Catastrophic Risk Analysis of Infrastructure Systems: A Research Agenda

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Abstract
In recent years, the world has suffered from a series of major natural and man-made catastrophic events. The social and economic impact arising from these events were devastating. In some cases, the events severely handicapped proper functioning of affected infrastructure systems. The evaluation and risk assessment of many infrastructure projects focus mainly on "traditional" risk factors, such as construction, technology, law and regulations, demand, interest rate, foreign exchange, inflation and operation. Although many are aware of catastrophic risks, these are usually treated under the category of "force majeure risks". To promote better economic efficiency, there is a need to re-examine whether project stakeholders can manage such risks in a more involved manner. After all, risk transfer is simply a zero sum game. This paper starts with basic descriptions of catastrophic risks before drawing the connection to project evaluation and risk management of infrastructure systems under a conceptual framework. It is suggested that the study of financial impact and management of catastrophic risks may be more readily applied to projects that are procured under a public-private partnership (PPP) financing scheme, such as Build-Operate-Transfer. This is because the terms and conditions of a long-term concession would explicitly provide a basis for evaluating the impact.

Keywords
Build-operate transfer, catastrophic risks, concessions, infrastructure systems, public-private partnership.

1. Introduction

The complex economic environment of the 21st century demands a strong and reliable network of infrastructure systems to support country development and trades. Due to increasing integration of the global economy, a local event may in fact create global consequences and effects beyond the local regime. Catastrophic events vividly exhibit such characteristics; while natural catastrophes respect no geographical and political boundaries, terrorism and pandemic diseases are also capable of creating both direct and indirect impact that transcend such boundaries.

A catastrophe may be defined as a low probability event with high severity. This can be conceptualized as a simple diagram in Figure 1. The importance of catastrophic risk analysis and management is highlighted by the potential of catastrophes in creating shocks to the existing economic and social systems and imposing significant financial losses. This was exemplified by recent events such as the 2004 South Asia tsunami, the 2005 Hurricane Katrina in the U.S., the London bombing, and Hurricane Durian in the Philippines in 2006. Catastrophic risk management, however, covers a very broad scope. In terms of phases, it encompasses pre-disaster mitigation and prevention measures, emergency response and relief efforts during the crisis, and post-disaster recovery and reconstruction. In terms of disciplines, catastrophic risk management covers the social aspects (e.g. relocation of residents in view of imminent volcano eruption), engineering aspects (e.g. installing isolation bases to structures in an earthquake prone regime), commercial aspects (e.g. choosing proper locations for business headquarters, warehouses etc.), financial aspects (e.g. transfer of financial implications to insurance) and economic aspects at large (e.g. loss of production and economic value from a nation's standpoint). The discussions in this paper largely concern the financial aspects of catastrophic risk management.

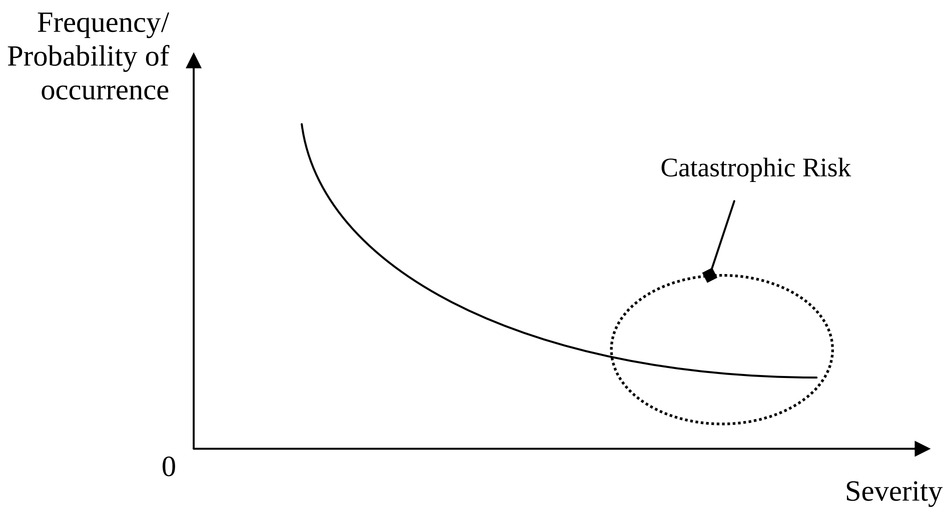

Figure 1: Probability/Severity Profile of Catastrophic Risk

By and large, most direct attentions have been given to residential and commercial buildings, since these are the primary premises where people live and work, and a disruption to the social and economic activities would be severe. In view of the scale of the market and scope involved, property and casualty insurance for catastrophic-prone areas are abundant, constantly designed and priced based on the modeling of loss scenarios to these buildings. After the 9/11/01 event, a lot of attention has also been given to developing proper evacuation and emergency response systems in building occupations.

On a relative basis, less has been reported on assessing the loss of functionality of other key infrastructure systems, such as highways, power plants, water treatment plants etc. Understandably, quantifying the economic value of infrastructure systems is tough enough, perhaps drawing on concepts such as shadow pricing. Still, for infrastructure systems procured using a public-private partnership (PPP) financing scheme such as Build-Operate-Transfer (BOT), the terms and conditions of the concession serve as a proxy for quantification.

The diversity of themes housed under catastrophic risk management underlines the need to explore some of these infrastructure systems as subjects that are separated from buildings. Furthermore, each infrastructure system has its unique physical, operational and economical characteristics. The objective of this paper is to set up a research framework that would help to study the impact of catastrophic risk to the economic functioning of infrastructure system. As mentioned, the scope of discussion in this paper is limited to financial concerns.

2. Catastrophic Risk Management Process

Similar to a conventional risk management process, catastrophic risk management consists of the following steps: risk identification, risk analysis, risk control and mitigation.

2.1 Risk Identification

Under risk identification, catastrophic perils are generally separated into natural and man-made catastrophes (Banks, 2005). Banks further 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. Risk Management Solutions Inc., one of the few catastrophic exposure modeling firms, have regarded outbreak of pandemic diseases (e.g. H5N1) as a “non-traditional” threat. Obviously, different infrastructure systems, depending on its physical and geographical characteristics, are exposed to varying degrees of catastrophic risks.

2.2 Risk Analysis

In relation to catastrophic risks, the risk analysis procedure can be separated into 3 modules: hazard assessment, vulnerability assessment, and loss assessment.

2.2.1 Hazard assessment

The hazard module defines catastrophic events by severity and frequency (probabilities of occurrence), as previously depicted in Figure 1. Risks characterized by a high frequency/low severity combination, such as car accidents and household fires, have a rich history of data, which renders statistical modeling of such events relatively straightforward. Characterizing a catastrophic event, however, would require advanced statistical modeling of extreme values (Coles, 2001). Even then, it is generally difficult to make a precise prediction when one is working with the tails of any probability distributions.

Perils need to be modeled in the light of their unique characteristics, including geographical, geological, topographic, atmospheric, technological, urban or geopolitical features. Some natural catastrophes are governed by the laws of nature and are better understood – thanks to the substantial contributing efforts of scientists and researchers in the respective fields.

The Earth’s seismic activity, for example, is studied based on the science of plate tectonics and movements along the fault lines. Technical parameters of an earthquake, such as rupture length, dip angle, depth, seismic wave amplitude etc. help to determine frequency and locational intensity. Although it is not possible to make a precise prediction of when an earthquake will occur, probabilities can be calculated for potential future earthquakes using historical data (though more limited compared to daily events such as car accidents). For example, scientists estimate that over the next 30 years the probability of a major earthquake occurring in the San Francisco Bay area is 67% and 60% in Southern California (USGS, 2006). The locational intensity can also be modeled through regression weighted by distance to epicenter or through attenuation functions.

Likewise, the spatial location and intensity of a hurricane are tracked using a combination of meteorological data and weather conditions. Some variables include landfall location, central pressure, wind speed and radius. Over time, accumulation of scientific knowledge helps to derive more reliable versions of frequency/severity curves for a particular natural catastrophe event and for a specific region.

It would be harder to make parallel modeling efforts for man-made catastrophes, particularly terrorist acts, since these are governed by human behavior, geopolitics, religions and many other dynamic socio-economical factors. For terrorist acts, location and frequency are even harder to predict. Some have resorted to game theory to model terrorism, but this is generally an area that requires far more research compared to natural catastrophes (Woo, 2002).

2.2.2 Vulnerability assessment

The vulnerability module attempts to quantify the level of exposure of a particular region subjected to the peril intensity and frequency identified in the hazard module. Relevant subjects of exposure would include human beings, infrastructure, properties, contents and operating activities in the region. This stage essentially overlays a local event of certain peril intensity onto an exposed region through a mathematical damage function. For example, with an earthquake magnitude 7.0 occurring and having an epicenter that is 50 km away, Building A of steel moment-frame design may have a longer natural period (lower natural frequency) and experience less damage, while Building B of a stiffer reinforced concrete design might experience resonance and more severe damage.

Evidently, tremendous efforts in data collation are required, including population density, types of construction, asset contents, security measures in place etc. In theory, individual damage functions can be developed for different building types and construction methods, incorporating a spectrum of damage from total to partial. The “granularity” of data available at this stage will subsequently dictate the level of accuracy in subsequent loss assessment. For example, a city that has an up-to-date compilation of building or neighborhood data will be in a better position to assess losses compared to one that relies on regional or ZIP code data.

The concept of vulnerability has to be coupled with hazard assessment since a peril occurring in an area with zero vulnerability (e.g. a hurricane striking a deserted island) essentially produces no losses and therefore little risk management interest. On the other hand, with an increased pace of urbanization and economic development, metropolitans, cities and financial centers are highly populated and housed with a vast amount of activities. These factors contribute to a higher level of vulnerability – inevitably for man-made catastrophes and possibly for natural catastrophes (depending on location).

2.2.3 Loss assessment

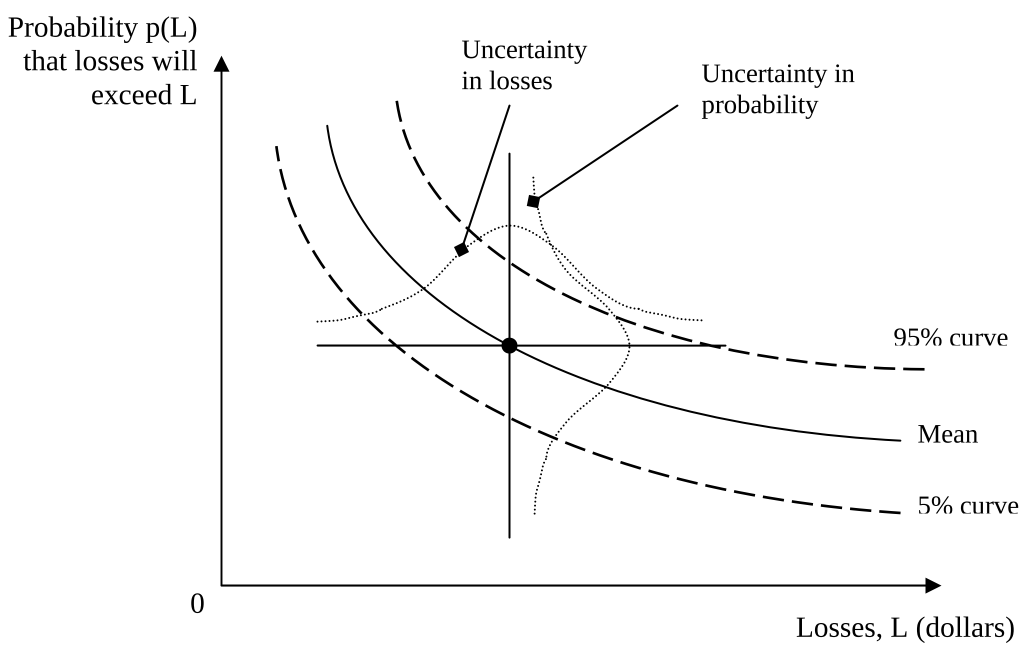

Figure 2: Exceedance Probability Curves incorporating Uncertainties in Estimation [Source: Kunreuther (2002)]

Losses can come from direct consequences, such as damage to structure and contents, and indirect sources, such as loss of use and business interruption (Banks, 2005). Obviously, losses vary with the position of parties (e.g. government versus private sector, building owner versus building occupants) and any contractual agreements that may be tied to the event (e.g. insurance contracts, catastrophe-linked securities). The loss assessment module essentially translates probability, intensity, and damage into dollars and cents as evaluated from a specific party’s standpoint.

The simple frequency/severity curve in Figure 1 can be extended to an "exceedance probability curve" (Figure 2). 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 (2002) 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).

2.3 Risk Control, Mitigation and Risk (Loss) Financing

Traditionally, risk control and mitigation measures can be further divided into risk avoidance, risk reduction and risk transfer. Risk control and mitigation measures can usually be targeted at many fronts. Effectively, one can also think of risk control and mitigation measures as attempts to lower exposure level or vulnerability. For example, as a measure to avoid risk, an enterprise can attempt to plan and locate its key operations in a region that is least affected by natural catastrophes. If, however, due to strategic reasons, the enterprise has to operate in a country affected by natural catastrophes, it can still reduce risk by spreading out certain operations to different locations within the country (e.g. warehousing). Alternatively, if the major threat is earthquake, building facilities that houses some of the operations may be structurally strengthened or equipped with seismic base isolation devices.

As for risk transfer, the obvious channel is to purchase relevant insurance policies. However, this should not be taken as a default option. This is because insurance cover:

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

In the context of catastrophic risk management, risk transfer is related to a broader but important concept of *risk financing*, which can be defined as the financing of consequential losses and expenditures required for recovery. Risk financing is particularly significant not just due to the scale of potential damages caused by catastrophes, but also because capital may not be available or only available at very high costs at the time when the affected commercial entity most require funds to sustain. At the policy level, there is strong indication of a need for public-private partnerships (Kunreuther, 2000). In a political sense, however, low probability of occurrence of catastrophes exacerbates the difficulty for any public or private agencies to solicit internal/external supports and accumulate reserve funds *prior* to the event. This problem needs to be overcome given continual economic growth and concentration in population due to urbanization.

Globally, some public sector financing and insurance programs have been developed. Some examples include:

- U.S: National Flood Insurance Program, Hurricane Catastrophic Fund in Florida, California Earthquake Authority, Terrorism Risk Insurance Act (recently extended till Dec 31, 2007);
- Japan: Japan Earthquake Reinsurance Company;
- Turkey: Turkish Catastrophe Insurance Pool (with support from the World Bank)

For the private sector, the financing options that have been explored include contingent capital and the issuance or catastrophic-linked securities (such as catastrophic derivatives and catastrophe bonds).

3. Catastrophic Risk In The Context Of Infrastructure Systems

As mentioned in the Introduction section, compared to buildings, less research has been performed to understand financial consequences due to catastrophic events for infrastructure systems. The fundamentals of catastrophic risk management process discussed in Section 2 serve as a precursor to constructing a research agenda to fill this gap.

3.1 Research Agenda

To assess the financial impact of catastrophic risks on infrastructure systems, 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 van der Tak, 1992). The author would propose to start with analyzing infrastructure projects that are funded under a public-private partnership (PPP) scheme, especially those that are utilizing the Build-Operate-Transfer financing scheme. This proposition is founded on the following factors:

a. 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.

b. The concession period defined in the contract serves as a finite and realistic time frame for catastrophic risk assessment, rather than keeping the problem open-ended.

For example, catastrophic risks may be superimposed onto a set of *pro forma* cash flows and represented as a potential disruption to the annual cash flows (or social benefits) for a specified duration. Resumption of annual cash flows would depend on the expected recovery period. Subsequently, adjustments can be made according to different severities of catastrophes (e.g. magnitude of earthquake) and the associated duration of cash flow disruptions and recovery periods. The various degree of severities, timing of catastrophes, duration of disruptions and recovery period would then lead to the generation of different risk (loss) financing options.

As mentioned, public private partnerships are increasingly viewed necessary as a concerted effort to respond to catastrophic risks. For a BOT project, 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 *et al*., 2004).

3.2 Challenges

The research agenda outlined obviously points to the need to assemble a multidisciplinary expertise. This serves as a main challenge, since the expertise involved are quite diverse and originated from vastly different culture. This picture is represented by Figure 3.

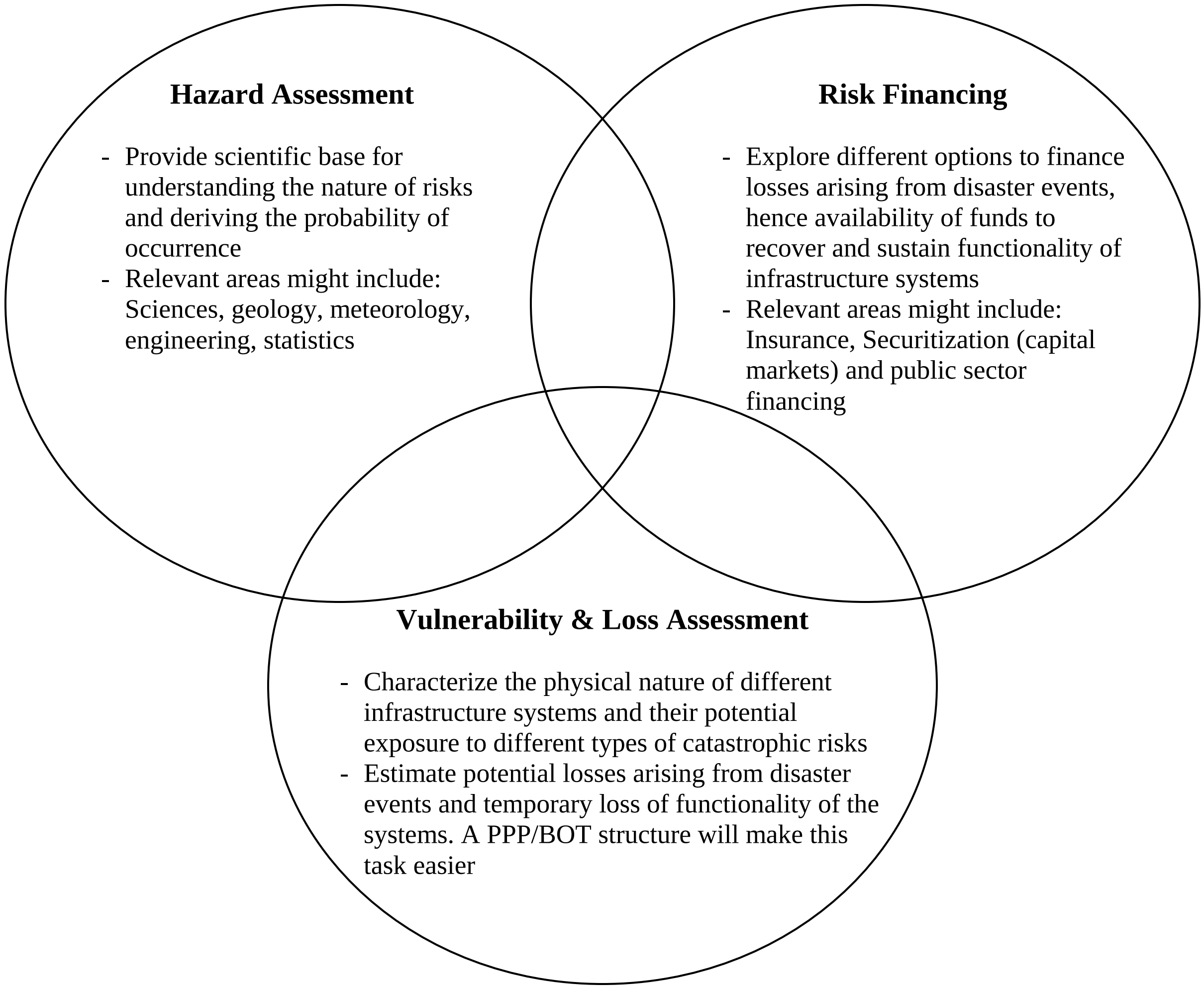

Figure 3: Overall Framework of Research and Expertise Involved

To be realistic, however, one could always narrow down the scope to a specific type of hazard (e.g. seismic) and infrastructure system (e.g. highway), and then assess the corresponding risk profile and viable loss financing mechanisms. With the inevitable trends of urbanization, population growth and environmental threats (e.g. global warming) leading to more natural and man made catastrophes, knowledge needs to be built incrementally in this area.

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