure assets should be conducted. After evaluation, some assets may be regarded as not suitable for reinforcement. For example, if the construction site is located in an area vulnerable to mud-rock flow, landslide, collapse, subsidence, ground fracturing, or at cliffside, at the bottom of cliff, in wind gap or flood channel, the original building should be abandoned and it should be rebuilt in a new area which is away from this kind of area listed above. If the building is heavily damaged after catastrophe events and identified as no restore value, it should be pulled down and rebuilt. Or if the costs of reinforcement are more than 70% of rebuilt costs, the existing assets may be abandoned and rebuilt. Therefore, withdrawal should be the last resort after careful examination and thorough analysis by government for PPP infrastructure assets.

6.3 Summary

Risk mitigation strategy includes loss control and risk reduction. The main difference between the two risk mitigation measures is timing. Loss control is one type of ex ante measures which are preventive and active. As an essential element of proper governance and management, loss control should always be advocated if there are no extra costs involved. In fact, for some mitigation measures such as retrofit, additional costs are necessary. In order to develop an optimal strategy for infrastructure projects, the tradeoff between costs and benefits as well as dynamic risk management should be taken into account. The results indicate that incentive to adopt dynamic risk management will increase with potential cost increases for project managers who run after profit maximization and efficiency maximization.

For most parameters such as project revenue, mitigation cost, discount rate, repair cost, cost-benefit ratio of mitigation, the best strategy for project managers who run after profit maximization remains to be no mitigation. However, the decision may vary with occurrence probability changes. When the probability of occurrence is high (0.05 in the case study), the best strategy changes to mitigation in the first beginning of the project. It is easy to conclude that project managers who run after profit maximization tend to select no mitigation as the best strategy except when there is high occurrence probability.

For most parameters such as occurrence probability, project revenue, mitigation cost, discount rate and repair cost, the best strategy for project managers who run after efficiency maximization remains to be mitigation in the first beginning of the project. When the cost benefit ratio is equal to 0, the selected strategy is no mitigation at all. It will change to mitigation in the beginning when the ratio varies from 5 to 50. It is reasonable to conclude that the best strategy should be to mitigate in the first beginning because in practice the extreme situation of the benefit of mitigation equals to 0 will not happen. Hence, it is inferred from this scenario case study that project managers who run after efficiency maximization prefer mitigation in the beginning as the optimal strategy.

As for sponsor who may be faced with plenty of investment opportunity, mitigation after the construction period is identified to incorporate value of deferment option. After taking deferment option into consideration, the sponsor will select mitigation after construction period as the optimal strategy which conflicts with the selected strategy of concessionaire. More negotiation may be necessary in order to achieve an optimal mitigation strategy accepted by both parties.

Compared with loss control, risk reduction is one type of ex post measures which is normally passive and negative except for ex post arrangement on resource management and allocation. However, the project managers may find the relationship between the selected variables and NPVs through sensitivity analysis. Based on such results, limited resources can be allocated and managed efficiently. Apart from the above ex post arrangement, all the other ex post measures should not be advocated. For example, negotiation with government for more than what contract terms has stated may bring more financial losses due to longer business interruption as well as unexpected financial burden to government.

Chapter 7 Case Study: Highway Project in China

It is easily questioned that if a single case study can contribute to scientific development because people normally think one cannot generalize on the basis of an individual case. However, generalization is only one of many ways by which people gain and accumulate knowledge. A case study without any attempt to generalize has often helped cut a path toward scientific innovation. In a word, one can often generalize on the basis of a single case, and the case study may be central to scientific development via generalization as supplement or alternative to other methods (Flyvbjerg 2006).

Only one case study of a highway project in China is selected as a study target due to data availability. This case study is used to help cut a path towards a pilot research of catastrophic risk management of PPP infrastructure projects.

7.1 Background

The transportation infrastructure in China is under tremendous stress to keep up with development in the country. The network intensity of roads in China, as measured by length of road per square km of land, is only about 0.12; such level of intensity is about 1/5 of that of the United States, 1/14 of Germany’s, and 1/24 of Japan’s.

The JS Highway project (the name is kept anonymous due to confidential requirements of project) was proposed back in the mid-1990s to promote economic growth for one of the major cities in the east. The project was planned to undergo two phases of construction. Phase I would start in 1997, spanning a period of 3 years, which covers all foundation and pavement works. Although the highway was designed to have 6 lanes in total, only the 4 outer lanes would be paved initially, with the inner two lanes being reserved as a “green zone”. Phase II would take place two years upon completion of Phase I, which then converts the reserved “green zone” into two additional lanes of highway. The area of roadways is 1.26 million square meter in total including 10 bridges.

The project was funded as a sino-foreign joint venture that lasts until 2020. The foreign investors were allowed to purchase a portion of the equity and able to recoup their returns based on cash flow distribution rights as specified in the contract. The total cost of the project was approximately RMB 1.1 billion for Phase I, which was funded with 40% equity and 60% debt. In addition, about RMB 15 million was incurred in 2001 for the addition of safety infrastructure, and RMB 248 million in 2002 for the Phase II conversion. The breakdown of the capital expenditure and capital drawdown is given in Table 7.1 & Table 7.2, wherein the capital expenditure for bridges-related is 128.65 RMB million.

Table 7.1 Capital Expenditure (in RMB million)

Year	1997	1998	1999	2001	2002
CAPEX	214.3	441.8	443.9	14.9	248.0

Table 7.2 Capital Drawdown for Phase I (in RMB million)

Year	1997	1998	1999
Debt drawdown during construction	203.18	446.57	10.25
Equity drawdown	110.00	330.00	0.00

The debt payment plan complies with the loan agreement between the Project Company and banks. The interest rate for the repayment is 5.36% and the payback period is 15 years. The amortization of debt is drafted in Table 7.3. As Table 7.3 listed, the total debt is more than 6.6 billion because there will be following debt drawdown for the phase II expansion construction. But the debt to equity ratio is calculated as 6.6/4.4 = 1.5 because the baseline time is 2000.

Table 7.3 Amortization of Debt (in RMB million)

Year	Debt drawdown	Principal payments of debt	Interest payments of debt	Annual debt payment
1997	203.18	0.00	0.00	0.00
1998	446.57	0.00	0.00	0.00
1999	10.25	0.00	0.00	0.00
2000	0.00	40.48	48.11	88.59
2001	14.95	42.65	45.94	88.59
2002	247.99	44.94	43.65	88.59
2003	0.00	47.35	41.25	88.59
2004	0.00	49.88	38.71	88.59
2005	0.00	52.56	36.03	88.59
2006	0.00	55.38	33.22	88.59
2007	0.00	58.34	30.25	88.59
2008	0.00	61.47	27.12	88.59
2009	0.00	64.77	23.83	88.59
2010	0.00	68.24	20.36	88.59
2011	0.00	71.89	16.70	88.59
2012	0.00	75.75	12.84	88.59
2013	0.00	79.81	8.78	88.59
2014	0.00	84.09	4.51	88.59
Sum	897.59	897.59		

The annual operation and maintenance of JS highway during the concession period is forecasted based on the current data (Italic number). Three overhauls will be arranged in 2007, 2013 and 2018 separately. More details are given in the following Table 7.4.

Table 7.4 Operating and Maintenance Costs (in RMB million)

Year	Overhaul costs	Maintenance costs	Operating costs
2000	*0.00*	*1.20*	*9.58*
2001	*0.00*	*17.94*	*11.56*
2002	*0.00*	*1.08*	*11.20*
2003	*0.00*	*3.62*	*9.93*
2004	*0.00*	*2.87*	*11.17*
2005	0.00	2.87	11.34
2006	0.00	3.17	11.56
2007	74.36	1.58	11.98
2008	0.00	3.27	12.31
2009	0.00	3.38	12.67
2010	0.00	3.47	13.05
2011	0.00	3.57	13.43
2012	0.00	3.68	13.82
2013	83.64	1.89	14.22
2014	0.00	3.90	14.64
2015	0.00	4.01	15.07
2016	0.00	4.13	15.51
2017	0.00	4.25	15.96
2018	100.38	2.19	16.43
2019	0.00	4.50	16.91
2020	0.00	4.63	17.41

7.2 Seismic Impact on the Highway Project

When projecting loss estimation as the result of a potential earthquake, the primary focus for many entities is typically on the potential damage to the direct economic losses. Another significant concern to public entities is the time that they will be out of service or that their capacity to produce their service will be curtailed. This level of “downtime” is often referred to as “business interruption” and can be expressed in terms of time, dollars, or a combination of both. (Gould and Ballantyne 2005) In this case, downtime consists of recovery period, recovery costs, and the revenue decreased due to interruption of transportation. Gould (2004) pointed out that the relative cost of nonstructural damage and related business interruption costs, as compared to the costs associated with structural damage, is often extremely high.

Figure 7.1 shows the framework of the case study. Since this case study is derived from Figure 1.1, the phrases in Italic and underlined also have the same meaning with the one in Figure 1.1. The first part shown in line of dashes rectangle refers to the base case without earthquake scenarios. The hazard impact defines the frequency and severity of the catastrophe at a specific location within the region of interest. This is normally done by reviewing historical data, ground-motion data and scientific studies available for the region. The hazard impact and vulnerability assessment are combined to estimate the potential damage to the infrastructure projects. Loss module and recovery module help estimate economic loss including direct losses (recovery/rebuilt costs) and indirect losses (business interruption costs) due to the earthquake. These parts constitute the main body of loss estimation which needs more historical data and engineer's knowledge. They are more like engineering's business and case-specific which exceed this research's area. In Figure 7.1, they are marked in shadow which means that they are mainly based on assumptions and simplified during calculation. Since large uncertainties are inherent in various scenarios with different severity, frequency and losses, risk models combined with MATLAB program will be developed in this research in order to incorporate probabilistic and stochastic characteristics. Further analysis catastrophic risk management strategy is developed based on the loss estimation. The calculated losses will be divided into 3 layers where lower layer is shared by private sector, upper layer is financed by government and middle layer is transferred to financial instruments including catastrophe insurance or catastrophe bond.

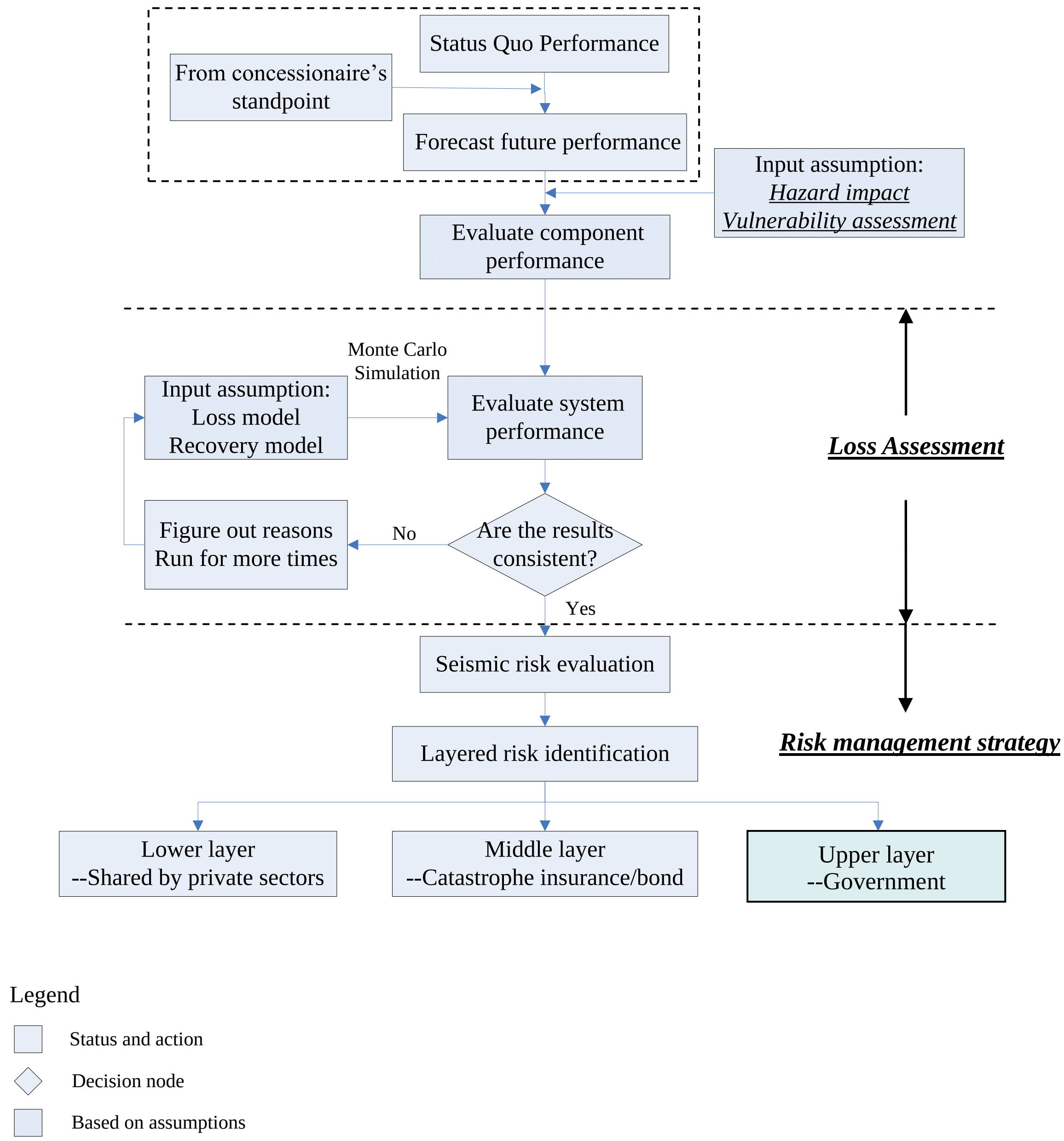


Figure 7.1 Framework of Seismic Risk Analysis for A Highway Project

7.2.1 Hazard Assessment

Hazard assessment provides scientific base for understanding the nature of risks and deriving the probability of occurrence. The relevant areas might include: sciences, geology, meteorology, engineering and statistics which are beyond this research area, so the details of this step will be skipped in this case study.

7.2.2 Vulnerability and Loss Assessment

Vulnerability assessment characterizes the physical nature of the infrastructure projects and their potential exposure to seismic risk. Many facets which were discussed in the vulnerability assessment as chapter 2 listed were simplified for this case study. Damage states incorporate the impact of different years of construction. Cash flow from concessionaire’s standpoint forms the basis of loss assessment. Occurrence of earthquake was assumed to be randomly and only one time during the operation period.

Loss assessment estimates direct losses arising from disaster events and indirect losses of discontinuing functionality of the systems. Direct losses include losses due to physical damage from ground shaking and ground deformations, and represent the repair (and rebuilt if any) costs of damaged components. Indirect losses result from closure of particular sessions because of excessive damage to key components such as bridges, or due to reduced flow capacity (either from imposed lower speed limit or closure of a number of available traffic lanes) owing to damage of different degrees. Based on the above analysis and the below assumptions, catastrophe loss can be estimated from difference of NPV between the normal situation and the one under earthquake scenario.

7.2.3 Facts and Assumptions

7.2.3.1 Recovery Costs

As introduced in the previous session, it is hard to set up generic model which can capture the gross characteristics of the various components. In this research, the assumption of recovery costs for the whole highway system will be given based on the recovery costs of the bridges since bridges are vital components in highway network. In addition to the seismic hazard curves and fragility models, the present value of total losses presented is also a function of the remaining life, discount factor, and cost associate with repair of each damage state. Costs associated with repair from each damage state are estimated as a fraction of the replacement cost using the repair cost ratios estimated by Basoz and Mander (1999) shown as below.

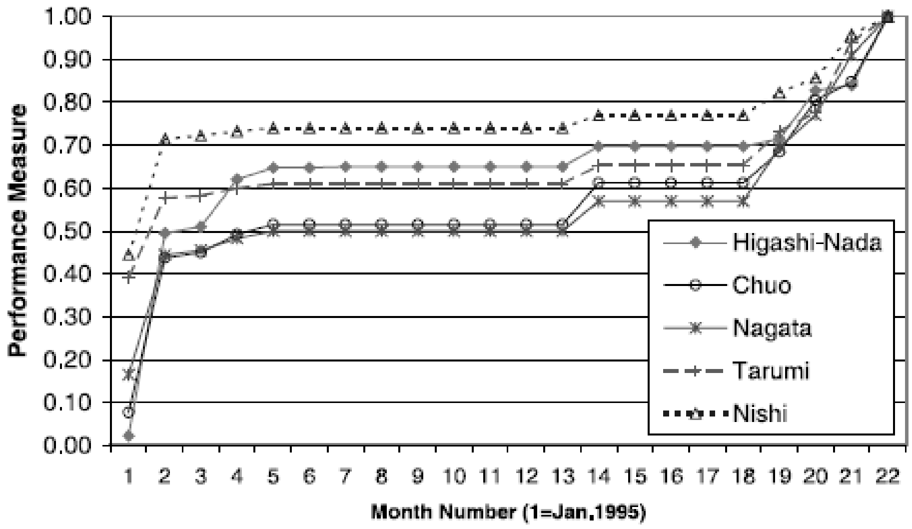
Table 7.5 presents the best mean repair cost ratios for each damage state assessed in the fragility analysis. The losses estimated as the fraction of replacement cost include only direct losses due to physical damage. The indirect losses are explicit such as increased costs of project completion due to the disruption in a smooth flow of capital. However, the indirect losses due to increased travel time from bridge damage have been found in past studies to be on the order of 5－20 times larger than the direct losses (1991).

Table 7.5 Bridge Repair Costs

Damage State	Slight	Moderate	Extensive	Complete
Repair Cost Ratio	0.03	0.08	0.25	1.00

7.2.3.2 Recovery Period

The recovery period varies with the different magnitudes of earthquake and different ages of the asset as well. In the Hyogoken-Nanbu earthquake, with a moment magnitude of 6.9, the closure times for the repair of the bridges ranged from three to nine months. Since damage on the three year old Wangan route was much less severe than on the approximately 30 year old Hanshin Expressway, the Wangan route was reopened in states, with the complete route open 5.5 months after the earthquake. However, the Hanshin Expressway was not reopened until 20.5 months after the earthquake because of the extensive damage (Wilson 2003).



(Source: Stephanie E. Chang 2001)

Figure 7.2 Highway Performance Restoration

Figure 7.2 shows the restoration of highway accessibility over time for selected sessions of Kobe City Wards due to Hyogoken-Nanbu earthquake. A level of performance measure equal to 1.0 indicates that the system has regained pre-disaster traffic levels. The curves demonstrate the vast disparity in highway service loss between the wards, indicating that a citywide average does not adequately represent the situation across the study area. Furthermore, it shows that relative highway accessibility remained fairly consistent throughout most of the restoration period, so that spatial disparities will be ignored and a uniform recovery period for the whole JS highway will be given in this case study. Since almost all of the systems will reach at least 50% of the pre-earthquake level after 12 months, 12 months will be adopted as the recovery period for all the damage states. Although under actual situation the system will recover step by step as the figure shows below and there may be different recovery period for different scenarios, 1 year is accepted as the uniform recovery period in the simplified model.

7.3 Loss Estimation based on Cash Flow Model

As introduced in chapter 4, estimated financial losses due to catastrophic events are based on cash flow for concessionaire during the project life. This model will be developed mainly from the concessionaire's perspective. A general catastrophic risk management strategy will be introduced for government briefly.

7.3.1 Cash Flow Projection without Earthquake

7.3.1.1 Traffic Revenue Forecast

Based on the past data of planning for similar projects, annual operating and maintenance expenses (with inflation) can be estimated. The highway would require major rehabilitation works in 2007, 2013 and 2018. Toll charges for the highway are categorized into five classes in practice, while the forecast of the traffic flow is simplified to be the first class during the calculation. The tariff is 0.71 RMB / km, and decrease to 0.55 RMB / km since 2005. And total charge for whole session is 25 RMB and becomes to 20 RMB since 2005. The traffic volume is assumed to increase annually according to the traffic growth rate shown in Table 7.6.

Table 7.6 Annual Traffic Growth Rate (%)

Period	2005-2010	2011-2015	2015-2020
Highway	15	7.2	7

Source: (Meng, Zheng et al. 2006; 2007)

Given the actual traffic flow from 2000 to 2004 (in italic), the future traffic volume and toll revenues can be forecasted accordingly as shown in Table 7.7.

Table 7.7 Traffic Flow Forecast

Year	Toll rate(RMB)	Traffic volume (mil)	Toll revenue(mil RMB)
2000	*25.00*	*2.05*	*51.15*
2001	*25.00*	*2.85*	*71.32*
2002	*25.00*	*3.69*	*92.33*
2003	*25.00*	*4.89*	*122.15*
2004	*25.00*	*7.87*	*196.68*
2005	20.00	9.05	180.94
2006	20.00	10.40	208.08
2007	20.00	11.96	239.30
2008	20.00	13.76	275.19
2009	20.00	15.82	316.47
2010	20.00	18.20	363.94
2011	20.00	19.51	390.14
2012	20.00	20.91	418.23
2013	20.00	22.42	448.34
2014	20.00	24.03	480.63
2015	20.00	25.76	515.23
2016	20.00	27.56	551.30
2017	20.00	29.49	589.89
2018	20.00	31.56	631.18
2019	20.00	33.77	675.36
2020	20.00	36.13	722.64

7.3.1.2 Discount Rate

Normally the discount rate is a combination of two factors by the general time value of money (i.e. related to financial market interest rates); and a premium for the particular risks involved in the investment (E.R.Yescombe 2007). Cost of capital was initially selected to be the discount rate. The debt payments are equally apportioned to the first 15 years during the operation period according to the contract. The required return-on-debt (r_d) is calculated as "Interest rate – Tax savings". As this case is free of taxes, r_d becomes 5.36%.

The Capital Asset Pricing Model (Sharp) is commonly used to estimate the required return-on-equity (r_e):

$$r_e = r_f + \beta_e * (r_m - r_f)$$

To get an appropriate value for β_e, five toll road operators (including Dongbei Expressway, Ganyue Expressway, Shen Expressway, Fujian Expressway, Ninghu Expressway), whose shares are publicly traded in China, were identified as proxies (Qian, Wang et al. 2007). After adjusting for differences in leverage, β_e is estimated as 1.457. The yield of 5-year government bonds, which was about 5%, is used to represent the risk-free rate, r_f. The value of domestic stock market index spanning 1995-2002 is used to determine an average market return r_m of 9.7%. Based on the above assumptions and data, r_e is determined as 11.85%.

So the weighted average cost of capital (WACC) is calculated as follows:

$$\text{WACC} = w_d\, r_d + w_e\, r_e = 3/5*11.85\%+2/5*5.36\% = 7.956\%$$

For the normal situation, WACC should be appropriate as a discount rate for such projects. However, given the East Asian financial crisis around 1997, the equity market was highly unstable for the period considered of 1995-2002. According to the “Guide on feasibility study of investment projects” stipulated by Chinese Committee of National Development Planning (2002), the discount rate is revised to be social discount rate of 10%.

7.3.2 Cash Flow Projection under Earthquake Scenarios

7.3.2.1 Hypothesis of Earthquake Occurrence

In Equation (2-4), a probability that at least one earthquake with magnitude ≥ m to occur within operation period can be easily obtained from the Poisson model. Based on the Poisson model, the probability that at most one earthquake with magnitude ≥ m to occur within the operation period can be obtained as well, which will be cited in this research for simplification of assumptions.

The exceedance probability (EP) curve shown in Figure 7.3, extended from the standard frequency/severity curve, is a very common way of conveying loss information. It depicts the probability of losing more than a particular amount on the vertical axis versus the amount of loss on the horizontal access. That is to say, for a certain loss x shown in the horizontal axis due to the earthquake, the exceedance probability P (loss>x) is given in the vertical axis according to the distribution curve (Banks 2005).

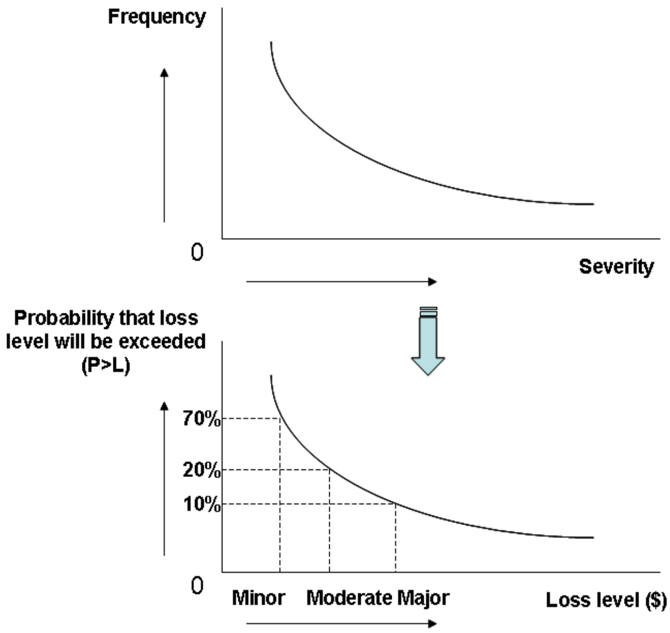


Figure 7.3 Exceedance Probability Curve

With the distribution function of EP curve, the estimated loss can be calculated accurately. Since it is hard to obtain this distribution function without enough information including earthquake engineering and structure engineering, three representative scenarios with certain probability are given alternatively to simplify the analysis procedure in this case study. Minor, moderate and major as shown in the horizontal axis quotes the definition of the different link condition in Chapter 2. 70%, 20% and 10% denotes the occurrence of probability of the three damage states respectively.

The built highway belongs to Class B according to the classification in "Guidelines for seismic design of highway bridges" (2008). Therefore it must meet the requirements of Chinese government which should be e+f+g which is more strictly than a+b+c+d, the basic requirements of seismic design for normal bridges in Table 7.8. Explanation of performance state is stated in Table 7.9.

According to Xie and Wang (2011), intensity 7 or greater could be expected in the Beijing–Tianjin–Tangshan area which includes the area of this JS highway project in the next 100 years. The probability of experiencing intensity 8 or greater in the area is larger than 10 percent. Based on the resistance ability of the JS highway project and the underlying seismic risk, it is easy to find out the estimated losses based on the actual situation will be too subtle to reflect the changing trend of the variation of NPV. Since this research is developed from management's perspective, the focus is to develop catastrophic risk management strategy which may be derived from the changing trend of NPVs under different situation. Therefore, the assumptions in this case study exaggerate the losses in order to provide guiding information for the downstream risk management strategy development.

Table 7.8 The Target of Seismic Design for Highway Bridges

	The performance of the highway bridges			
Probability of EQ occurrence	Work well	Can work temporarily	Maintain safe structure	Remain stand, not collapsed
1/50	a			
1/75(1/100)	e	b		
1/475	h	f	c	
1/2000	j	i	g	d

For probability of EQ occurrence, expressway takes the number in bracket.

Table 7.9 Explanation of Performance State

Performance State	Capability description	Economic loss (of construction costs)
Work well	Can continue working without maintenance	1%
Can work temporarily	Slightly damaged, can continue working with minor maintenance or without maintenance	5%
Maintain safe structure	Structure is damaged but can resume pre-EQ performance level	20%
Remain stand, not collapsed	Structure remains not collapsed, can continue operating partially after maintenance	30%-50%

7.3.2.2 Hypothesis of Catastrophe Recovery

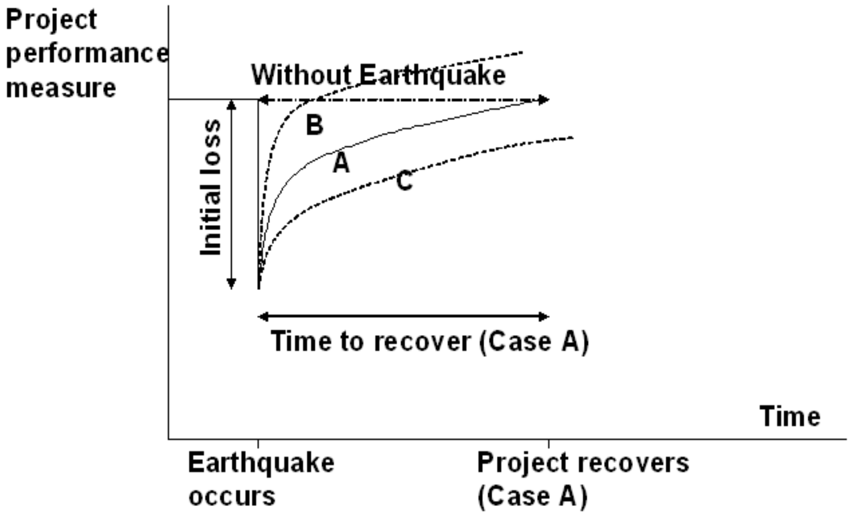


Figure 7.4 Schematic of Catastrophe Recovery

While the literature on loss modeling has been growing rapidly, modeling of recovery processes and time frames has been largely neglected. The significance of this distinction can be illustrated by the schematic diagram of recovery in Figure 7.4. Loss models generally focus on initial loss caused by a disaster where initial loss is measured in terms of post-disaster NPV of the project relative to what would have occurred without the disaster. It is noted that a project does not necessarily return to the baseline performance (pre-disaster condition); it may exceed it (case B in the figure) due to such factors as effective recovery planning or substantial inflow of disaster assistance, or it may suffer permanent losses and fall far below the baseline (case C). As for our case, case A will be assumed and the relevant traffic volume will develop according to the same trend from the year when the earthquake happens, that is to say, the original traffic volume is postponed for the recovery period from the moment when the earthquake happens.

As Figure 7.5 shows, the solid curve represents the situation without earthquake, and the dot-and-dash line refers to the situation after recovery works. The curve with dot-and-dash line exactly parallels to the curve with solid line. That is to say, the project after recovery in this case study will return to the pre-disaster condition.

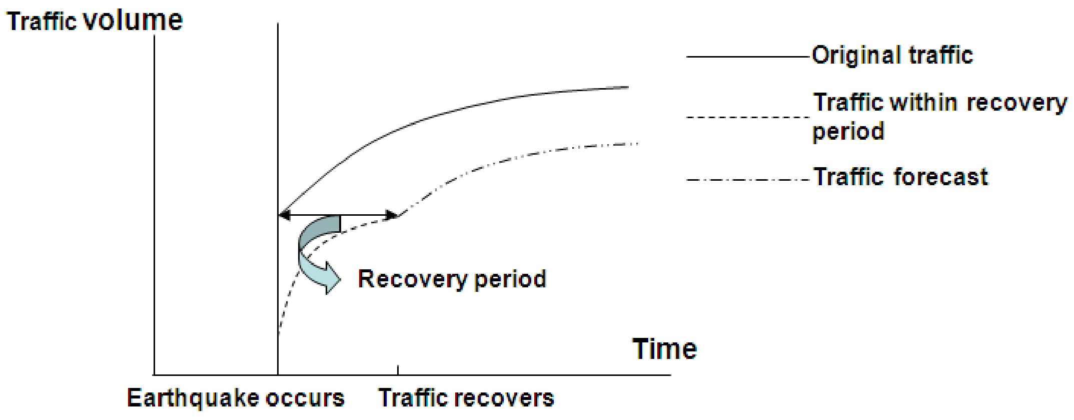


Figure 7.5 Traffic Volume Projections after Earthquake

Concessionaire is assumed to be responsible for the recovery costs in the original assumptions of the case study. As the externalities of infrastructure are important for the economic development, concessionaire may negotiate with the government for sharing the recovery costs before the agreement and/or after catastrophic events.

Table 7.10 Assumptions during the Recovery Period for Highway

Link Damage State	Recovery costs (%) classified by bridge age (year)		Capacity/Toll Revenue (%)	Operating and maintenance costs
	(0,10]	(10,20]		
Minor Damage	25	25.7	75	0
Moderate Damage	65	65.7	50	0
Major Damage	100	100.7	25	0

In Table 7.10, the repair costs are referred as the percentage of replacement costs of highway (Present value of CAPEX). And since the tariff remains the same during the concession period, the toll revenue will change with the flow capacity. The demand following the event is assumed to be the same as that before the earthquake, termed fixed demand analysis (Kiremidjian, Moore et al. 2007).

7.3.2.3 Hypothesis with Mitigation Strategy

There are three mitigation options as introduced in chapter 6. One is M-0, which means no mitigation in the whole project life at all. The second one is M-1, which means mitigation is conducted in the first beginning of the project. The third one is M-2, which means that mitigation is conducted after the construction period. In this case, the earthquake events are supposed to occur after construction period which means that there is little difference between M-1 and M-2. Therefore, in this case, M-1 will be discussed as a simplified illustration of mitigation strategy. Retrofit costs are assumed to be 20% of the replacement value of each bridge in this study.

The seismic performance of bridges, the most seismically vulnerable components in the highway transportation network, is probabilistically described by fragility curves, and can be significantly enhanced by various retrofit measures, such as steel jacketing, elastomeric bearing, restrainer cable and shear key etc. (Padgett, Dennemann et al. 2010). When subject to future earthquake events, the retrofitted bridges will not only experience less severe physical damage but will also result in significant improvement of the system performance by decreasing drivers' delay, a comprehensive index of system performance (Shinozuka, Murachi et al. 2003). It can be conceived that when more bridges are retrofitted in a highway network, repair costs for damaged bridges will be lower, and loss due to the business interruption will be less. A lot of research work has been conducted to study the feasibility of mitigation strategy for highway projects. In Padgett and Dennemann, et al (2010)'s study, the benefit-cost ratio varies from 0.03 to 1.19 with different mitigation measures.

Figure 7.6 shows that the fragility curves for bridges with and without retrofit. The fragility curve for retrofitted bridges shows a 55%, 75%, 104%, and 143% improvement for minor, moderate, major and collapse damage states, respectively (Shinozuka, S.H. Kushiyama et al. 2002).

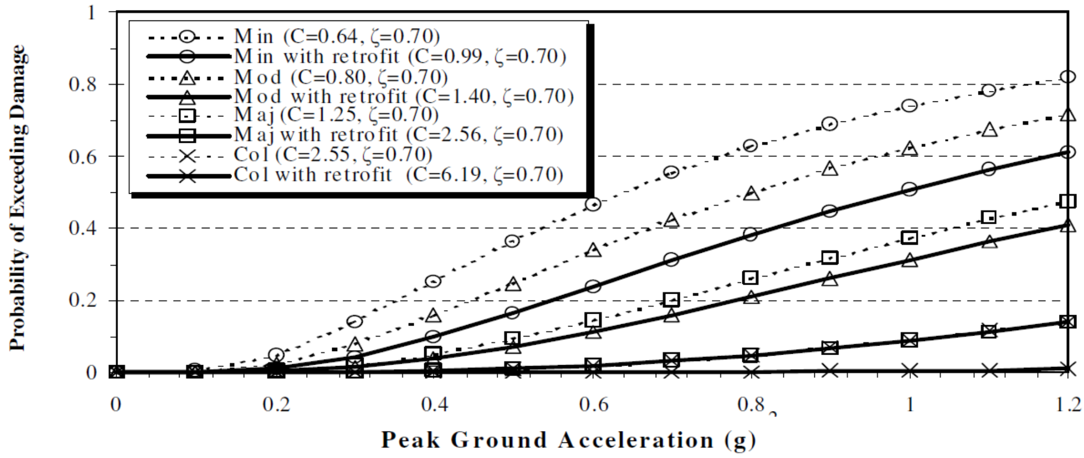


Figure 7.6 Fragility Curve for Bridges With and Without Retrofit

Following the 1994 Northridge Earthquake, the highway transportation system in the Los Angeles metropolitan area demonstrated a degree of system resiliency that was activated by enlisting and integrating some seismically unaffected secondary highways and artillery streets into the expressway network after it had suffered from the loss of several bridges. For this reason, in this analysis, alternate routes are considered to exist, although they had less traffic capabilities in terms of both free cash flow speed and capabilities as shown in Table 7.11, in terms of percent relative to the values under intact conditions, depending on the degree of the link damage. Link damage is represented by the worst state of the bridges on that link (this is a bottle-neck hypothesis; if, for example, one of the bridges on a link suffers from a major damage, and if that is the worst state of the damage, the link is assumed to have major damage.) The values in Table 7.11 are hypothetical and future research is needed to develop reliable values.

Table 7.11 Change in Road Capacity and Free Flow Speed

State of Link Damage	Capacity Change Rate	Free Flow Speed Change Rate
No Damage	100%	100%
Minor Damage	100%	75%
Moderate Damage	75%	50%
Major Damage	50%	50%
Collapse	50%*	50%*

Based on the cited case above, the assumption on costs and benefits of mitigation measure in this case study is given in Table 7.12. It is assumed that recovery costs will be reduced by 60% and toll revenue will increase by 60% as shown in Table 7.12. Please note that the actual benefit due to retrofit will not be restricted to the two items listed in the table below. However, many invisible benefits, i.e. reduced business interruption, are hard to measure and quantify, therefore the numbers denoted by the two factors are kind of exaggerated to try to be closed to the actual situation.

Table 7.12 Assumptions during the Recovery Period for Highway with Mitigation Measure

Link Damage State	Recovery costs (%) classified by bridge age (year)		Capacity/Toll Revenue (%)	Operating and maintenance costs
	(0,10]	(10,20]		
Minor Damage	10	10.28	120	0
Moderate Damage	26	26.28	80	0
Major Damage	40	40.28	40	0

7.3.2.4 Implementation of the Model

Given the importance of infrastructure projects, the government has relatively high seismic requirements such as Table 7.8 stated. According to compulsory requirements by Chinese government, JS highway should be able to resist earthquake of at least one in hundred without any impact. In this example, the model is implemented through Monte Carlo simulation, with the purpose to provide suggestions to catastrophic risk management. If the simulation is based on the actual situation, the temporal influence on NPV will be too subtle because the project life is too limited compared with the long reoccurrence period of earthquake. Therefore, the probability of damage is exaggerated in this numeral example so that some hint can be obtained from the changing trend of results. The overall damage state has to be simplified to be 3 types as shown in Table 7.13.

Table 7.13 Assumptions of Damage State Distribution

Damage state	Minor damage	Moderate damage	Major damage
Probability (%)	70	20	10

Initial prototyping of the model implementation was completed in a spreadsheet, which is inefficient for large datasets but helps to refine the model and will provide a check on the results from the final model implementation.

The full implementation is written in MATLAB. The programs of MATLAB type are particularly useful when studying an advanced analysis method that can be directly picked up from an available toolbox. MATLAB helps to enable temporal uncertainty and clear data structure design. It is designed to be portable, so it can easily fulfill different requirements.

The design of MATLAB program is shown in the flowchart as Figure 7.7 shows. The program starts from the first year of the operation period (Year 4) and runs annually. If the random (between 0-1) is less than the occurrence probability of earthquake, the logic flow path selected as the exit from the decision diamond is true path and will execute the next decision diamond. Otherwise, the logic flow path selected as the exit is false path and will go to Year i+1. Before the damage status is decided, the year of earthquake occurrence will lead to two different damage input data. After that, another random will decide which damage state it belongs to. If the second random (between 0-1) is not more than occurrence probability of minor damage state, minor damage data will be inputted to the cash flow model. If the random is less than the difference of 1 and occurrence probability of major damage state, major damage data will be inputted to the cash flow model. Otherwise, moderate damage data will be inputted to the cash flow model. Since the underlying assumption is that the earthquake doesn't happen more than one time, the earthquake occurrence circle will run only one time. After combining the annual cash flow with different path, NPV can be easily obtained and program ends. The whole program is attached in appendix I. The following sensitivity analysis is conducted based on this program as appendix II shows.

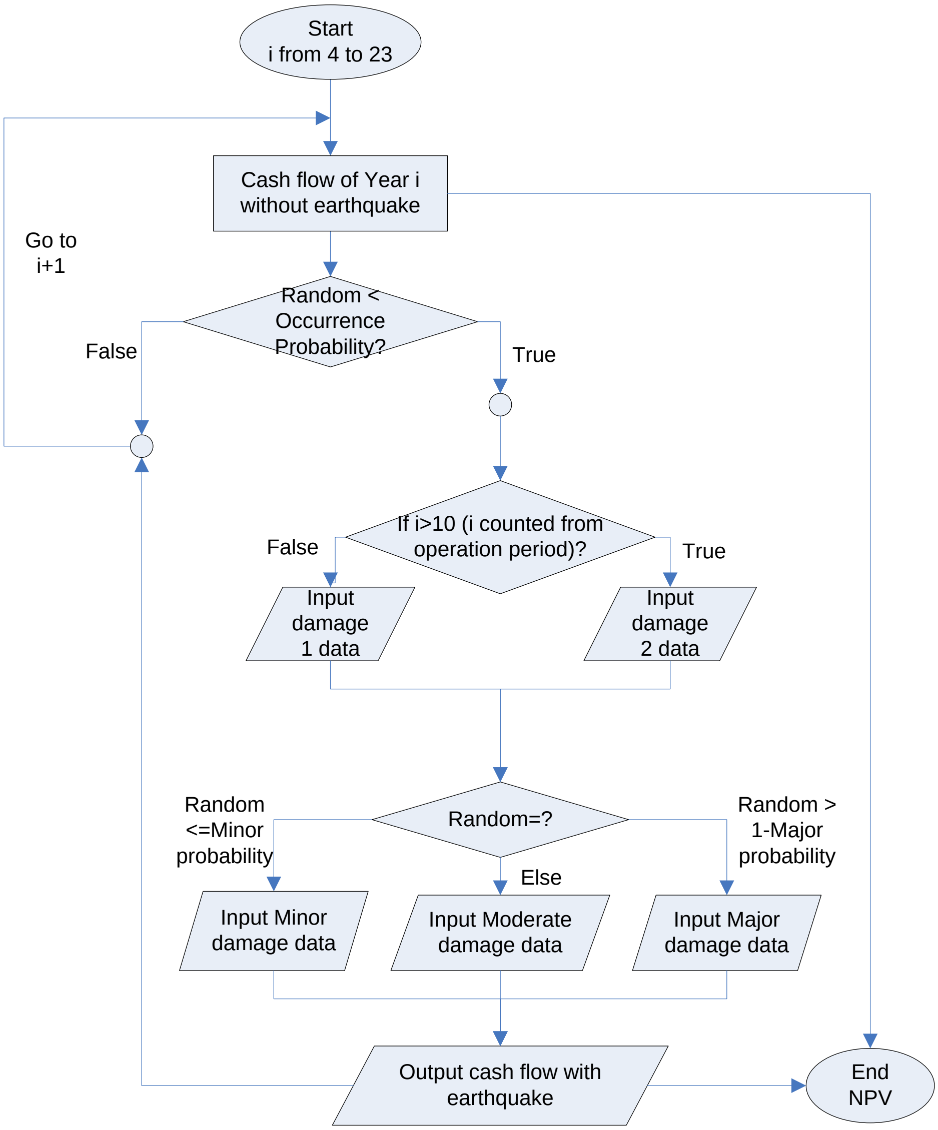


Figure 7.7 Flow Chart of the Programming of Seismic Impact on Cash Flow Model

7.3.2.5 Testing the Stability of Scenario Assumptions

There will be simplified assumptions and idealizations in the availability models of complex processes and phenomena. These simplifications and idealizations generate uncertainties which can be classified as aleatory (arising due to randomness) and/or epistemic (due to lack of knowledge). The problem of acknowledging and treating uncertainty is vital for practical usability of reliability analysis results.

Sources of uncertainty are associated with each phase of modeling and simulation. Aleatory uncertainty is used to describe the inherent variation associated with the physical system or the environment under consideration. Sources of aleatory uncertainty can commonly be singled out from other contributors to total modeling and simulation uncertainty by their representation as distributed quantities that can take on values in an established or knowledge range, but for which the exact value will vary by chance from unit to unit or from time to time. It is also referred to as irreducible uncertainty, inherent uncertainty, variability and stochastic uncertainty. Epistemic uncertainty is defined as potential inaccuracy in any phase or activity of the modeling process that is due to lack of knowledge. It is also referred to as reducible uncertainty, subjective uncertainty and cognitive uncertainty (Oberkampf, Deland et al. 2002).

The inherent variability such as earthquake occurrence and thereafter repair costs and period of the project imposes the use of probabilistic models; as such phenomena cannot be dealt with deterministic approaches. This variability is sometimes referred as randomness or stochastic uncertainty, commonly known as aleatory uncertainty, which cannot be reduced. However, probabilistic approach is built on a number of model assumptions and model parameters that are based on what is currently known about the physics of the relevant processes and the behavior of systems under given conditions. There is uncertainty associated with these conditions, which depends upon state of knowledge, is referred as epistemic uncertainty. It is important that the uncertainties in inherent variability of physical processes (i.e., aleatory uncertainty) and the uncertainties in knowledge of these processes (i.e., epistemic uncertainty) are properly accounted for.

In order to minimize the influence of epistemic uncertainty in the simulation model, sensitivity analysis needs to be conducted to set a reasonable number of run times. The standard deviation of NPV for a series of run times ranging from 1000 to 35000 under different occurrence probability is given separately in Figure 7.8.

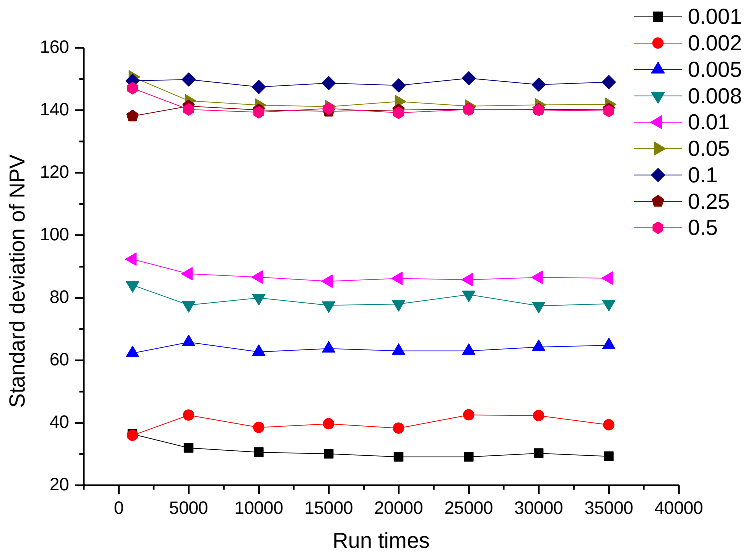


Figure 7.8 Run Times of Different Probability of Occurrence

It is surprising to find out that the results show little relevance to run times. Every curve remains little change and fluctuates slightly disorderly with run times vary. The possible reason may be that aleatory uncertainty in this simulation process overweighs epistemic uncertainty. In this case, the results can be hardly improved by increasing times of simulation. The epistemic uncertainty which mainly comes from temporal uncertainty of earthquake occurrence dominates the variation of results.

Moreover, it is interesting to note that the standard deviation of simulation has an obvious descending trend with the probability decreases. Especially after the occurrence probability becomes more than 0.1, the value of standard deviation will become relatively stable around 140. What's more, the values under different occurrence probability even become messed together. In order to have a better idea of the situation above, Figure 7.9 provides a clear picture of standard deviation of

NPV with different occurrence probability of earthquake. With the occurrence probability increases from 0.001 to 0.5, the standard deviation increases by around five times. It is easy to understand that the scenarios with earthquake substantially differ from each other, not to mention the differences between scenarios with earthquake and without earthquake, the larger probability the earthquake will happen, the more volatility the standard deviation will exhibit. When the occurrence probability is large as 0.1, the aleatory uncertainty overweighs the epistemic uncertainty so that the standard deviation exhibits relatively stable performance.

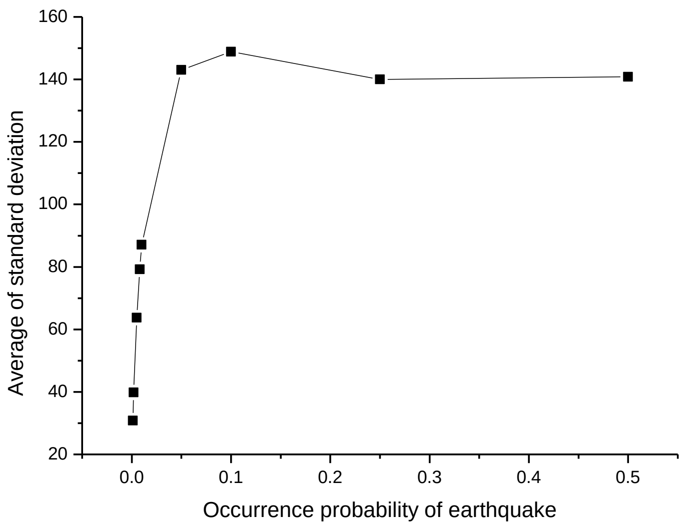


Figure 7.9 Standard Deviation of NPVs for Different Occurrence Probability of Earthquake

After careful examination, we can see that the standard deviation almost remains relatively less fluctuated when the run time is more than 10000. So the monitor times in this research will be selected to be 10000. In this case, the results obtained from the program are regarded as stable and reliable.

7.3.2.6 Catastrophic Risk Management for Concessionaire

When the estimated losses are achieved from the loss assessment module of Figure

7.1, the losses can be divided into 3 layers: lower layer which will be shared by private sectors; middle layer which can be provided by catastrophe insurance or catastrophe bond subsidized by government; upper layer which will be fully absorbed by government.

For JS highway, the average loss with occurrence probability of 0.5% is around 220 million RMB while NPV without earthquake scenario is 403 million RMB. So the estimated seismic loss should be around 183 million RMB. It is assumed that 10 million RMB is allocated to concessionaire, government is responsible of above 150 million RMB, while the amount between 10 to 150 million RMB is absorbed by catastrophe insurance. Based on this scenario, more details are discussed regarding catastrophic risk management strategy for concessionaire as below.

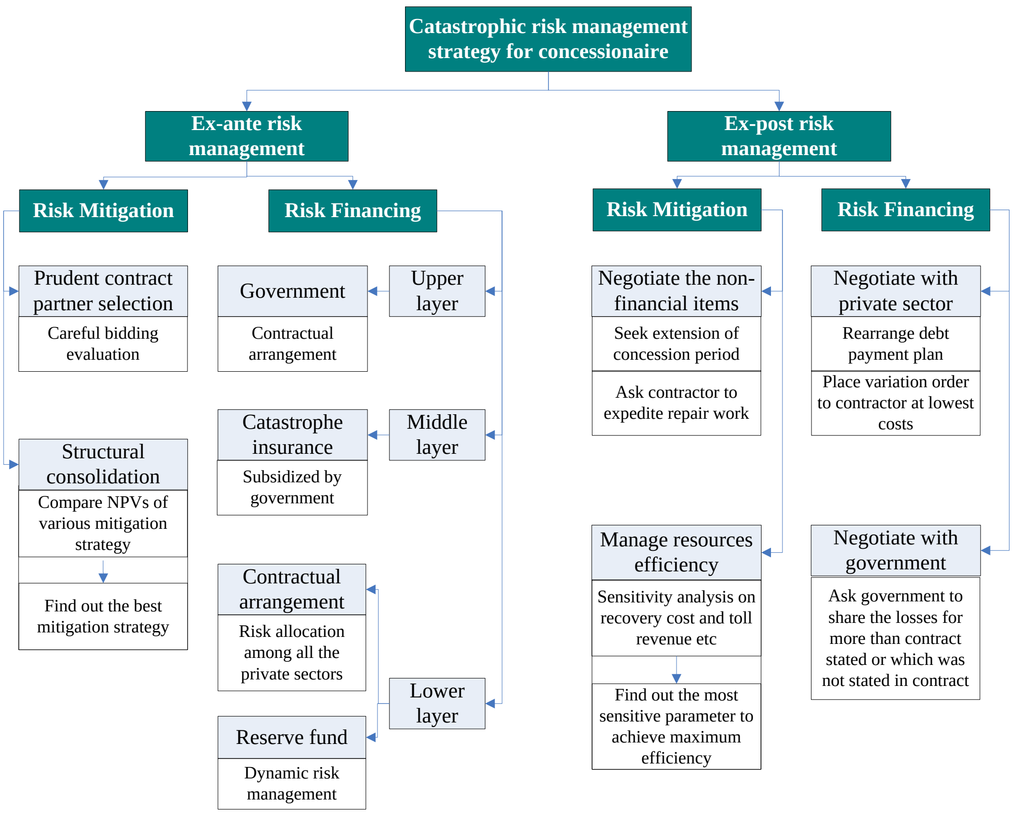


Figure 7.10 Catastrophic Risk Management Strategy for Concessionaire

Figure 7.10 shows catastrophic risk management strategy for concessionaire. One should note that the effects of ex-ante and ex-post arrangement vary even for the same measure. Ex-ante arrangement can secure immediate liquidity and minimize business interruption, while ex-post arrangement will incur extra costs due to business interruption brought by catastrophe events and increase the difficulty of negotiation. At the same time, concessionaire may be required to pay some fees for such ex-ante arrangement (which is not involved in this research) because of potential benefit provided by the other party given earthquake occurrence. In this case, cost-benefit analysis needs to be conducted to help develop an efficient risk management strategy.

7.4 Ex-ante Catastrophic Risk Management for concessionaire

7.4.1 Catastrophic Risk Mitigation

7.4.1.1 Prudent Contract Partner Selection

Prudential contract partner selection can secure the quality of the facility and decrease the default risk in case of catastrophic events. In order to find reputable and trustable partner, the concessionaire must be very careful in bidding evaluation stage. In this case study, JS highway project adopted invited tendering. All the invited bidders are believed to be trustable and have similar working experience before. Bidding evaluation is strictly based on “Procurement Guidelines” of Asian Development Bank (ADB) as well as relevant principles and procedures of tendering documents approved by ADB.

7.4.1.2 Structural Consolidation

Structural consolidation can reinforce the resistance ability of the facility. As stated in chapter 4, there are 3 options regarding mitigation measure: no retrofit (M-0), retrofit in the beginning (M-1), retrofit after construction period (M-2).

In practice, M-1 and M-2 need comprehensive tradeoff analysis. M-1 will impose heavy financial stress to the project since the costs of retrofit coincide with huge

CAPEX at the beginning of the project. M-2 will be more favorable compared with M-1 because the former happens to avoid the heavy outflow of the project. However, it also should be noted that the facilities will be more vulnerable in the construction period for M-2 than M-1.

In this simplified model, we assume that earthquake will not occur during the construction period, the potential benefit of M-1 in the construction period will be neglected in this way. NPVs of M-1 and M-2 will have slight difference given assumption of no earthquake in construction period. Only M-1 will be given as an example for mitigation strategy.Figure **7.11**Figure 7.11 shows the relationship of NPV under the variation of benefit brought by retrofit. The real line corresponds to the bottom x-axis and the dash line corresponds to the top x-axis. The y-axis is shared by two types of lines. The dash line refers to the situation without retrofit measure. That is to say, M-1 denotes that mitigation will be conducted (denoted by real line) and M-0 denotes no mitigation strategy (denoted by dash line).

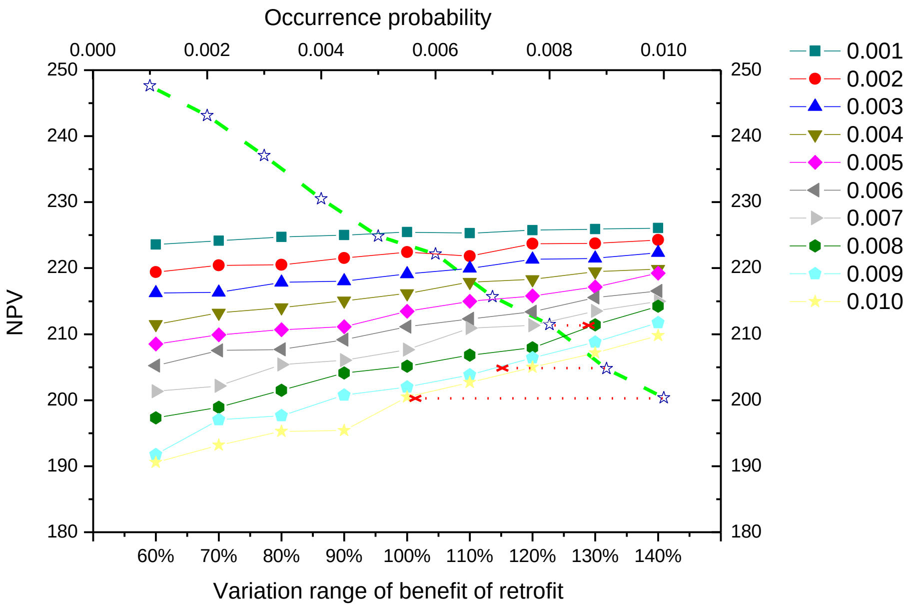


Figure 7.11 NPV of Different Mitigation Strategies

Figure 7.11 shows that when the occurrence probability is small varying from 0.001 to 0.007, NPV of M-0 is more than that of M-1 regardless of variation.

When the occurrence probability is large as of 0.008 to 0.010, NPV of M-0 will fall in the variation area of NPV of M-1, which means that NPV of M-1 sometimes exceeds and sometimes less than that of M-0. The red dotted line in Figure 7.11 connects the two NPVs under respective mitigation schemes. The crossover denotes that the two mitigation schemes will have the same NPV given the same occurrence probability. Take occurrence probability of 0.01 for an example, the crossover is around 100%. When the benefit of retrofit is more than this point, M-1 will achieve more NPV than M-0, and mitigation measure may be adopted by concessionaire. Otherwise, the concessionaire will prefer M-0 due to more NPV achieved. The result is in accordance with common sense. With the benefit of mitigation increases, the incentive of adoption of mitigation increases.

However, recall that in Chapter 6 optimal strategy selection program is introduced which implies that NPV is not the only determinants of strategy selection. The dynamic financial demand is another important factor which should be taken into consideration. Hence, concessionaire may wish to reconsider the mitigation decision when thinking of another important factor as Figure 7.12 shows.

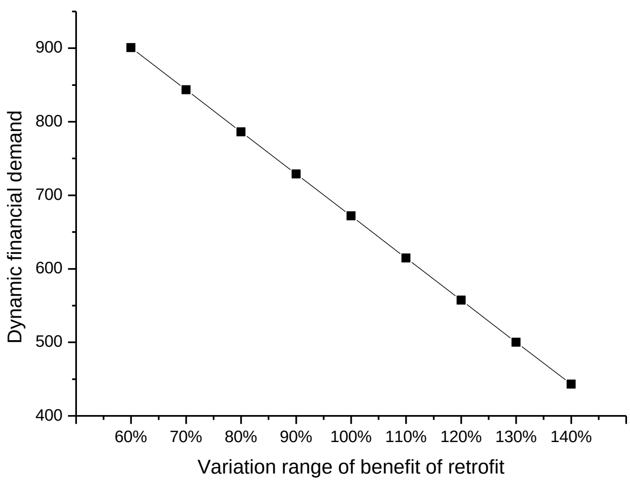


Figure 7.12 Dynamic Financial Demand with Different Retrofit Schemes

In order to develop an optimal strategy, the largest NPV will be compared with the second largest one. If the decreased amount of NPV is more than decreased financial demand, the strategy with the second largest NPV will be selected as an optimal strategy. In this way, we can easily find out that “140%” scheme remains to be the optimal strategy when occurrence probability varies from 0.001 to 0.01. The strength of M-0 is highly offset by the large dynamic financial demand. Therefore, mitigation will be carried out when taking dynamic financial demand into account.

Since MATLAB simulation designed in this case study assumes that there will be no earthquake occurrence in the construction period, it is no point to calculate NPVs of M-1 and M-2 using the current program. More assumptions on recovery module during the construction period need to be given if the model is used to incorporate the earthquake occurrence in the construction period. What’s more, dynamic financial demand due to catastrophe events should also be taken into account in order to develop an efficient risk financing strategy.

It is reasonable to infer that for concessionaire, once mitigation strategy is decided, the sooner the better it should be conducted because the dynamic financial demand should be overwhelming once earthquake occurs during the construction period. That is to say, although it is not sure if M-2 will have larger NPV, the save of dynamic financial demand of M-1 will definitely overweigh the possible increased NPV of M-2. So M-1 should be always better than M-2 in terms of optimal strategy selection from concessionaire’s perspective if there is no financial constraint.

7.4.2 Catastrophic Risk financing

7.4.2.1 Reserve Fund

Concessionaire need prepare a certain amount as reserve fund in case of catastrophes. The first determinant of reserve fund is dynamic financial demand. Dynamic financial demand specially increased by catastrophic events can be easily quantified as *max* [$F_d^1, F_d^2, F_d^3, \ldots F_d^t$] ($t$ = project life) according to dynamic risk management. In contrast, traditional financial demand is quantified as cumulative losses of the project life. The former is proved to be more effective and realistic than the latter because it may be kind of waste to make such a large amount of fund earmarked for reserve fund only.

For JS highway project, given the assumption of no catastrophic events in the construction period, the dynamic financial demand should be decided by the extra financial need due to catastrophes annually during the operation period. Since revenue is overwhelmingly larger than operation and maintenance costs for JS highway, the decrease of revenue will offset the decrease of operation and maintenance costs, and decrease of revenue becomes the dominant determinant. It is easy to conclude that dynamic financial demand should result from the difference of cash flows for the two scenarios (with and without catastrophes) of the year with the largest revenue.

The second determinant of reserve fund is financial constraint of the project. If there is no enough fund, reserve fund cannot be set up at all. Hence, reserve fund is restricted by the fund available no matter how much financial demand is indicated by the cash flow injection.

Last but also the most important determinant of reserve fund is risk management strategy. Even though there is enough fund to cover dynamic financial demand, concessionaire may not necessarily put the amount required by financial demand into reserve fund. Corresponding contractual arrangement will be used to allocate all the risk to other stakeholders such as government, contractor, supplier, banker, etc. Financial instrument such as catastrophe insurance can also be introduced to transfer some risk. After all the risks have been absorbed by other parties, concessionaire may use reserve fund to cover the residual financial gap.

7.4.2.2 Contractual Arrangement

The lower layer financial demand due to catastrophic risk is normally shared among the private sector. The specific terms and conditions of allocating catastrophic risk need to be negotiated and determined before reaching agreement. In the contract, it must be clearly stated that how the risk is allocated to each party, how to secure the recovery/rebuilt work, the costs and time related to the recovery/rebuilt work, etc. The contract should forecast and incorporate all the works related to catastrophic risk to avoid potential variation order and arbitration. For example, concessionaire may ask for sharing recovery costs with contractor in case of catastrophes; or concessionaire may ask for expediting recovery work without extra costs in the contract; or concessionaire may negotiate with the banks and ask for deferring or cutting down the debt payments.

Negotiation with banks may take various forms. For example, concessionaire can negotiate for extending repayment period, decrease interest rate, increase loan, or some other types of agreements which imply concession of the bank. Here we just proposed one type of negotiation as an illustrative example. The original assumption is that the debt payment could be deducted or waived during the recovery period if there is earthquake occurrence, the deducted part will be added back at the end of the repayment period without extra interest. For this sensitivity analysis, in order to have a clearer picture, we give a more extreme assumption that the debt payment could be deducted or waived according to the parameter selected during the recovery period with earthquake occurrence, the rest repayment plan will remain the same and no complement will be made later for the deducted part.

In this case, the financial pressure of the concessionaire brought by earthquake will be smaller and NPV will be improved accordingly. Figure 7.13 shows the results of the NPV and dynamic financial demand with different assumptions. x% of horizontal axis means that the debt payment becomes x% of the original debt payment in the recovery period. For example, x equals to 25% means that the debt holders will only get 25% of the original debt payment during the recovery period.

As have been introduced previously, dynamic financial demand of each year is the annual maximum financial gap considering all the possibility. Dynamic financial demand for the project is defined as the maximum financial gap of the whole project life. Given the simulation times of 10000 which are large enough to eliminate random impact, the maximum financial demand during the operation period must appear at the year with minimum cash flow and major damage state which will not vary with different occurrence probability. The conclusion is in accordance with the result of simulation as appendix IV shows.

Figure 7.13 shows that NPV under different debt repayment schemes. It is easy to find out that NPV will increase with occurrence probability increases from 0.001 to 0.01 which is in accordance with the common sense. The green dash line refers to dynamic financial demand under different debt repayment schemes. It is easy to understand that with debt repayment increases, dynamic financial demand will increase.

Different debt repayment schemes may provide various financial protection which may reduce the financial burden to different degree. Some costs will need to be paid for the respective schemes, and there is different dynamic financial demand for each of them. How to combine them together and achieve a best strategy remains to be a big issue for concessionaire. We use NPV which takes into account benefits and costs of the various measures to combine the effects of financial protection and costs incurred. One should note that NPV can be used to help make decision but not an absolute determinant for the final decision, because the financial protection is potential and invisible in the future, and the incurred costs are actual and concrete at the moment.

An ideal risk financing strategy should have maximum NPV and minimum dynamic financial demand at the same time. However, it may be difficult to achieve the ideal targets for one single scheme. Therefore, a most efficient strategy is necessary to be developed as the methodology introduced in chapter 6. Let's recall the procedure of developing an optimal strategy. In order to find the most efficient strategy, we need make comparison between difference of *NPVs* and F_d (Financial demand). Tradeoff between the decrease of F_d and *NPVs* need to be studied. The first step is to pick out the largest *NPV* among the various *NPVs* for the same F_d. The smaller ones will be deleted and the larger one will be remained for further comparison. The second step should start from the strategy with minimum F_d. With F_d of the first strategy increases, *NPV* should increase accordingly. Otherwise the second strategy should be eliminated. If *NPV* increases with F_d, comparison between the increasing amounts for both of them will be made. When difference of *NPV* is larger than that of F_d, the opportunity value of F_d is larger than its cost. In other words, the potential benefits of increased financial demand are more than its costs. In this case, strategy with the larger NPV is proved to be more efficient and should be selected.

According to the principle listed above, the optimal strategy remains to be "0% debt repayment" when occurrence probability varies from 0.001 to 0.01, which imply that negotiation with bank is always necessary. One should note that in practice, some costs need to be paid for contractual arrangements like this, which should be taken into account but are omitted for simplification in this case study.

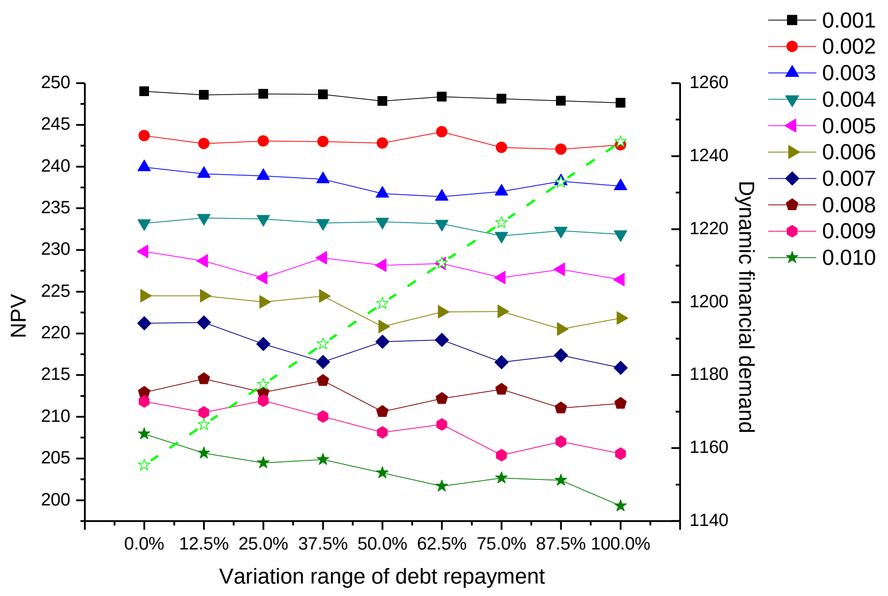


Figure 7.13 NPV and Dynamic Financial Demand under Different Debt Repayment Schemes

As Figure 7.14 shows, the curves fluctuate and with obvious descending trend when the original debt repayment is deducted or waived. The reason of disorderly variation may origin from the temporal uncertainty embedded in the simulation process which overweighs the potential benefit brought by the rescheduled debt repayment plan. With sensitivity analysis of variation of NPV versus various debt repayment schemes, we can find out that the need of debt negotiation grows with the occurrence probability increases. In the area with low occurrence probability, less fluctuation and less relevance is observed through such arrangement, so it may be of low interest to negotiate with banks or other debt holders because even though the banks grant zero payment in the recovery period, NPV will not be improved greatly although the dynamic financial demand may be improved certainly. In the area with high occurrence probability, the negotiation with debt holders is relatively more worthwhile.

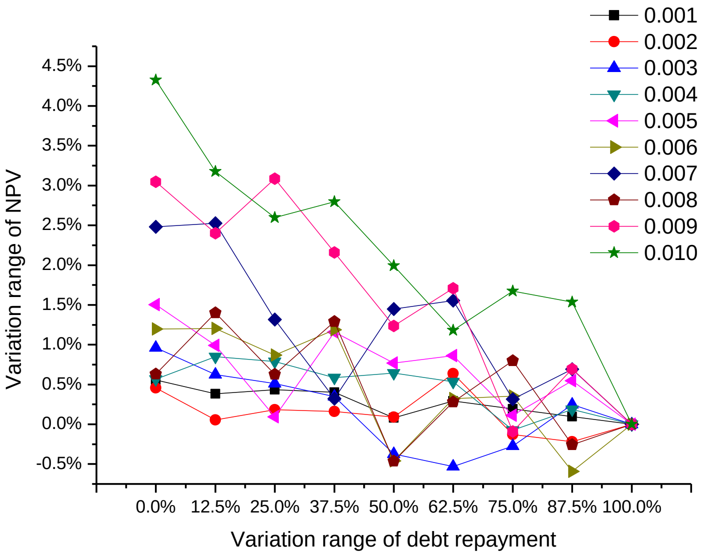


Figure 7.14 Variation of NPV under Different Debt Repayment Schemes

7.4.2.3 Catastrophe Insurance

Catastrophe insurance is available for concessionaire seeking to transfer their catastrophic risk which covers risks with an uncertain probability/size of loss (e.g., earthquake) and risks with an unknown probability/size of loss (e.g., nuclear accident or terrorist attack) when government provides financial and/or legislative support. Catastrophic coverage commonly will include several different dimensions such as property and casualty (P&C), liability and life, etc., but only P&C and business interruption as two of the most important dimensions will be explored here.

P&C coverage is intended to provide post-loss financing for any physical property that is damaged or destroyed by catastrophic events. Under many P&C contracts insurers use actual cash value which is replacement less depreciation to determine post-loss settlement if property is destroyed and not rebuilt or replaced. For PPP infrastructure system, it may not easily be destroyed by a catastrophe event; hence the terms regarding recovery costs may be designed carefully to be involved.

Business interruption coverage aims to provide compensation for revenues lost as a result of an inability to operate business in a normal fashion after a catastrophe strikes. In most policies the coverage is written on the basis of "actual losses sustained", meaning that concessionaire and insurers must mutually agree on amounts lost. The most difficult part of business interruption is how to calculate the indirect losses. For PPP infrastructure facilities, the impact of catastrophes may not necessarily equal to the losses reflected by the decreased revenues at the same time of occurrence or even during the recovery period. The regional economy need time to be recovered; therefore the revenue of infrastructure facilities which is highly related to the regional economy may also be affected for quite a long time after catastrophe occurrence.

Deductible and policy caps can be used to define a level of risk retention by limiting the insurer's settlement liability to concessionaire: the higher the deductible, and/or the smaller the cap, the greater the ultimate retention and the lower the transfer. In practice, risk retention varies with different policy coverage/exclusions. By specifically defining the scope of desired coverage the concessionaire indicates which risks it is willing to retain and which it prefers to transfer. Concessionaire is responsible for identifying and specifically removing exposures that it wants to retain. In this case study, concessionaire seeking to transfer a significant amount of catastrophic exposure (from 10 million to 150 million for this JS case study) might feature a 150m policy cap and a 10m aggregate deductible. After the first 10m RMB of losses which may come from a single event or many smaller ones, the next 150m RMB of losses is fully covered by the insurance company.

7.4.2.4 Absorbed By Government

Government is always the last resort of concessionaire. Obviously, it will be responsible for the economic losses above the cap of catastrophe insurance. In addition, concessionaire will seek compensation from government for all the controversial losses and unexpected losses which are not stated in the contract. Normally these losses beyond the contractual arrangement should be shared by both public sector and private sector. There is no standard and fixed stipulation for specific allocation scheme. It varies with different cases and depends on negotiation between both parties. For example, concessionaire may ask government to compensate the mitigation costs if retrofit will be conducted at the beginning of the project; or concessionaire may ask government to share the recovery costs, etc. Sensitivity analysis is conducted below to find the impact of variation of recovery costs on NPV under the scenario of moderate damage.

x% in the horizontal axis means that the recovery costs become x% of the original assumption, and the rest of recovery costs should be borne by the government and counted out from the recovery costs from concessionaire's standpoint. The green dash line refers to dynamic financial demand under different recovery costs.

Figure 7.15 shows that NPV will decrease with occurrence probability increases, and with recovery cost increase for the same occurrence probability. With occurrence probability increases, the dynamic financial demand will increase. According to the methodology introduced above, an optimal strategy will be "60% of recovery costs" when occurrence probability varies from 0.001 to 0.01. That is to say, the optimal strategy is to transfer recovery costs to other parties as more as possible. It is noted that such negotiation is more worthwhile in earthquake prone area.

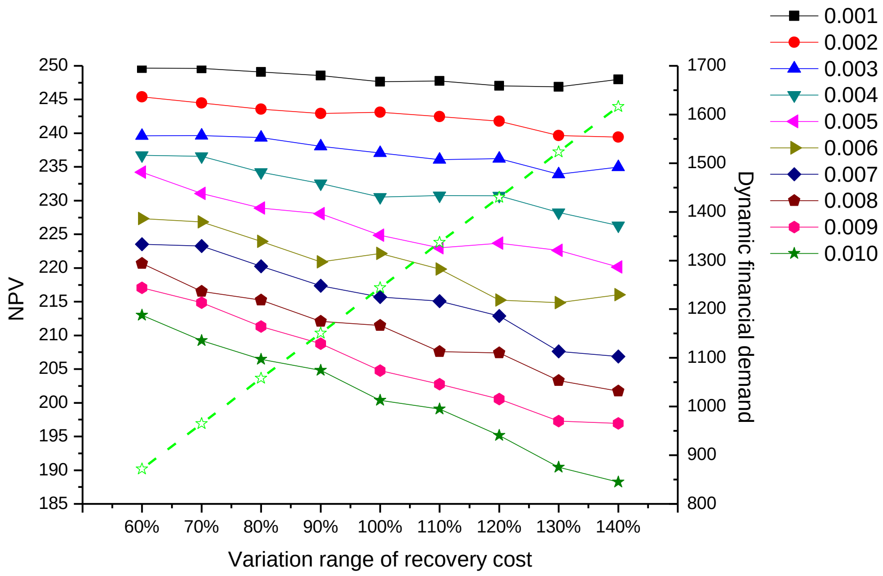


Figure 7.15 NPV and Dynamic Financial Demand with Different Recovery Costs

Figure 7.16 gives a clearer picture on this point that NPV will decrease with recovery cost increases, and NPV variation will be greater with higher occurrence probability. Based on the results, concessionaire should try to negotiate with government and transfer as more recovery costs as possible to government.

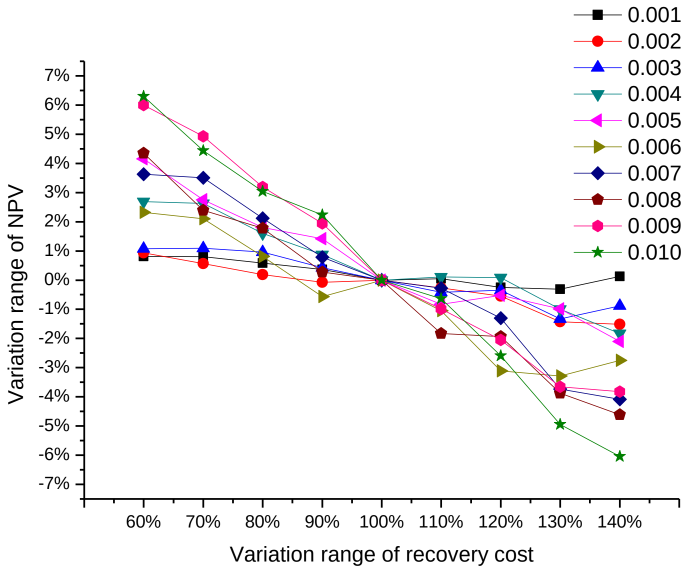


Figure 7.16 Variation of NPV with Different Recovery Costs

7.5 Ex-post Catastrophic Risk Management for Concessionaire

Active risk management as an essential element of proper governance and management is popularly accepted for high frequency/low severity risks. However, it is not as widely used in the context of catastrophic risk. The process of formally reviewing the relative costs and benefits of catastrophic loss control, loss financing and risk reduction of PPP infrastructure projects is not well established for public and private sectors. Some of the efforts are temporary, and in some instances the process is viewed as a secondary priority. The stakeholders of PPP infrastructure projects often focus risk management efforts on the small but frequent risk problems that can affect daily operations. Those lacking fist-hand experience with catastrophic losses may not fully appreciate the financial distress that can arise with a disaster. As a result, active management of catastrophic risk is not yet uniform across the industries and countries. This will become a more significant problem as vulnerabilities grow, as well as frequency and severity of catastrophes increase. Although most of ex-post catastrophic risk management is passive action and not advocated, it can be used to complement ex-ante risk management given lack of active risk management.

7.5.1 Catastrophic Risk Mitigation

7.5.1.1 Negotiate the Non-financial Items

Normally the cumulative revenues of the PPP infrastructure facilities increase with time passes by. Concessionaire may negotiate with government for extension of concession period, so that more revenues are expected to cover the losses due to catastrophic events. Such negotiation does not involve any direct extra costs, hence it may be easier for government to accept compared with risk financing negotiation such as asking for sharing unexpected losses.

The sooner the facility is recovered, the sooner the revenue resumes. Concessionaire may also ask contractor to expedite the recovery progress and reduce recovery period. Such negotiation may be difficult to proceed. The recovery work may face with safety issue when there is high possibility of secondary hazards. Very often earthquakes with different magnitude triggered different secondary hazardous events, frequently attributed to the epicentral area of a strong earthquake. Aftershocks are the main secondary process accompanying earthquakes of different magnitudes. Other secondary hazards such as landslides, rockfalls, liquefaction, avalanches and tsunamis etc. also have the potential to impede the recovery work and make the expedition more difficult.

7.5.1.2 Manage Resource Efficiently

Resources are limited and precious when a catastrophe strikes. Effective management of resource can expedite the recovery work and reduce economic losses. For example, for JS highway project, among the 3 damage scenarios, moderate damage scenario as the most common situation is selected to be as the base case. Sensitivity analysis under moderate damage scenario is conducted as below to find the most sensitive parameter to achieve maximum efficiency.

Figure 7.17 shows the relationship of revenue variation and NPV variation. x% in the horizontal axis means that revenue becomes x% of original assumption. The vertical axis refers to the percentage variation of NPV according to the different variation of assumptions respectively, and is calculated as the formula shows: (New NPV— original NPV)/absolute value of original NPV. Please note that the vertical axis named as "variation of NPV" has the same meaning in this report except special demonstration. All the condition remains the same except that "Damage_Rand" is fixed at 0.8 in MATLAB simulation program so that the damage state will be fixed at "moderate damage".

As Figure 7.17 shows, with toll revenue increases, NPV will increase accordingly. With other situation the same, one percent variation of toll revenue will produce around 3 percent variation of NPV. Therefore, it implies that toll revenue is a sensitive parameter since small change in assumptions will lead to large change in NPV.

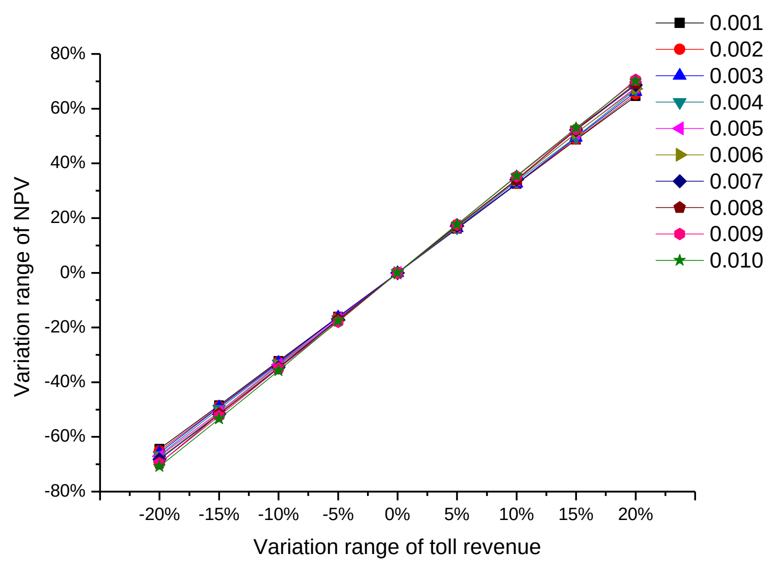


Figure 7.17 Revenue Sensitivity Analysis for Moderate Damage

As Figure 7.18 shows, the curves fluctuate but have an obvious descending trend with recovery costs increase. It is also noted that the variation range of NPV falls into relatively small area. Therefore the variation of recovery costs shows little relevance to fluctuation of NPV. That is to say, recovery cost is not a sensitive parameter which may influence NPV greatly.

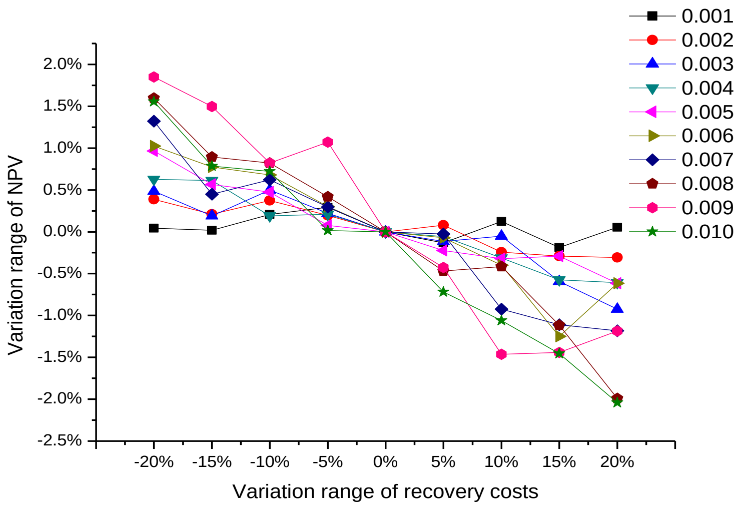


Figure 7.18 Recovery Cost Sensitivity Analysis for Moderate Damage

The results from the two figures above show that concessionaire should pay more attention to revenue instead of focusing on recovery cost because increase of revenue may achieve more NPV than decrease of recovery cost with the same efforts.

In practice, such sensitivity analysis can be used to analyze all the factors which will influence NPV of the project. Through such analysis, it is easy to find out the relationship of impact factors and NPV. In this way, concessionaire may easily develop catastrophic risk management strategy through setting the priority of those impact factors.

7.5.2 Catastrophic Risk financing

7.5.2.1 Negotiate with the Private Sector

Concessionaire may negotiate with the private sector to seek direct and indirect financial aid. Same as ex-ante contractual arrangement, concessionaire may negotiate with the banks and ask for deferring or cutting down the debt payments. The agreement between the two parties is better to be reached at the beginning of the project as an active risk management strategy. Otherwise it can also be arranged after earthquake occurrence as a passive reaction which is normally not advocated. Such ex-post negotiation may be viable because the banks will be difficult to get principal and interest back if the highway closes or even the project company declares bankruptcy. The same debt sensitivity analysis as that of contractual arrangement can be conducted to explore the impact of negotiation with banks on variation of NPV.

7.5.2.2 Negotiate with the Government

In practice, recovery cost is shared by public sector and private sector. The specific allocation scheme is case depended. Even though there are specific stipulations in the contract, concessionaire may ask for transferring more recovery costs than those included in the contract to government. This kind of negotiation is viable because the externalities of infrastructure projects are important for the government. Same sensitivity analysis as that for ex-ante agreement can be conducted to explore the impact of variation of recovery costs on NPV.

7.6 Catastrophic Risk Management for Government

Similar with catastrophic risk management strategy, the strategy developed for government is structured as Figure 7.19 shows.

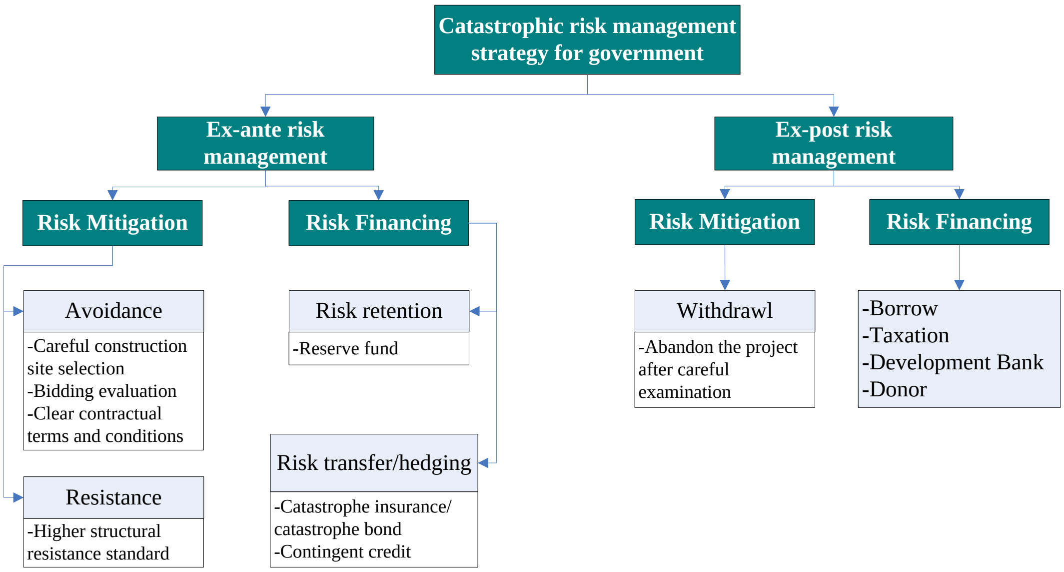


Figure 7.19 Catastrophic Risk Management Strategy for Government

7.6.1 Ex-ante Risk Management for Government

7.6.1.1 Catastrophic Risk Mitigation

Government should avoid or at least reduce catastrophic risk starting from the beginning of the project and lasting for the whole facility life. For example, government should be careful during construction site selection. There are relatively less options for highway projects because the shortest route connecting two destinations is roughly decided. Thorough research must be conducted to convince government that the route must be changed due to high catastrophic risk. In this case, alternative route will be proposed to replace the original one.

According to compulsory requirements by Chinese government, JS highway should be able to resist earthquake of at least one in hundred without any impact. In this case study, the model is implemented based on the cash flow of the project through Monte Carlo simulation, with the purpose to provide suggestions to catastrophic risk management. If the simulation is based on the actual situation, the seismic influence on NPV will be too subtle because the project life is too limited compared with the long reoccurrence period of earthquake. Therefore, the severity of damage is exaggerated in this numeral example so that some hint can be obtained from the changing trend of results.

Government may also wish to improve structural earthquake resistance standard if enough proof shows that the current structural resistance cannot meet the current earthquake resistance requirements. For JS highway, if Chinese government finds that there will be high possibility to incur large seismic losses with current earthquake resistance code, government may issue higher earthquake resistance code, requiring concessionaire and contractor to improve the earthquake resistance capability. Such legislation may be difficult to put into practice because there will be more costs incurred due to such requirements. Private sector may ask for compensation from government if government issues higher earthquake resistance standard.

In addition to careful site selection and legislation on earthquake resistance standard, careful examination of bidding evaluation must be conducted to avoid default risk of concessionaire in case of catastrophes. Clear contractual terms and conditions are also used to keep the government away from distribution and being claimed for more than contract states after catastrophes.

7.6.1.2 Catastrophic Risk Financing

For all the risks assumed by government stipulated by concessionaire agreement, government may set up a certain amount of reserve fund which will be available at the first time after a catastrophe strikes. In addition, financial instruments such as catastrophe insurance, catastrophe bond and contingent credit can be used to transfer catastrophic risks. For JS highway, the government may arrange for a 150 million RMB, 5-year contingency loan that becomes available when earthquake creates at least 150 million RMB of claims on policies that it has been insured; for any losses below that amount it may simply rely on standard catastrophe insurance. Since the government has far less flexibility in draw down under a contingency loan than a standard facility, and the probability of draw down is much lower, it pays a smaller fee. Key terms of the contingency loan are defined in advance, including maximum draw down amount, fixed or floating rate, maturity, repayment schedule, triggers, and so forth. Facilities are often syndicated broadly, so that each participating bank has only a moderate share of what might otherwise be a large commitment.

7.6.2 Ex-post Risk Management for Government

Ex-post risk mitigation for government has nothing to do but abandon the project to minimize the losses given the extreme situation. Abandon of PPP infrastructure projects will be under careful examination because the special attributes of such projects. For JS highway, alternate routes are considered to exist, although they had less traffic capabilities in terms of both free cash flow speed and capabilities. Given the extreme situation, JS highway will be abandoned and alternate routes will be adopted.

Ex-post risk financing for government includes borrow, taxation, aid from international institution and donor etc. In case of earthquake, Chinese government may borrow from domestic citizens by issuing government bond; or government also can borrow from abroad institutions such as ADB. During the recovery period, Chinese government may request higher taxation from other provinces/districts such as Guangdong Province which is exempt from seismic impact. In this case, the financial stress of the disaster area may be relieved temporarily. Donor from abroad and domestic sources also can be used for recovery works of JS highway.

7.7 Summary

Figure 7.20 covers the full range of catastrophic risk management strategy development for PPP infrastructure projects. Based on the hazard module, vulnerability module and loss module, with temporal uncertainty incorporated by Monte Carlo simulation, the financial losses including direct and indirect losses of the PPP infrastructure projects can be obtained from concessionaire's perspective. Catastrophic risk management strategy for such projects is developed from concessionaire's and government's perspective respectively based on the estimated loss derived from catastrophe model.

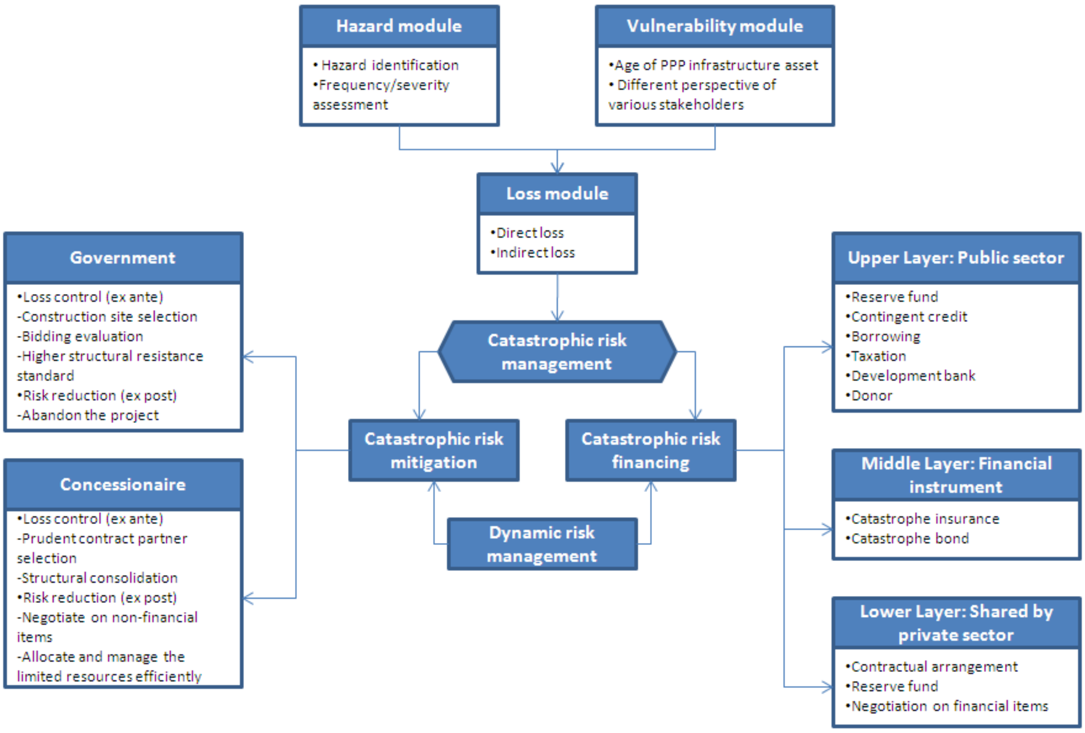


Figure 7.20 Catastrophic Risk Management for PPP Infrastructure Projects

The catastrophe model of calculating financial losses is developed for highway project of seismic risk, and it can be applied to other highway projects and even other types of PPP infrastructure projects depended on the similarity of cash flow generation. It is easy to understand that the input module for loss estimation including hazard module, vulnerability module, and damage module, etc will change for different projects and catastrophes. Hazard module varies with location changes even for the same catastrophic event. Different projects cannot remain vulnerability unchanged; hence the damage module will be different surely. However these input module change, the same MATLAB program can be generally applied only if the cash flow will have similar projection with and without catastrophe events. If the cash flow of the project has different performance after catastrophe occurrence, with some revision on the program, similar methodology can be utilized to calculate the loss estimation and therefore provide suggestion on catastrophic risk management strategy development. In a word, this methodology can be applied to the highway projects with similar cash flow projection and may be extended to the other types of PPP infrastructure assets of other types of catastrophic risk when respective revisions of MATLAB program are available.

Although the first three module including hazard module, vulnerability module and loss module are limited to seismic risk for highway projects, catastrophic risk management strategy developed based on the estimated losses derived from the first three modules can be easily applicable to other types of infrastructure system and catastrophes.

Catastrophic risk management includes ex-ante risk management and ex-post risk management. Ex-ante risk management is always better than ex-post risk management since it need less costs and may prevent or decrease potential losses. However, given lack of cognition of catastrophic risk or inappropriate/insufficient arrangement of ex-ante risk management, the project has to resort to ex-post risk management for most actual cases.

Catastrophic risk management also can be divided into risk mitigation and risk financing. For JS highway, most of proposed ex-ante risk mitigation measures including prudent construction site selection, careful bidding evaluation and higher structural resistance standard have been achieved by Chinese government. Ex-ante risk mitigation such as mitigation is more complex for concessionaire. M-1 (mitigation in the beginning) definitely gains superiority compared with M-2 (mitigation after the construction period) when taking dynamic risk management into account. Therefore, if mitigation is decided, concessionaire will select M-1 rather than M-2 as an optimal strategy.

Ex-post risk mitigation of concessionaire involves negotiation on the non-financial items and effective allocation of the resources. Some negotiation such as extension on concession period may be more attractive compared with the costs-related negotiation for government because it doesn't impose instant financial stress during the financial crisis caused by catastrophic events. For JS highway, sensitivity analysis is conducted to examine the impact factors with the purpose to find the relationship of variation of such factors on NPV. The result shows that toll revenue is more important than recovery costs for concessionaire. Concessionaire need pay more attention to toll revenue rather than recovery costs. In other words, concessionaire need make more efforts and/or put more resources to maintain the revenue than reducing recovery costs. It does not mean decrease of recovery costs is not important, but it just points out priority of resource management and guides efficient resource allocation based on limited resources.

Catastrophic risk financing is based on three layers decided by concession agreement between government and concessionaire. The lower layer is shared by private sector. Concessionaire will allocate such risks among all the private stakeholders including contractor, banks and suppliers, etc through contractual arrangement. For JS highway, sensitivity analysis of debt repayment plan is conducted to provide suggestion for negotiation with banks. The result shows that in the area with low occurrence probability, it is of low interest to negotiate with banks or other debt holders while in the area with high occurrence probability, the negotiation with debt holders is relatively more worthwhile.

The middle layer will be financed by financial instrument such as catastrophe bond or catastrophe insurance. Due to the special attributes of PPP infrastructure assets, such financial products can only be available with government's subsidy. For JS highway, it is assumed that catastrophe insurance will cover catastrophic losses above 10 million RMB and will cap at 150 million RMB.

Government covers the upper layer of catastrophic risk financing, and it is the last resort of risk transfer for the infrastructure projects. The catastrophic risk faced by government is far more than a single infrastructure project because the impact of catastrophic events may be spatially disperse and wide-range. So when the catastrophic loss is huge to exceed the upper limit (150 million RMB in this case) which concessionaire cannot sustain, the government is also faced with extreme financial burden due to catastrophe event. Government need develop ex-ante risk financing strategy to be prepared well for the potential catastrophic risks. Reserve fund is important to secure immediate recovery works so that extra losses due to delay in resuming operation can be avoided. Besides reserve fund, government may resort to financial instruments such as contingent credit to make sure that there will be fund available for recovery works in case of overwhelming disasters.

In practice, not a single risk financing measure will be used, but all the possible risk financing measures including catastrophe insurance etc. should be considered and analyzed. An optimal risk financing strategy should conduct comprehensive cost benefit analysis of all these measures as well as dynamic financial demand of each measure. In this way, all the possible risk financing measures are combined together to achieve the most efficiency, which produce an optimal strategy.

Chapter 8 Conclusions and Recommendations

The last chapter first introduced catastrophe model based on cash flow of the PPP infrastructure projects which takes the temporal uncertainty of catastrophe events into account through Monte Carlo Simulation by MATLAB programming. Then the design and development of catastrophic risk management strategy from concessionaire and government's standpoint respectively was summarized. Finally, the chapter closes with limitation of this research as well as recommendations for further research.

8.1 Design of Catastrophic Risk Management Strategy

8.1.1 Catastrophe Model based on Cash Flow of PPP Infrastructure Projects

Catastrophe model based on cash flow of PPP infrastructure projects is developed with MONTE CARLO simulation to incorporate temporal uncertainty. Annual cash flow of the project forms the basis of MATLAB program. The cash flow of past years reflects the actual operating performance of the project directly, and the future cash flow is forecasted based on the past performance and assumed growth rate of annual traffic volume. Hazard module and vulnerability module is better constructed with engineering's experience in order to obtain the accurate losses from the model. This research is mainly set up from management's perspective, so the input from vulnerability module and hazard module is mostly based on assumptions, the result will guide the following risk management strategy development because the absolute value of the number is meaningless and the changing trend of numbers can hardly be influenced by assumptions.

The catastrophe model aims to calculate the catastrophic losses of the project from concessionaire's perspective. In principle, the average cost of capital (WACC) should be selected as discount rate of the cash flow from the concessionaire's perspective in order to calculate NPV. For some special case which coincides with extreme fluctuation of equity markets, WACC is not stable enough to be accepted and alternative discount rate may be proposed. For example, the project life of JS highway project overlaps East Asian financial crisis around 1997. In this case, social discount rate is proposed to be discount rate by Chinese government. After the data is converted to the available format and inputted to hazard module and vulnerability module, the average loss can be obtained through selected times of simulation. Such average loss is regarded to be the estimated catastrophic loss of the project during the project life.

8.1.2 Catastrophic Risk Management Strategy for PPP Infrastructure Projects

Catastrophic events bring about devastating damage to the infrastructure assets. Loss brought by a specific catastrophe event may be enormous lasting a long period. In this case, financial demand may be sudden and quite huge due to the given event. The project may be interrupted or terminated without immediate and enough fund available. The usual operating of the infrastructure project can only be guaranteed with proper-designed catastrophic risk management strategy.

Reducing the PPP infrastructure's catastrophe exposure to natural disasters requires active catastrophic risk management at the project level, which consists of risk mitigation and risk financing, in terms of ex-ante and ex-post measures. By employing risk management strategy, based on the estimated loss derived from catastrophe model, the project can 1) improve resistance to catastrophic events physically and financially; 2) reduce their fiscal exposure to natural disasters; 3) secure and speed recovery work following natural disasters by gaining immediate access to liquidity.

Figure 1.2 gives a framework of catastrophic risk management strategies both for concessionaire and government. Depended on whether it is directly related to financial arrangement, the strategies are divided into two types: risk mitigation (non-financing item) and risk financing.

One of the most important principles which determine risk allocation is that risk should be allocated to one who is able to control the risk and bear the risk at the lowest cost. Based on this principle, catastrophic risk of the project will be financed by three layers. The lower layer will be shared by all the private sectors, and the allocation scheme is decided by contract and agreement among the private stakeholders. The middle layer is financed through financial instrument such as catastrophe insurance and/or catastrophe bond. The upper layer is absorbed by government.

Risk mitigation measures refer to non-financing measures which will help prevent and decrease the potential catastrophic losses of the project. Structural consolidation (retrofit) as one of the most important ex-ante mitigation measures was explored emphatically. Retrofit has a great potential for reducing the underlying structural risk of physical assets, with the ensuing effect of dramatically reducing the potential losses of infrastructure projects at risk. This in turn has the benefits of commanding lower premiums when catastrophe insurance is available. Given the benefits of retrofit which is obvious and enormous, government will always support retrofit measures from public sector's perspective. As private sectors, concessionaire will carefully examine the tradeoff between the corresponding costs and benefits before retrofit decision is made. Different retrofit measures have various impacts on the infrastructure's expected value under catastrophe events' threat because costs and benefits may vary with different measures.

Concessionaire concerns the costs and benefits of mitigation measures and corresponding financial demand for different situation. For JS case study, mitigation in the first beginning will be adopted as the optimal measure for concessionaire. Since the mitigation costs coincide with CAPEX of the project, concessionaire may be possible to negotiate for government's subsidy on the mitigation costs.

An optimal strategy may not be one single measure but combination of several measures. Different measures may provide various financial protection which may reduce the financial burden to different degree. In practice, some costs will need to be paid for the respective measures. What's more, there is different dynamic financial demand for each of them. An ideal risk financing strategy should have maximum NPV and minimum dynamic financial demand at the same time. However, it may be difficult to achieve the ideal target in one single strategy. Therefore, a most efficient strategy is necessary to be developed.

Dynamic risk management can improve the efficiency of risk management strategy. Scenario case study was conducted to show the variation of incentive of dynamic risk management under different scenarios. It implies that for most concessionaires (runs for efficiency maximization), any decrease of mitigation costs, WACC and cost-benefit ratio of mitigation, as well as any increase of repair costs will lead to increase of financial demand, which means that the incentive of dynamic risk management will be increased.

Comprehensive cost benefit analysis should be carried out to examine the various costs and benefits of different measures. In addition, in order to develop an optimal catastrophic risk management strategy, dynamic financial demand which is set up based on the financial demand of each year should be identified. Obviously dynamic financial demand defined as $max\ [F_d^{\,1}, F_d^{\,2}, F_d^{\,3}, \ldots F_d^{\,t}]$ (t = project life) may reduce traditional financial demand greatly. The difference of NPV of two different strategies is defined as the opportunity cost of financial demand. If the increased financial demand is more than the increased amount of NPV which means that the opportunity cost of financial demand is more than its benefits, the strategy with larger NPV will not be selected as an optimal strategy. In this way, tradeoff between NPVs and dynamic financial demand with different strategies is able to guide the selection of an optimal strategy.

For PPP infrastructure projects, ex-ante risk management measures are usually better than ex-post risk management measures. For instance, post-disaster financing is highly exposed to relatively exhibitive costs of capital, even though it may not be asked for high returns such as donor, it may not be available immediately after catastrophe events. In this case, extra losses will come together with business interruption due to delay of recovery costs available. Given the lack of recognition of catastrophic risks, ex-post risk management strategy must be taken into account to secure speedy recovery works and minimize the catastrophic losses. In this case, although ex-ante risk management strategy is more efficient and proactive than ex-post strategy, an optimal catastrophic risk financing strategy may not be ex-ante measures only but a combination of several ex-ante and ex-post measures.

8.2 Catastrophic Risk Management Strategy for Concessionaire

Figure 7.10 shows catastrophic risk management strategy for concessionaire. All the risk management measures are divided into ex-ante and ex-post measures based on the different timing. The effects of ex-ante and ex-post arrangement vary even for the same measure. Ex-ante arrangement can secure immediate liquidity and minimize business interruption, while extra financial demand derived from such ex-ante measures (if any) coincides with CAPEX of the project which makes concessionaire faced by greater financial stress. Ex-post arrangement will incur extra costs due to business interruption brought by catastrophic events, increase the difficulty of negotiation and even force the project abandoned in case of extreme situation, while such ex-post measures will not give any financial stress at the beginning of the project.

Catastrophic risk management for concessionaire starts from the beginning of the project and lasts for the whole life project. At the beginning of the project, concessionaire must be careful of partner selection to secure quality of the project and decrease the default risk in case of catastrophes. Concessionaire needs to select partner such as contractor, supplier and operator etc. carefully. Good reputation of such participants is necessary for the implement of recovery works. Prudent examination and selection of partners before signing agreement is critical to secure recovery works. Cost-benefit analysis of potential retrofit measures is necessary before any retrofit measures are put into practice.

Based on the estimated loss derived from catastrophe model, concessionaire may divide the whole risks into three layers through concession agreement with government. For the lower layer, concessionaire need allocate the risks among all the stakeholders except government. The clearer the contractual terms defines the allocation of catastrophic risks, the less arbitration there will be. Smooth and speedy recovery/rebuilt works can be secured through such contractual terms.

Some of ex-ante arrangement (such as rearrange debt payment plan) require some fees because of potential benefits provided by the other party given earthquake occurrence. In this case, cost-benefit analysis will be conducted to help decision making. At the same time, dynamic financial demand is also introduced to develop an optimal strategy which combining the several measures.

Although it is important to be prepared well before catastrophes, ex-post risk management is used to help mitigate and transfer risk as a complement after catastrophe occurrence. It is especially necessary when ex-ante risk management is not enough to cover the losses.

Concessionaire may ask for government to extend concession period or ask contractor to expedite repair works after catastrophes or ask the banks to waive or postpone repayment schedule, etc. Negotiation with other stakeholders may take different forms, with the same objective to ease the catastrophic financial stress and resume the normal operation of the project as soon as possible.

When catastrophe occurs, the project is normally faced with financial constraint. Sensitivity analysis may be conducted on the impact factors to find the most sensitive factor which influence NPV of the project. Through such analysis, it is easy to find out the relationship of impact factors and NPV. In this way, concessionaire may easily develop catastrophic risk management strategy through setting the priority of those impact factors.

After catastrophes, concessionaire may negotiate with other private stakeholders for what the contract does not state specifically or what not included in the contract or even more than what the contract has stated. It is easy to understand that the first two formers are easier to negotiate compared with the last one because such controversial items come from unclear contractual terms.

Similar as negotiation with private sectors, concessionaire may negotiate for what the contract does not state specifically or what not included in the contract or even more than what the contract has stated. Such negotiation may be easier to achieve compared with private sectors because of the special attributes of PPP infrastructure facilities. However, it is not advocated because concessionaire may lose the good reputation which is very important for an enterprise’s long-term development.

8.3 Catastrophic Risk Management Strategy for Government

Similar with catastrophic risk management strategy, the strategy developed for government is structured as Figure 7.19 shows. Catastrophic risk management for government lasts from the beginning of the project to the end of the PPP infrastructure assets’ life because the ownership of infrastructure facilities will be transferred to government in the end after concession period. Since all the PPP infrastructure assets belong to the government in the end, government does not view the PPP infrastructure project as a separate project as concessionaire does. Instead, government views the PPP infrastructure project as part of the infrastructure system. Catastrophic risk management strategy for government discussed here can be applicable to the PPP infrastructure system as well.

Since the ownership of PPP infrastructure projects was, is or will be the government in the end depending on various contractual terms, the government should decide construction site carefully because many types of natural catastrophic events are location-specific. For example, coastal area may be hit by tsunami and building on active fault line may be destroyed by earthquake, etc. Government also should examine and evaluate bidding documents prudentially to select a trustable concessionaire so that possible default due to catastrophes may be avoided. From government’s perspective, it is ideal if all the buildings have the highest structural resistance. However, the mitigation costs may be prohibitive. Therefore, it is necessary for government to draw up a reasonable structural resistance standard which gives different levels with respective importance. Higher standard should be enforced for PPP infrastructure projects given the great importance. In addition, government may conduct catastrophic risk evaluation for each specific project respectively. It may be required to achieve higher structural resistance standard if the estimated catastrophic loss is beyond what the government can withstand. During bidding evaluation, concessionaire need submit a thorough proposal on catastrophic risk management and government should examine such documents carefully. Before contract assignment, government and all the other stakeholders should negotiate and agree on the proposed catastrophic risk allocation to make sure all the catastrophic risks have been approached properly.

Along with the ex-ante risk mitigation arrangement mentioned above, in order to protect PPP infrastructure system away from catastrophic risks, government should develop ex-ante risk financing strategy consisting of reserve fund, contingent credit, catastrophe insurance and/or catastrophe bond, etc. By arranging such ex ante sources of risk financing, the PPP infrastructure projects can receive access to liquidity immediately following natural disasters. In addition, such insurance arrangements are likely to result in considerable improvements in countries' overall risk management, subsequent reductions in their financial vulnerabilities to natural disasters in the long run and improved prospects for investment and economic growth.

Although severe catastrophic events occur infrequently, when they do occur traditional budgetary funding is often insufficient. This creates a post-event funding-gap of the infrastructure project, which must be financed through ex-post strategies which involve additional government borrowing, taxation and donation if funding from ex-ante arrangement is not available or not enough. Compared with ex ante financing measures, ex post financing measures are not suggested and should be the last resort of the government. Besides the relatively higher cost of capital, the other shortcoming of such financing measures is delay in availability. For infrastructure projects which provide fundamental supply to the society, indirect financial losses caused by disruption may be far more than the direct losses. Therefore, ex post financing measures should only be used as supplementary instrument even though they have reasonable cost of capital.

Abandon of the infrastructure project as one type of ex-post risk mitigation strategy should be the last resort. Take China's stipulation as an example, if the building is heavily damaged after catastrophe events and identified as no restore value, it should be pulled down and rebuilt.

Given the importance of PPP infrastructure system, public sector must consider the optimal level of government involvement in catastrophic risk management, and how public sector initiatives should interact with those created by the private sector. In general, it is observed that in many countries private insurance/financial intermediation is used to protect private property and private sector enterprise, while public support is used to protect public property as well as private property exposed to flood and other uninsurable risks. When proper private sector mechanisms are lacking or inadequate, the public sector generally assumes a larger role, until private mechanisms can be developed.

8.4 Limitation and Future Study

Obviously, this research represents only an incremental step towards closing the gap between risk management for PPP infrastructure system and catastrophe model application. Inevitably, there are limitations to this research and the author prompts further investigations into the following aspects.

8.4.1 Careful Application to Other Types of Catastrophic Events and Infrastructure Projects

PPP infrastructure projects have some common characteristics such as no revenues in construction period and increasing revenues in operation period. At the same time, various types of infrastructure projects have some special attributes which differentiate them from others.

The developed catastrophe model which consists of hazard module, vulnerability module and loss module is designed for seismic risk of highway projects. It can be applied to other types of highway projects and even other types of PPP infrastructure projects depended on similarity of cash flow generation. It is easy to understand that the input module for loss estimation will change for different projects and catastrophe events. For example, hazard module varies with location changes even for the same catastrophic event. Different projects cannot remain vulnerability unchanged; hence the damage module will differ surely. However these input modules change, the principle of Monte Carlo simulation can be generally applied only if the cash flow will have similar projection under the scenarios with and without catastrophe events. If it wants to be applied to other types of infrastructure projects, careful examination need to be taken into consideration regarding discrepancy of cash flow model as well as adjustments of other modules such vulnerability module impacted by the special properties of different types of infrastructure projects.

The principle of developed risk management strategy can be more generally applicable compared with the catastrophe model mentioned above. Most of risk management strategy can be applied to other types of catastrophe events and infrastructure projects such as catastrophic risk financing strategy. One should note that some risk mitigation measures designed specifically for one type of catastrophe events (which is earthquake in the case study) need to be revised accordingly if the strategy is applied to other types of catastrophe events. What's more, the different infrastructure projects may have various attributes which may influence the risk management strategy development. For example, meltdown in a nuclear power plant will lead to massive radioactive contamination in the most parts of the country and even the whole country. It will therefore be important to provide short-term economic incentives to encourage long-term planning to manage extreme events. In a word, the developed risk management strategy may be applied to various types of infrastructure projects of different catastrophe risk with some revision and adjustments accordingly.

8.4.2 Combination with Engineering Input and Management Perspective

This research is set up mainly from management's perspective to develop risk management strategy for PPP infrastructure projects. Obviously, catastrophe model based on assumptions of hazard module and vulnerability module will be better improved with more accurate engineering's input. With engineering background, it is able to obtain estimated losses based on the actual hazard module and vulnerability module, which may turn out to be more close to the actual losses. Therefore, the future research may develop towards the direction which combines engineers and researchers from different discipline including engineering input and management perspective together.

Appendix I MATLAB Program for Estimation of Cash Flow Loss due to Earthquake for Concessionaire

```
% define parameters%%%%
Period1=14;                %    second period start year(include the construction year)
Total_Year=24;         % total year of monitor
NPV_Para=0.10;      % social discount rate
Proba_Flag=0.001;         % the probability of every year
Cost_para=893.45;       % base for calculation of recovery costs
num_monitor=10000;         % monitor times
%Cost_retrofit=25.724;
%%%%%%%%%%%%%%%%%%%%%%%%%
Period1=Period1-4;
%Period2=Period2-4;

%%%%%%%%%%%%%%%%%%%%%%%%%
Damage_Para1=xlsread('damage1.xls');
Damage_Para2=xlsread('damage2.xls');

Cash_Flow=xlsread('cash_flow_FCFF.xls');

for j=1:num_monitor

  %%%%%%%%START%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Cash_Con_1=Cash_Flow(6,1)-Cash_Flow(1,1);
Cash_Con_2=Cash_Flow(6,2)-Cash_Flow(1,2);
Cash_Con_3=Cash_Flow(6,3)-Cash_Flow(1,3);
Start_Cash=Cash_Con_1/(1+NPV_Para)+Cash_Con_2/((1+NPV_Para)^2)+Cash_
Con_3/((1+NPV_Para)^3);    % present value of cash flow in construction period

Flag_Onetime=0; % only occur one time
Damage_Para=Damage_Para1;
UC_Flag=1;          %user charge flag
debt_repay=0;
debt_pay=0;
for i=1:(Total_Year-3) % from 4rd to the end year

    %Start_Flag=0.98
```

```
    Start_Flag=rand(1);

     if i>Period1
    Damage_Para=Damage_Para2; %damage state decided by the bridge age
(within 10 years or after 10 years)
     end

  if (Start_Flag<Proba_Flag)&(Flag_Onetime==0)
        Flag_Onetime=1;
        Damage_Rand=rand(1);
        %Damage_Rand=0.1;                determine the damage state
        High_Damage=Damage_Para(1,1)+Damage_Para(2,1);
        Start_Year=i+1999;
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%start1
         if Damage_Rand>High_Damage      %%%%major damage
random>(0.2+0.7)


Cash_Out=-Cash_Flow(2,i+3)-Cash_Flow(3,i+3)*Damage_Para(3,3)-Cash_Flow(4
,i+3)-Cash_Flow(5,i+3)*Damage_Para(3,4)+Cash_Flow(7,i+3)*Damage_Para(3,2)
+Cash_Flow(8,i+3)-Damage_Para(3,6)*Cost_para;
        Cash_Net(i)=Cash_Out/((1+NPV_Para)^(i+3));
        debt_pay=Cash_Flow(5,i+3)*(1-Damage_Para(3,4));

        elseif Damage_Rand<=Damage_Para(1,1)   %%%% minor damage
damage random<0.7

Cash_Out=-Cash_Flow(2,i+3)-Cash_Flow(3,i+3)*Damage_Para(1,3)-Cash_Flow(4
,i+3)-Cash_Flow(5,i+3)*Damage_Para(1,4)+Cash_Flow(7,i+3)*Damage_Para(1,2)
+Cash_Flow(8,i+3)-Damage_Para(1,6)*Cost_para;
        Cash_Net(i)=Cash_Out/((1+NPV_Para)^(i+3));
        debt_pay=Cash_Flow(5,i+3)*(1-Damage_Para(1,4));

        else    %%%%%   moderate damage

Cash_Out=-Cash_Flow(2,i+3)-Cash_Flow(3,i+3)*Damage_Para(2,3)-Cash_Flow(4
,i+3)-Cash_Flow(5,i+3)*Damage_Para(2,4)+Cash_Flow(7,i+3)*Damage_Para(2,2)
+Cash_Flow(8,i+3)-Damage_Para(2,6)*Cost_para;
        Cash_Net(i)=Cash_Out/((1+NPV_Para)^(i+3));
        debt_pay=Cash_Flow(5,i+3)*(1-Damage_Para(2,4));

        end
```

```
    else      %%%74
        if (i==15)
            debt_repay=debt_pay;       % if earthquake occur within 15 years, the
omission of debt will be repaid at the end of 15 yrs.
        end

Cash_Out=-Cash_Flow(2,i+3)-Cash_Flow(3,i+3)-Cash_Flow(4,i+3)-Cash_Flow(5,i
+3)+Cash_Flow(7,UC_Flag+3)+Cash_Flow(8,i+3)-debt_repay;

        Cash_Net(i)=Cash_Out/((1+NPV_Para)^(i+3));
        UC_Flag=UC_Flag+1;
        debt_repay=0;    %all the debt has been cleared.
    end       %%%74

end

      Sum_Cash(j,1)=sum(Cash_Net)+Start_Cash;
end
Sum_Cash
Std_value=std(Sum_Cash)
average_value=mean(Sum_Cash)
```

Appendix II MATLAB Program of Sensitivity Analysis for Concessionaire

```
%%%%%%%%%%%%%%%%%%%%%%%
% define parameters%%%%
Period1=14;              %    first period years
Total_Year=24;         % total year of monitor
NPV_Para=0.10;      % social discount
Proba_Flag=0.01;        % the probability of occurrence
Cost_para=893.45;       % CAPEX discounted by social discount for recovery cost
basis
num_monitor=10000;        % monitor times
Retrofit_Cost=25.73       %20% of construction costs of bridges
Retrofit_Para=0.6
%%%%%%%%%%%%%%%%%%%%%%%
Period1=Period1-4;
Cashout_max=0;
Cash_Out=0;

%%%%%%%%%%%%%%%%%%%%%%%

Damage_Para1=xlsread('damage1.xls');
Damage_Para2=xlsread('damage2.xls');

Cash_Flow=xlsread('cash_flow_FCFF.xls');

Sensa_Para=xlsread('sensitivity.xls');
Sensa_matr=size(Sensa_Para);
Sensa_X=Sensa_matr(2);     %=9
Sensa_Y=Sensa_matr(1);    %=3
TT=1;
kk=1;
mm=1;
ss=1;
%Rotrofit=100000;
for kk=1:Sensa_Y       % for the type of sensitivity


   for mm=1:Sensa_X      % for the change of parameters

        if kk==1
```

```
            Para_RF=Sensa_Para(kk,mm);
            Para_PI=1.0;
            Para_RC=1.0;
            Retrofit_whether=1;

          elseif kk==2
            Para_RF=1.0;
            Para_PI=Sensa_Para(kk,mm);
            Para_RC=1.0;
            Retrofit_whether=0;
          else
            Para_RF=1.0;
            Para_PI=1.0;
            Para_RC=Sensa_Para(kk,mm);
            Retrofit_whether=0;
        end

Cashout_max=0;


    for j=1:num_monitor

%%%%%%%%START%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Cash_Con_1=Cash_Flow(6,1)-Cash_Flow(1,1);
Cash_Con_2=Cash_Flow(6,2)-Cash_Flow(1,2);
Cash_Con_3=Cash_Flow(6,3)-Cash_Flow(1,3);
Start_Cash=Cash_Con_1/(1+NPV_Para)+Cash_Con_2/((1+NPV_Para)^2)+Cash_Con_3/((1+NPV_Para)^3)-Retrofit_Cost*Retrofit_whether;    % present value for construction period

Flag_Onetime=0; % only one time
Damage_Para=Damage_Para1;
UC_Flag=1;          %user charge flag
debt_repay=0;
debt_pay=0;

   for i=1:(Total_Year-3) % from 3rd to the end year
     Cash_Out=0;
   Start_Flag=rand(1);


        if i>Period1
```

```
    Damage_Para=Damage_Para2;
  end


  if (Start_Flag<Proba_Flag)&(Flag_Onetime==0)

       Flag_Onetime=1;
    Damage_Rand=rand(1);
    %Damage_Rand=0.1;       %     change the value to get the damage
    High_Damage=Damage_Para(1,1)+Damage_Para(2,1);
    Start_Year=i+1999;
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%start1
    if Damage_Rand>High_Damage       %%%%high damage
random>(0.2+0.7)


Cash_Out=-Cash_Flow(2,i+3)-Cash_Flow(3,i+3)*Damage_Para(3,3)-Cash_Flow(4
,i+3)-Cash_Flow(5,i+3)*Damage_Para(3,4)*Para_PI+Cash_Flow(7,i+3)*Damage_
Para(3,2)*(1+Retrofit_Para*Retrofit_whether*Para_RF)-Damage_Para(3,6)*Cost_
para*Para_RC*(1-Retrofit_Para*Retrofit_whether*Para_RF);
    Cash_Net(i)=Cash_Out/((1+NPV_Para)^(i+3));
    debt_pay=Cash_Flow(5,i+3)*(1-Damage_Para(3,4)*Para_PI);
    %debt_pay=0;                    for debt sensitivity analysis

    elseif Damage_Rand<=Damage_Para(1,1)    %%%% low damage
0<damage random<0.7

Cash_Out=-Cash_Flow(2,i+3)-Cash_Flow(3,i+3)*Damage_Para(1,3)-Cash_Flow(4
,i+3)-Cash_Flow(5,i+3)*Damage_Para(1,4)*Para_PI+Cash_Flow(7,i+3)*Damage_
Para(1,2)*(1+Retrofit_Para*Retrofit_whether*Para_RF)-Damage_Para(1,6)*Cost_
para*Para_RC*(1-Retrofit_Para*Retrofit_whether*Para_RF);
    Cash_Net(i)=Cash_Out/((1+NPV_Para)^(i+3));
    debt_pay=Cash_Flow(5,i+3)*(1-Damage_Para(1,4)*Para_PI);
    %debt_pay=0;

    else     %%%%%    middle damage    %0.7<?<0.9

Cash_Out=-Cash_Flow(2,i+3)-Cash_Flow(3,i+3)*Damage_Para(2,3)-Cash_Flow(4
,i+3)-Cash_Flow(5,i+3)*Damage_Para(2,4)*Para_PI+Cash_Flow(7,i+3)*Damage_
Para(2,2)*(1+Retrofit_Para*Retrofit_whether*Para_RF)-Damage_Para(2,6)*Cost_
para*Para_RC*(1-Retrofit_Para*Retrofit_whether*Para_RF);
    Cash_Net(i)=Cash_Out/((1+NPV_Para)^(i+3));
    debt_pay=Cash_Flow(5,i+3)*(1-Damage_Para(2,4)*Para_PI);
```

```
          %debt_pay=0;

          end


       else      %%%79
          if (i==15)
                debt_repay=debt_pay;
          end

Cash_Out=-Cash_Flow(2,i+3)-Cash_Flow(3,i+3)-Cash_Flow(4,i+3)-Cash_Flow(5,i
+3)+Cash_Flow(7,UC_Flag+3);

          Cash_Net(i)=Cash_Out/((1+NPV_Para)^(i+3));
          UC_Flag=UC_Flag+1;
          debt_repay=0;


       end

       if (Cash_Out<0)&(abs(Cash_Out)>abs(Cashout_max))
                 Cashout_max=Cash_Out;
                 Cashout_M(kk,mm)=Cashout_max;
          end

   end


    Sum_Cash(j)=sum(Cash_Net)+Start_Cash;
    end
Sum_Cash;
Std_value=std(Sum_Cash);
average_value=mean(Sum_Cash);
Std_final(kk,mm)=Std_value;
Average_final(kk,mm)=average_value;
TT=TT+1;

   end


end

Sensa_Para
```

```
Std_final
Average_final
Cashout_M

xlswrite('d:\Std_final.xls',Std_final);
xlswrite('d:\Average_final.xls',Average_final);
xlswrite('d:\Cashout_Max.xls',Cashout_M);
```

Appendix III MATLAB Program for Optimal Strategy Selection

```
%read the fd value from xls file
fd= xlsread('nv_calculation_base.xls','repairc','e101:h103');
%read the NVs value from xls file
NVs = xlsread('nv_calculation_base.xls','repairc','j34:m36');

[NVs_row,NVs_col]=size(NVs);
[fd_row,fd_col]=size(fd);
%initialize the result
result(1)=fd(1,1);
result(2)=NVs(1,1);
if (NVs_row==fd_row)&(NVs_col==fd_col) %compare the size of fd and NVs
    for m=1:(NVs_row)
        for n=1:(NVs_col)
          if fd(m,n)>=result(1)

            if (fd(m,n)-result(1))<(NVs(m,n)-result(2))
                result(1)=fd(m,n);
                result(2)=NVs(m,n);
            end

          else

            if (result(1)-fd(m,n))<(result(2)-NVs(m,n))
            else
                result(1)=fd(m,n);
                result(2)=NVs(m,n);
            end

          end
        end
    end
else
     pause;
end
result
```

Appendix IV MATLAB Program for Dynamic Financial Demand

```
Period1=14;                 %    first period years
Total_Year=24;          % total year of monitor
NPV_Para=0.07956;       % NPV value
Proba_Flag=0.01;         % the probability of occurrence
Cost_para=893.45;        % CAPEX discounted by social discount for recovery cost
basis
num_monitor=10000;          % monitor times
Retrofit_Cost=25.73       %20% of construction costs of bridges
Retrofit_Para=0.6
%%%%%%%%%%%%%%%%%%%%%%%%%%
Period1=Period1-4;
Cashout_max=0;
Cash_Out=0;
 %%%%%%%%%%%%%%%%%%%%%%%%%%
Damage_Para1=xlsread('damage1.xls');
Damage_Para2=xlsread('damage2.xls');

Cash_Flow=xlsread('cash_flow_FCFF.xls');

Sensa_Para=xlsread('sensitivity.xls');
Sensa_matr=size(Sensa_Para);
Sensa_X=Sensa_matr(2);      %=9
Sensa_Y=Sensa_matr(1);    %=3
TT=1;
kk=1;
mm=1;
ss=1;
%Rotrofit=100000;
for kk=1:Sensa_Y        % for the type of sensitivity


   for mm=1:Sensa_X      % for the change of parameters

        if kk==1
            Para_RF=Sensa_Para(kk,mm);
            Para_PI=1.0;
            Para_RC=1.0;
            Retrofit_whether=1;
```

```
        elseif kk==2
          Para_RF=1.0;
          Para_PI=Sensa_Para(kk,mm);
          Para_RC=1.0;
          Retrofit_whether=0;
        else
          Para_RF=1.0;
          Para_PI=1.0;
          Para_RC=Sensa_Para(kk,mm);
          Retrofit_whether=0;
      end

Cashout_max=0;


   for j=1:num_monitor

%%%%%%%START%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Cash_Con_1=Cash_Flow(6,1)-Cash_Flow(1,1);
Cash_Con_2=Cash_Flow(6,2)-Cash_Flow(1,2);
Cash_Con_3=Cash_Flow(6,3)-Cash_Flow(1,3);
Start_Cash=Cash_Con_1/(1+NPV_Para)+Cash_Con_2/((1+NPV_Para)^2)+Cash_
Con_3/((1+NPV_Para)^3)-Retrofit_Cost*Retrofit_whether;    % present value for
construction period

Flag_Onetime=0; % only one time
Damage_Para=Damage_Para1;
UC_Flag=1;         %user charge flag
debt_repay=0;
debt_pay=0;

  for i=1:(Total_Year-3) % from 3rd to the end year
    Cash_Out=0;
  Start_Flag=rand(1);

      if i>Period1
        Damage_Para=Damage_Para2;
      end

      if (Start_Flag<Proba_Flag)&(Flag_Onetime==0)
```

```
        Flag_Onetime=1;
      Damage_Rand=rand(1);
      %Damage_Rand=0.1;       %     change the value to get the damage
      High_Damage=Damage_Para(1,1)+Damage_Para(2,1);
      Start_Year=i+1999;
      %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%start1
      if Damage_Rand>High_Damage       %%%%high damage
random>(0.2+0.7)

Cash_Out=-Cash_Flow(2,i+3)-Cash_Flow(3,i+3)*Damage_Para(3,3)-Cash_Flow(4
,i+3)-Cash_Flow(5,i+3)*Damage_Para(3,4)*Para_PI+Cash_Flow(7,i+3)*Damage_
Para(3,2)*(1+Retrofit_Para*Retrofit_whether*Para_RF)-Damage_Para(3,6)*Cost_
para*Para_RC*(1-Retrofit_Para*Retrofit_whether*Para_RF);
      Cash_Net(i)=Cash_Out/((1+NPV_Para)^(i+3));
      debt_pay=Cash_Flow(5,i+3)*(1-Damage_Para(3,4)*Para_PI);
      %debt_pay=0;

      elseif Damage_Rand<=Damage_Para(1,1)    %%%% low damage
0<damage random<0.7

Cash_Out=-Cash_Flow(2,i+3)-Cash_Flow(3,i+3)*Damage_Para(1,3)-Cash_Flow(4
,i+3)-Cash_Flow(5,i+3)*Damage_Para(1,4)*Para_PI+Cash_Flow(7,i+3)*Damage_
Para(1,2)*(1+Retrofit_Para*Retrofit_whether*Para_RF)-Damage_Para(1,6)*Cost_
para*Para_RC*(1-Retrofit_Para*Retrofit_whether*Para_RF);
      Cash_Net(i)=Cash_Out/((1+NPV_Para)^(i+3));
      debt_pay=Cash_Flow(5,i+3)*(1-Damage_Para(1,4)*Para_PI);
      %debt_pay=0;

      else     %%%%%    middle damage    %0.7<?<0.9

Cash_Out=-Cash_Flow(2,i+3)-Cash_Flow(3,i+3)*Damage_Para(2,3)-Cash_Flow(4
,i+3)-Cash_Flow(5,i+3)*Damage_Para(2,4)*Para_PI+Cash_Flow(7,i+3)*Damage_
Para(2,2)*(1+Retrofit_Para*Retrofit_whether*Para_RF)-Damage_Para(2,6)*Cost_
para*Para_RC*(1-Retrofit_Para*Retrofit_whether*Para_RF);
      Cash_Net(i)=Cash_Out/((1+NPV_Para)^(i+3));
      debt_pay=Cash_Flow(5,i+3)*(1-Damage_Para(2,4)*Para_PI);
      %debt_pay=0;

      end


    else     %%%79
      if (i==15)
```

```
            debt_repay=debt_pay;
        end

Cash_Out=-Cash_Flow(2,i+3)-Cash_Flow(3,i+3)-Cash_Flow(4,i+3)-Cash_Flow(5,i
+3)+Cash_Flow(7,UC_Flag+3);%-debt_repay;

        Cash_Net(i)=Cash_Out/((1+NPV_Para)^(i+3));
        UC_Flag=UC_Flag+1;
        debt_repay=0;


      end       %%% 90 if

      if (Cash_Out<0)&(abs(Cash_Out)>abs(Cashout_max))
            Cashout_max=Cash_Out;
            Cashout_M(kk,mm)=Cashout_max;
        end

    end         % 76 for


     Sum_Cash(j)=sum(Cash_Net)+Start_Cash;
     end        %   60 for
Sum_Cash;
Std_value=std(Sum_Cash);
average_value=mean(Sum_Cash);
Std_final(kk,mm)=Std_value;
Average_final(kk,mm)=average_value;
TT=TT+1;

    end       %   42 for


end       % 38 for

Sensa_Para
Std_final
Average_final
Cashout_M

xlswrite('d:\Std_final.xls',Std_final);
xlswrite('d:\Average_final.xls',Average_final);
xlswrite('d:\Cashout_Max.xls',Cashout_M);
```

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