Financial instruments integrated with engineering risk assessment for earthquake disaster reduction

X. X. Tao1,2 & Z. R. Tao1
1Institute of Engineering Mechanics, China Earthquake Administration
2Harbin Institute of Technology, China

Abstract

Financial instruments for earthquake disaster reduction are dealt with in this paper. In general, there are two kinds of instruments to reduce earthquake disaster, one is engineering mitigation measures and the other is referred to as non-engineering countermeasures. The former contributed a lot in disaster prevention for many years, and the latter has been emphasized in these years as the economic structure in urban areas is getting more and more complicated. The financial instruments, e.g. earthquake insurance and catastrophe bonds (cat bonds), are adopted to disperse the risk. The main point of earthquake insurance is to set the rate rationally and correctly. A seismic risk assessment based method of setting the rate for earthquake property and personal insurances with two kinds of deductibles is presented in detail in this paper. Cat bonds have been one of the most active catastrophe insurance derivatives nowadays to supply catastrophe insurance. Since the middle of the 1990s, some insurers have become insolvent or on the edge of insolvency from catastrophes. A framework of setting the annual coupon rate for earthquake cat bonds is also built, in which the probability of earthquake catastrophe occurrence from seismic risk assessment, the yields of reinvestment, the principal protected ratio and the issuance fee ratio are designed as the four factors. Finally, some further ideas to improve the integration of the financial instruments with the engineering seismic risk assessment are discussed briefly.

Keywords: earthquake risk management, earthquake insurance, cat bonds, engineering seismic risk assessment.
1 Introduction

The purpose of earthquake risk management is to reduce unacceptable risk to acceptable levels with engineering measures and non-engineering countermeasures, and to obtain the greatest mitigating achievement with the least possible investment, i.e. the cost-benefit principle, Tao and Tao [1]. Engineering measures played a leading part in the primary stage of the management, and nowadays, non-engineering countermeasures are emphasized increasingly as the process of urbanization is expedited and management instruments are diversified. The traditional instruments in China, mainly developed under the planning system, should be changed as the economy develops and reforms from the planning system to the market system in the country, especially after China entered into the WTO. Some financial instruments, [2-5], e.g. earthquake insurance and cat bonds, will be effective to promote the reformation of the management. Engineering seismic risk assessment based methods of setting rates for earthquake insurance and the annual coupon rate for cat bonds are presented in detail in this paper.

2 Earthquake insurance integrated with engineering seismic risk assessment

Earthquake risk has traditionally been distributed through insurance and reinsurance: insurance companies accumulate the risk of individual entities and redistribute it to the global reinsurance industry. It is considered as the most effective and equitable means of protection against earthquake hazard, and plays a major role in catastrophic risk markets of some countries. In China, earthquake insurance lasted just a dozen of years and was terminated as an exclusion in property insurance contract in 1996. However, the demand has increased recently with the further opening of the Chinese market to the outside world, and it is often a necessary condition to purchase earthquake insurance in some projects associated with international finance organizations (Tao and Tao [6]). By this way, earthquake insurance is going to be activated again in China earthquake risk management. The main point is to set the rate rationally and correctly: the purchase enthusiasm will drop off if the rate is too high; on the contrary, the risk of insurers is large, which might very well lead to deficits, even insolvency. Some studies, [7-10], are based on damage experience, where the intensity is adopted as the main parameter to set the rate, that is, as the expected damage to estimate expected compensation; while some others, such as Dong [11], are based on the statistics of insured losses, which is restricted by limited data of earthquake damages. All of these methods cannot recognize the effect of structural vulnerability on the rate. Therefore methods integrated with engineering vulnerability evaluation, [6, 12-14], are suggested.

2.1 Pure premium rate

Losses from earthquakes, involving property and life, can be mainly derived from damage of engineering structures, and a method to set earthquake insurance
rates is developed from the engineering point of view as following. The engineering seismic risk of buildings in the next $T$ years is described as:

$$ P_S(D_k) = \sum_{l=0}^{9} P_S(D_k|I) \cdot P(I) $$

(1)

where $P_S(D_k)$ is the probability of $S_{th}$ type buildings being in $k_{th}$ damage state; $P_S(D_k|I)$ is the conditional probability of $P_S(D_k)$ given intensity $I$, called the vulnerability of $S_{th}$ type buildings, which is evaluated from damage experience, analysis of a certain number of buildings and sometimes from results of experiments; $P(I)$ is the possibility of intensity $I$ occurrence, which describes the seismic environment and the attenuation relationship of regional ground motion, and can be obtained from seismic hazard curve. The expected loss ratio can be calculated by:

$$ E_S(R_k) = \sum_{l=0}^{5} \sum_{k=1}^{5} P(I) \cdot P_S(D_k|I) \cdot R_S(D_k) $$

(2)

where $k=1, 2, 3, 4, 5$, for 5 damage states (None, Slight, Moderate, Extensive and Complete); $R_S(D_k)$ is the loss ratio of $S_{th}$ type buildings being in $k_{th}$ damage state.

In the method of setting the premium rate, there are two portions in the premium rate for earthquake property insurance, pure premium rate and loading rate, (Zhang and Zheng [15]). The former is a ratio of insured losses from defined perils in the contract to premium amount, thus pure premium is a product of pure premium rate and premium amount. The latter is used to add an insurer’s own business expense and profit modifiers into the premium rate, i.e. how much the insurer will need to run the business and provide adequate yields. To be simplified, the latter is used as a proportion of pure premium rate in the following.

It needs to be pointed out here that the above losses are only direct economic losses from an earthquake, because it is quite difficult to estimate indirect economic losses, which involve not only damage of structures or facilities but influence on society and economy. A simple mathematical model cannot describe the whole impact from an earthquake, since the structure of modern society is quite complex.

Earthquake property insurance is for buildings or indoor property. A method of setting pure premium rate for property insurance, Zhang and Zheng [15], is adopted for earthquake property insurance:

$$ \text{Pure premium rate} = \text{excepted loss ratio} \times (1.0 + \text{stability factor}) $$

(3)

where excepted loss ratio is a mean value, i.e. fifty-fifty venture if the excepted loss ratio is used as premium rate. Although the loss ratio of an earthquake might
be less than the expected loss ratio, insured losses from a destructive earthquake might impact the insurer or even the whole industry, if the earthquake occurs while the reverse has not been accumulated. So a stability factor for the dispersion degree of loss ratios is added on the expected loss ratio to reduce the risk. In practice, the stability factor can be adjusted on the basis of reverse accumulation, capability against risks, market risk and the relation between supply and demand.

Earthquake person insurance is for a natural person. A simple earthquake person insurance method is proposed here: the peril in this contract is the insured death from an earthquake, and the premium amount might be chosen by policyholders as the numerical ceiling of compensation, Tao and Tao [2]. Because an earthquake is an unexpected natural hazard, the death is independent of age, so the rate depends just on seismic hazard, vulnerability and death ratios in damage states.

2.2 Deductible

Deductibles in earthquake insurance might be designed while the premium rate is set. It is good to stimulate purchase enthusiasm, decrease the number of little compensation, and bring the public’s emphasis on prevention against earthquake hazard.

Two kinds of deductibles are given here. The first one is a portion of premium amount borne by an insured before he is entitled to recovery from the insurer, Zhang and Zheng [15], that is, compensation can be paid only when insured losses over the deductible. In this case, the insurer’s risk is from insured losses over the deductible, and pure premium rate can be:

\[ R = R_L \times (p + F_S) \] (4)

where \( R \) is pure premium rate; \( R_L \) is excepted loss ratio; \( p \) is the probability of insured losses over the deductible; \( F_S \) is stability factor. Following eqn (2), the loss ratio of \( S_k \) type buildings given intensity \( I \) \( L_S(I) \) can be:

\[ L_S(I) = \sum_{k=1}^{5} P_S(D_k|I) \cdot R_S(D_k) \] (5)

An exceeding probability curve of loss ratios can be built with \( L_S(I) \) and \( P(I) \) when losses from an earthquake are given, on which \( p \) can be obtained.

The second one is a proportion of insured losses, Chen and Chen [10], that is, the insurer and the insured share the losses. The corresponding portion should be subtracted from the premium since the insured take a proportion of losses. The pure premium rate is:

\[ R = R_L \times (1.0 - d + F_S) \] (6)

where \( d \) is deductible, the others are the same as those in eqn (4).
2.3 An example

To illustrate the feasibility of this method in practice, an example of multi-story masonry buildings in an urban area on the Southeast coast of China is analysed; vulnerability matrix, loss ratios and death ratios are listed in Table 1.

Table 1: Vulnerability matrix, loss ratios and death ratios.

<table>
<thead>
<tr>
<th>intensity</th>
<th>None</th>
<th>Slight</th>
<th>Moderate</th>
<th>Extensive</th>
<th>Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>VI</td>
<td>0.785</td>
<td>0.165</td>
<td>0.050</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>VII</td>
<td>0.285</td>
<td>0.421</td>
<td>0.278</td>
<td>0.016</td>
<td>0.000</td>
</tr>
<tr>
<td>VIII</td>
<td>0.058</td>
<td>0.224</td>
<td>0.570</td>
<td>0.140</td>
<td>0.008</td>
</tr>
<tr>
<td>IX</td>
<td>0.000</td>
<td>0.078</td>
<td>0.311</td>
<td>0.508</td>
<td>0.103</td>
</tr>
</tbody>
</table>

| loss ratio of buildings | 0.000 | 0.080 | 0.200 | 0.600 | 0.900 |
| loss ratio of indoor property | 0.000 | 0.000 | 0.000 | 0.250 | 0.850 |
| death ratio            | 0.000 | 0.000 | 0.00001 | 0.001 | 0.017 |

The premium rates of earthquake property and person insurances are listed in Tables 2 – 4: deductible is designed as 0%, 3%, 5%, 10%, 20% and 50%, $A_0$ is pure premium rate, $A_1$ and $A_2$ are total premium rates with two loading rates (20% and 50% pure premium rate separately).

Table 2: Premium rates for multi-story masonry buildings.

<table>
<thead>
<tr>
<th>deductible</th>
<th>0%</th>
<th>3%</th>
<th>5%</th>
<th>10%</th>
<th>20%</th>
<th>50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_0$ (%)</td>
<td>0.4467</td>
<td>0.4024</td>
<td>0.2841</td>
<td>0.1081</td>
<td>0.0863</td>
<td>0.0797</td>
</tr>
<tr>
<td>$A_1$ (%)</td>
<td>0.5361</td>
<td>0.4829</td>
<td>0.3409</td>
<td>0.1298</td>
<td>0.1036</td>
<td>0.0956</td>
</tr>
<tr>
<td>$A_2$ (%)</td>
<td>0.6701</td>
<td>0.6036</td>
<td>0.4261</td>
<td>0.1622</td>
<td>0.1295</td>
<td>0.1195</td>
</tr>
</tbody>
</table>

Table 3: Premium rates for indoor property.

<table>
<thead>
<tr>
<th>deductible</th>
<th>0%</th>
<th>3%</th>
<th>5%</th>
<th>10%</th>
<th>20%</th>
<th>50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_0$ (%)</td>
<td>0.0360</td>
<td>0.0115</td>
<td>0.0113</td>
<td>0.0112</td>
<td>0.0110</td>
<td>0.0109</td>
</tr>
<tr>
<td>$A_1$ (%)</td>
<td>0.0432</td>
<td>0.0138</td>
<td>0.0136</td>
<td>0.0134</td>
<td>0.0132</td>
<td>0.0131</td>
</tr>
<tr>
<td>$A_2$ (%)</td>
<td>0.0540</td>
<td>0.0172</td>
<td>0.0170</td>
<td>0.0168</td>
<td>0.0165</td>
<td>0.0164</td>
</tr>
</tbody>
</table>

Table 4: Premium rates for person insurance.

<table>
<thead>
<tr>
<th>$A_0$ (%)</th>
<th>$A_1$ (%)</th>
<th>$A_2$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2.3271 \times 10^{-4}$</td>
<td>$2.7925 \times 10^{-4}$</td>
<td>$3.4906 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
3 Cat bonds integrated with engineering seismic risk assessment

Cat bonds initiated in the middle of the 1990s can be issued by (re)insurers or other non-insurance companies directly. In general, an insurer sets up a special purpose vehicle (SPV) to issue it, Gorvett [16]. The SPV issues cat bonds to entities who want to disperse catastrophe risk, and the entities pay cash flows on the bonds to supply catastrophe (re)insurance. For simplification, a kind of cat bond directly issued by primary insurers is discussed in this paper.

3.1 Pricing model

Some methods have been reviewed and analysed, Tao and Tao [17], which are on the view of financial economics to simulate the distribution of losses, claims or loss indices based on loss experience and the trading market. However, for earthquakes, the amount of losses cannot represent the component of losses.

If structure vulnerability is not taken into account in a pricing model, the uncertainty of the price is increased. Tao and Tao [18] developed a method based on engineering seismic risk assessment. Annual coupon rates of earthquake cat bonds are on the basis of the equilibrium between the incomes of investors and issuers, and calculated by the probability of earthquake catastrophe occurrence, the yields of reinvestment, the principal protected ratio and the issuance fee ratio. As a brief running rule: investors will lose interest, part or even the whole principal if an earthquake catastrophe occurs; otherwise, investors will be repaid the whole principal and higher interest than that of risk-free bonds. Firstly, it is necessary to define “catastrophe”, there are various standards, such as PCS’s. The definition from Tang [19] adopted in this paper is region dependent, an earthquake will be considered as a catastrophe if the loss ratio of aggregate losses to regional GDP in the last year ($R_P$) or that of casualties to regional population ($R_L$) measures up with either index in Table 5.

<table>
<thead>
<tr>
<th>State</th>
<th>Province / metropolis</th>
<th>City / County</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_P$</td>
<td>$R_L$ (%)</td>
<td>$R_P$</td>
</tr>
<tr>
<td>$&gt;2 \times 10^{-3}$</td>
<td>$&gt;8 \times 10^{-4}$</td>
<td>$&gt;1 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

Following eqn (2), the direct aggregate expected losses of $S_{th}$ type buildings are:

$$\sum_{k} E_s(R_L) = \sum_{k} R_s(D_k) \cdot P_s(D_k) \cdot A_s \cdot A_I$$ (7)
where $A_a$ is the aggregate area of $S_{th}$ type buildings; $A_I$ is the reconstruction or repair cost per unit area of $S_{th}$ type buildings. Then the loss ratio of the aggregate losses of typical buildings to GDP in the region will be obtained, and an exceeding probability curve of loss ratio can be constructed, on which one can get the probability of an earthquake catastrophe occurrence $p$.

If an earthquake catastrophe occurs before the maturity, the expected income $E_I$ of the issuer can be expressed as:

$$E_I = (AM + rM - BM) \times p$$

and the expected payout $E_O$ of the issuer if it does not occur, can be expressed as:

$$E_O = (cM - rM + BM) \times (1 - p)$$

According to the equilibrium between the incomes of investors and issuers, a general formula of pricing annual coupon rate $c$ is derived:

$$c = \frac{Ap + r - B}{1 - p}$$

where $A$ is the principal protected ratio; $r$ is the yields of reinvestment, such as treasury bills; $B$ is the issuance fee ratio, i.e. the ratio of issuance fee to the par value of cat bonds.

### 3.2 An example

The same example in 2.3 is adopted here to illustrate this pricing model. In this case, an earthquake will be a catastrophe when the ratio of aggregate losses to regional GDP is more than 1%, or the ratio of casualties to regional population is more than 0.03%. The annual coupon rates with the yields of reinvestment (3%, 5% and 10%), the issuance fee ratios (1%, 1.5% and 2.5%) and the principal protected ratios (0, 50% and 100%) are listed in Table 6.

<table>
<thead>
<tr>
<th>principal protected ratio</th>
<th>yield of reinvestment</th>
<th>3%</th>
<th>5%</th>
<th>10%</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>issuance fee ratio</td>
<td>1%</td>
<td>2.16%</td>
<td>4.31%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.5%</td>
<td>1.62%</td>
<td>3.77%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.5%</td>
<td>0.54%</td>
<td>2.69%</td>
</tr>
<tr>
<td>50%</td>
<td>issuance fee ratio</td>
<td>1%</td>
<td>6.05%</td>
<td>8.21%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.5%</td>
<td>5.51%</td>
<td>7.67%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.5%</td>
<td>4.44%</td>
<td>6.59%</td>
</tr>
<tr>
<td>100%</td>
<td>issuance fee ratio</td>
<td>1%</td>
<td>9.95%</td>
<td>12.11%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.5%</td>
<td>9.41%</td>
<td>11.57%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.5%</td>
<td>8.33%</td>
<td>10.49%</td>
</tr>
</tbody>
</table>
4 Conclusions

Earthquake risk management has been gradually emphasized in the prevention and mitigation against earthquake disaster in China, its content is more abundant and methods are more complex than before, and its measures are updated time after time. Financial instruments in the management system must be applied more and more actively, while the country is reforming from a planning system to a market system. The requirement of earthquake insurance is increasing in this process. Adopting the experience of developed countries for reference, catastrophe insurance derivatives can reduce the risk of insurers, and earthquake insurance will be promoted.

In this paper, these two financial instruments are taken to widen the mitigation channel against earthquake disaster. The main point is to combine the instruments in finance and insurance fields with engineering seismic risk assessment. From the engineering point of view, methods of setting rates for earthquake insurance and annual coupon rates for cat bonds are given primarily, and one example for multi-story masonry buildings in an urban area of the Southeast coast of China is analysed in this paper and another in Tao and Tao [20].

For further study, there is still some progress to be achieved. For example, one is the absonant between the seismic hazard assessment methods and the models of setting rates. Seismic hazard assessment for a place does not take care of the hazards at neighbouring places simultaneously. The financial instruments with the rates calculated from these assessments cannot disperse earthquake risk rationally, if the hazard is not assessed for a whole city or region. Another one is the fact that the method for annual coupon rate of cat bonds cannot describe the fluctuation of the values of catastrophe insurance derivatives with time. The Poisson process in the seismic hazard assessment is independent with time, while other models are time dependent, but quite complicated so that it is difficult to determine the parameters. Some time-predictable models are to be validated further.

It is a new issue to apply financial instruments in earthquake risk management in China. Just a primary frame from the point of engineering is built in this paper, and further study will be combined with finance and insurance research more closely.

References


