The Moment Magnitude of an Earthquake as a Parametric Trigger for a Catastrophe Bond: The Megathrust Mid 2 Sumatera, Indonesia, as a Case Study

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Abstract

Indonesia is the largest archipelago consisting of approximately 17,000 islands and is at the meeting point of three big tectonic plates: the Eurasian (*Sunda*), Australian, and Pacific Plates. It also consists of numerous numbers of volcanoes. Due to its geographical nature which is in the "Ring of Fire" area, Indonesia is prone to tectonics and volcanic earthquakes. An earthquake insurance is one way to obtain compensations on financial losses due to damages on properties and infrastructures caused by earthquakes. A reinsurance company or a government may issue a Catastrophe Bond (Cat Bond) to transfer the catastrophe insurance risks to investors through a capital market. The payment of the CAT Bond to a sponsor is triggered by a catastrophe event, such as an earthquake. In this paper, we show how the moment magnitude of an earthquake is used as a trigger of the payment of the corresponding CAT Bond. We use past earthquakes data at the Megathrust Mid 2 Sumatera, Indonesia, as a case study. The well-known Gutenberg-Richter Law in seismology, which is an equation which relates the frequency and the magnitude of earthquakes at a particular (geographical) site, could be explained by a probability model. By modeling the moment magnitudes of the mainshocks of the earthquakes with a Generalized Pareto Distribution, and by using the moment magnitude as a parametric trigger for the corresponding CAT Bond, we give an example of determining the premium of the corresponding CAT Bond. Examples of scenarios are also shown which may be used as an aid in decision making, either by the investors based on their risk appetite (the risk-averse and the risk-taker); or by the issuer of the CAT Bond.

Keywords: Moment Magnitude; Earthquake Insurance; Parametric Trigger; CAT Bond

JEL classification numbers: G22

1. Introduction

Indonesia is the largest archipelago consisting of approximately 17,000 islands and is at the meeting point of three big tectonic plates: the Eurasian (*Sunda*), Australian, and Pacific Plates. It also consists of numerous numbers of volcanoes. Due to its geographical nature which is in the "Ring of Fire" area, Indonesia is prone to tectonics and volcanic earthquakes. Many of the past earthquakes in Indonesia were so devastating causing the deaths of thousands of lives; and causing large financial losses due to damages on properties and infrastructures. Some major earthquakes (and tsunamis) in Indonesia are:

- 26 December 2004 Sumatera-Andaman Islands (Aceh): M_w 9.1 (tsunami); 227,898 fatalities
- 28 March 2005 Northern Sumatera (Nias region): M_w 8.6; 1,313 fatalities
- 27 May 2006 Java (Yogyakarta): M_w 6.3; 5,749 fatalities
- 30 September 2009 Southern Sumatera (Padang): M_w 7.6; 1,117 fatalities
- 5 August 2018 Lombok: M_w 7; hundreds fatalities; thousands of buildings, including schools ruined.
- 28 September 2018 Donggala and Palu, Sulawesi: M_w 7.4 (tsunami); around 2,000 fatalities.

According to the Indonesia Ministry of Finance, between the year 2000 to 2016, the financial losses due to damages on buildings and non-buildings caused by natural disasters in Indonesia, on average, is approximately IDR 22.8 trillion (22.8 trillion Indonesian Rupiah) every year. The financial losses due to the earthquakes and tsunami in Aceh in 2004 reached IDR 51.4 trillion and it took more than 5 years to rebuilt the region. (Source: https://fiskal.kemenkeu.go.id/Kliping/PARB/PARB2018.pdf).

Usually, for an Earthquake based CAT Bond, the Modified Mercalli Intensity or the MMI is used as a parametric trigger. The MMI is a function of the Peak Ground Acceleration (PGA); whereas the PGA itself is a function of the earthquake moment magnitude, the distance between the site and the source of the earthquake, and the soil condition. In this paper, we show how the moment magnitude of an earthquake is directly used as a trigger of the payment of the corresponding CAT Bond, instead of the MMI. We use past earthquakes data at the Megathrust Mid 2 Sumatera, Indonesia, as a case study. The Megathrust Mid 2 Sumatera is located at 97.298°E – 101.947°E and -5.418°S – 0.128°N, West Sumatera Province, Indonesia (Irsyam et al., 2010).

The Indonesia Ministry of Finance is currently developing a Strategy of Disaster Risk Financing in Indonesia (https://fiskal.kemenkeu.go.id/Kliping/PARB/PARB2018.pdf). There are layers of financing strategy being considered depending on the size of the financial losses caused by the natural disasters in Indonesia. Since issuing CAT Bonds is one way to finance the risk of financial losses caused by catastrophe events, research on determining an optimal parametric trigger, such as the earthquake moment magnitude, may be appealing to a reinsurance company, or maybe even to the Indonesian government.

2. The Model

The Gutenberg-Richter Law and the Generalized Pareto Distribution (GPD)

A Catastrophe (CAT) Model consists of four modules: Hazard, Vulnerability, Inventory, and Loss modules. For a complete discussion on a CAT model, see, for example, Chen and Scawthorn (2003). The complexity of a CAT model is dependent upon which natural hazard is being modeled. For example, whether the CAT model is for earthquakes, flood, hurricane, or tsunami, each CAT model is very specific and has its own complexity. For an Earthquake CAT model (Figure 2.1), the Hazard module will include modeling the moment magnitudes of earthquakes and determining the Peak Ground Acceleration (PGA) at different sites. The PGA at a geographical site is a function of the moment magnitude, the distance between the site and the source of the earthquake, and on the soil condition at the site. There are so many attenuation equations used to calculate the value of the PGA at a site; and usually, the PGA at a site is a combination of different attenuation equations considered appropriate for that site.

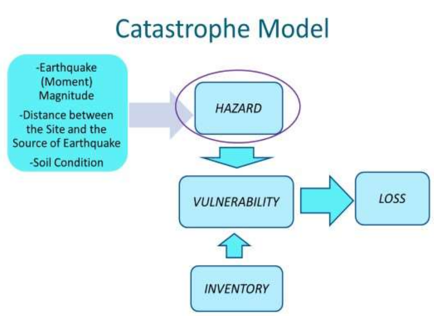


Figure 2.1 The Modules of an Earthquake CAT Model

The Inventory Module is the complete list of all the insured objects and their characteristics. For example, an inventory of an insured building will record the type of building, the structure, and other characteristics such as the number of stories of the building. The module may also record the value of the building. In the Vulnerability Module of an Earthquake CAT model, the Damage Curves of buildings at different sites are determined and recorded. Using this information, the resulting output in the Loss Module is the Event Loss Table (EVT). Usually, the EVT will be accompanied by an Exceedance Probability Plot of the amount (severity) of loss.

We would like to concentrate on modeling the magnitudes of earthquakes; hence it is part of the process in the hazard module. Seismologists and Geophysicists are familiar with the Gutenberg-Richter Law which described the relationship between the frequency and the magnitude of an earthquake at a site. The Gutenberg-Richter Law is given by the equation:

$$\ln N(m) = a - bm$$

where $N(m)$ is the number of earthquakes with magnitudes greater than or equal to m; a and b are parameters which indicate the characteristics of seismic activities at a site. In practice, it is of interest to examine earthquake magnitudes which are greater than or equal to a value m_t. Hence, the Gutenberg-Richter equation becomes

$$\ln N(m) = a_t - b(m - m_t)$$

$$\text{or} \quad N(m) = \exp[a_t - b(m - m_t)] \,,$$

where m is greater than or equal to m_t; and $N(m)$ is the number of earthquakes with magnitudes greater than or equal to m_t .

In this research, we will use the moment magnitude scale instead of the Richter scale to measure the magnitude of an earthquake. Let M_w be a random variable which denote the moment magnitude of an earthquake. Let Z be a random variable which denote the *scalar seismic moment* in Newton-meter or Nm. The relationship between the moment magnitude of an earthquake and the scalar seismic moment is

$$M_w = 2/3 \ln Z - 6$$

Hence, the number of earthquakes with M_w greater than or equal to M is given by the equation

$$N(M) = \exp[a_t - b(M - M_t)]$$

$$\text{or} \quad N(M) = \exp[a_t - b(2/3 \ln Z - 2/3 \ln Z_t)]$$

The equation above is equivalent to

$$N(M) = N(M_t) \left(\frac{Z_t}{Z}\right)^{\beta} \quad , \quad \text{where } \beta = 2/3\, b$$

Hence,

$$\Pr[M_w \geq M | M_w \geq M_t] = \left(\frac{Z_t}{Z}\right)^{\beta}$$

So, given M_w greater than or equal to M_t, the equation above is the survival function of a Pareto distribution with parameters β and Z_t . That is, given the moment magnitude is greater than or equal to a *threshold* M_t, the seismic moment Z follows a Pareto distribution with parameters β and Z_t.
This result leads to a hypothesis that the moment magnitude of earthquake mainshocks might follow a Generalized Pareto distribution.

There are many literatures explaining what a GPD is and how a GPD could be obtained from the Extreme Value Theory; one of them is Embrechts et al, 1997. Stupfler and Yang (2018) also explains about the Extreme Value Theory and GPD, and then explains further how the precipitation data collected in Fort McMurray, Canada, could be modelled by a GPD. A very low precipitation may trigger a (forest) fire. Since this paper focuses on how the moment magnitude of an earthquake maybe used as a trigger of the payment of a CAT Bond, then readers may want to look at those references. The distribution function of a GPD is given by the equation

$$F_X(x;\xi,u,\sigma) = \begin{cases} 1-\left(1+\xi\left(\frac{x-u}{\sigma}\right)\right)^{-1/\xi} & ,\xi \neq 0 \\ 1-\exp\left(-\left(\frac{x-u}{\sigma}\right)\right) & ,\xi = 0 \end{cases}$$

The Average Recurrence Interval

Let M_w be a random variable which denote the moment magnitudes of the earthquakes mainshocks. Further, let V be a random variable which denote the number of years needed until an earthquake with moment magnitudes at least a certain value, that is $M_w \geq M_t$, occurs for the first time. Then V follows a geometric distribution with the parameter $p = \Pr[M_w \geq M_t]$. The expected number of years needed until an earthquake with M_w at least M_t occurs for the first time is

$$E[V] = \frac{1}{\Pr[M_w \geq M_t]}$$

The "Average Recurrence Interval (ARI)" (some literature used the term "Return Period") is defined as the expected number of years until an earthquake with M_w at least M, given a moment magnitude threshold of M_t, occurs for the first time in a region. Hence,

$$\text{Average Recurrence Interval} = \tau = \frac{1}{P(M_w > M|M_w > M_t)}$$

The value $\frac{1}{\tau}$ is called the "Average Recurrence Rate".

Let N be the random variable which denote the number of earthquakes with M_w at least M, given a moment magnitude threshold of M_t, occurring in t years in a region. An important note at this stage: the period of t years here will be used later as "the period to maturity of the corresponding Earthquake CAT Bond". It is assumed that the earthquake (mainshocks) are independent of time and are independent of past earthquakes (mainshocks). Then the random variable N may be modeled by a Poisson distribution, with a probability mass function of

$$\Pr(N = n) = \frac{e^{-\frac{t}{\tau}}\left(\frac{t}{\tau}\right)^n}{n!}, \qquad n = 0,1,2,\ldots$$

The probability of at least one earthquake with M_w at least M, given a moment magnitude threshold of M_t , occurring in t years in a region, is

$$\Pr(N \geq 1) = 1 - \exp\left(\frac{t}{\tau}\right).$$

The above equation is used to calculate the *seismic risk* expressed as "x% PE in t years", that is x% Probability of Exceedance in t years for a given recurrence interval of earthquakes with a certain moment magnitude or greater.

Let us look at an example where the Probability of Exceedance is 10% and $t = 1$ year. Then,

$$0.1 = 1 - \exp\left(-\frac{1}{\tau}\right)$$

or the average recurrence interval is approximately

$$\exp\left(-\frac{1}{\tau}\right) = 0.9 \Leftrightarrow -\frac{1}{\tau} = \ln 0.9 \Leftrightarrow \tau = 9{,}491 \approx 9.5 \text{ years}$$

To give an illustration at this stage, we will use the estimates of the GPD parameters obtained from analyzing the moment magnitudes mainshocks data given in the next section. It is obtained that

$$u = M_t = 5.6 \,;\, \hat{\xi} = 0.1750 \,;\, \hat{\sigma} = 0.3037$$

Thus,

$$9.5 = \tau = \frac{1}{\Pr\left(M_w > M | M_w > 5.6\right)}$$

$$\Pr(M_w > M | M_w > 5.6) = \frac{1}{9.5}$$

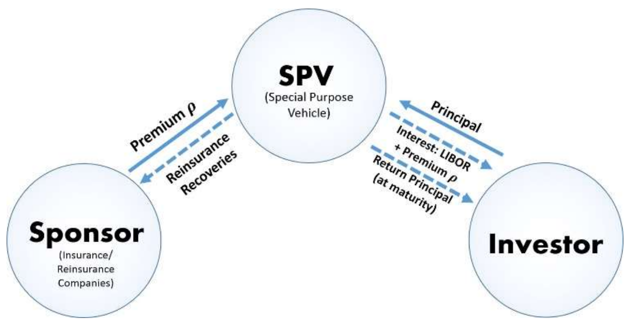
It is obtained that

$$M = u + \frac{\sigma}{\xi}\left(\left(\frac{1}{9.5}\right)^{-\xi} - 1\right) = 6.4376$$

So, the term in seismology that says "10% PE in 1 year", is actually means "*the probability of at least one earthquake with the moment magnitude of at least 6.4376, occurring in 1 year in the region, given that the average recurrence interval is 9.5 years, is 0.1*"

The Financial Loss Premium Principle

A Catastrophe (CAT) Bond transaction may be described using the diagram below:



A reinsurance company or a government may act as a Special Purpose Vehicle (SPV) which issue a CAT Bond that is link to a catastrophe event, such as an earthquake. A sponsor, for example a reinsurance company, pays a premium of the amount of ρ to the SPV to insure itself against the occurrence of an earthquake. An Investor may put some Principle for the CAT Bond in return for an interest or a coupon which is higher than LIBOR. If a trigger occurs, for example in the case of an earthquake is a pre-determined moment magnitude, then the Investor may loose some or all of its investment.

A new way of determining the premium of a CAT Bond, namely the Financial Loss Premium Principle is developed by Stupfler and Yang (2018). The Financial Loss Premium Principle includes a term measuring losses in the financial market that is represented by the Conditional Tail Expectation (CTE) of the negative daily log-return of the S&P 500 index. In their paper, as an application, Stupfler and Yang used the amount of precipitation in Fort McMurray, Canada, as a parametric trigger for the payment of a CAT Bond, in which the underlying catastrophe event is the 2016 Fort McMurray wildfire. We adapt the model obtained by Stupfler and Yang by using the moment magnitude of earthquake mainshocks as a parametric trigger for the payment of a CAT Bond. We use the earthquake data at Megathrust Mid 2 Sumatera, Indonesia, from January 1973 to December 2011, as a case study.

We are not going to explain about the methodology developed by Stupfler and Yang in this paper. We apply the methodology to our data; and use the same notations used by Stupfler and Yang in their paper. Readers are encouraged to read Stupfler's and Yang's paper.

3. Case Study: The Megathrust Mid 2 Sumatera

In this Section, we use the earthquakes data at the Megathrust Mid 2 Sumatera, Indonesia, from January 1973 to December 2011, as a case study. The data is obtained from the United States Geological Survey

(USGS) website. The earthquake *mainshocks* are separated from the earthquake *foreshocks* and *aftershocks*. The process is called *seismicity declustering*. The Gardner – Knopoff algorithm (1974) and the program written by Stiphout et al (2012) are used to decluster the earthquakes data.

After the declustering process, 151 earthquakes are categorized as earthquake mainshocks. The descriptive statistics of the earthquake mainshocks data are as follows:

Table 3.1 Descriptive Statistics of the earthquakes mainshocks

Number of observations	151
Mean	5.573
Variance	0.196
Standard Deviation	0.442
Skewness	2.845
Kurtosis	13.571
Minimum	4.800
1st quantile	5.415
Median	5.573
3rd quantile	5.816
Maximum	8.500

A GPD is fitted to the moment magnitudes of the earthquake mainshocks data. To estimate the parameters of the GPD, the Maximum Likelihood Estimation method is applied. At 5% significance level, the Cramer-von Mises test statistics showed that, given a threshold of moment magnitude of $M_t = 5.6$, the moment magnitudes of the earthquake mainshocks follows a GPD with parameters:

$$u = M_t = 5.6 \ ; \hat{\xi} = 0.1750 \ ; \hat{\sigma} = 0.3037$$

Given the obtained GPD model for the earthquake mainshocks at Megathrust Mid 2 Sumatera, from January 1973 to December 2011, Table 3.2 showed different trigger magnitudes for different periods to maturity t of the earthquake CAT Bonds, and for the exceedance probability of 10% and 20%.

Table 3.2 Trigger magnitudes for different periods to maturity t of the earthquake CAT Bonds

t	Probability of Exceedance of 10%		Probability of Exceedance of 20%	
	Average Recurrence Interval (year)	Trigger Magnitude	Average Recurrence Interval (year)	Trigger Magnitude
1	9.49	6.438	4.48	6.121
2	18.98	6.769	8.96	6.412
3	28.47	6.983	13.44	6.599
4	37.96	7.144	17.93	6.740
5	47.46	7.275	22.41	6.855
6	56.95	7.385	26.89	6.952
7	66.44	7.481	31.37	7.036
50	474.56	8.967	224.07	8.339

From the table above, if for example it is chosen that the period to maturity of an earthquake CAT Bond is 3 years, with a probability of exceedance of 10%, then the corresponding trigger magnitude selected is 6.983. For this case, the expected number of years until an earthquake with moment magnitude of at least 6.983, given a moment magnitude threshold of 5.6, occurs for the first time in the region, is approximately 28 to 29 years.

4. Example

Based on the result of the distribution of the moment magnitudes of the earthquakes mainshocks obtained in Section 3, and by using the moment magnitude as a parametric trigger of the corresponding

CAT Bond, in this section, we give an example of determining the premium of the corresponding CAT Bond using the Financial Loss Premium Principle developed by Stupfler and Yang (2018).

The determination of the premium ρ , from the point of view of the investors, can be categorized into two cases: the risk taker and the risk averse. The value of λ (see Stupfler and Yang, 2018) will determine whether an investor is a risk taker or a risk averse. λ is the ratio between the survival function at an exhaustion point and the attachment point. The higher the value of λ is, then the difference between the exhaustion point and the attachment point becomes smaller. Hence, the risk of the Investor will loose his/her Principal becomes higher.

In this paper, it is assumed that the CAT Bond is issued on 1 January 2019. We obtained the negative daily return of the S&P 500 data from Yahoo Finance for the period of 1 January 2018 to 31 December 2018. Using directly the model obtained by Stupfler and Yang (2018), we obtained the values in Table 4.1.

Table 4.1 The Premium ρ (in %) for different values of λ;
and for a Probability of Exceedance of 10% and 20%

PE (in %)	λ	The range of the difference (in %) of the Attachment Point and the Exhaustion Point	Attachment Point for a 5-year CAT Bond	Exhaustion Point for a 5-year CAT Bond	Premium ρ (in %)
10	0.1	19.8 – 24.0	7.28	8.97	0.078583
10	0.2	13.0 - 15.7	7.28	8.38	0.088236
10	0.3	9.4 – 11.3	7.28	8.07	0.095766
10	0.4	7.0 – 8.4	7.28	7.87	0.102229
10	0.5	5.2 – 6.2	7.28	7.71	0.108020
10	0.6	3.7 – 4.5	7.28	7.59	0.113338
10	0.7	2.6 – 3.1	7.28	7.49	0.118299
10	0.8	1.6 – 1.9	7.28	7.41	0.122978
10	0.9	0.7 – 0.9	7.28	7.34	0.127430
20	0.1	18.3 – 19.7	6.86	8.34	0.112486
20	0.2	12.0 – 14.7	6.86	7.83	0.132931
20	0.3	8.6 – 10.6	6.86	7.56	0.148879
20	0.4	6.4 – 7.8	6.86	7.38	0.162566
20	0.5	4.8 – 5.8	6.86	7.24	0.174831
20	0.6	3.4 – 4.2	6.86	7.13	0.186094
20	0.7	2.4 – 2.9	6.86	7.05	0.196601
20	0.8	1.5 – 1.8	6.86	6.97	0.206512
20	0.9	0.7 – 0.8	6.86	6.91	0.215936

Using Table 3.2 and Table 4.1, different scenarios may be simulated as an aid in decision making, either by the investors based on their risk appetite (the risk-averse and the risk-taker); or by the issuer of the CAT Bond.

5. Conclusion

1. In this paper we showed how the moment magnitude of the earthquake mainshocks may be used as a parametric trigger for an Earthquake Catastrophe (CAT) Bond. The Gutenberg-Richter Law which described the relationship between the frequency and the magnitude of an earthquake at a site suggested that the moment magnitudes of the earthquake mainshocks may follow a Generalized Pareto Distribution (GPD). Applied to the moment magnitudes of the earthquake mainshocks data at the Megathrust Mid 2 Sumatera, Indonesia, from January 1973 to December 2011, at 5% significance level, the moment magnitudes of the earthquake mainshocks follow a GPD with parameters:

$$u = M_t = 5.6 \; ; \hat{\xi} = 0.1750 \; ; \hat{\sigma} = 0.3037$$

2. The Average Recurrence Interval is defined as the expected number of years until an earthquake with (moment magnitude) M_w at least M, given a moment magnitude threshold of M_t, occurs for the first time in a region. Given the resulting GPD model for the moment magnitudes of the earthquakes main shocks at the Megathrust Mid 2 Sumatera, Indonesia, the term in seismology that says, for example, "20% PE in 5 years", is actually means "*the probability of at least one earthquake with moment magnitude of at least* $M = 6.855$ *occurring in* $t = 5$ *years in the region, given that the average recurrence interval is 22.41 years, is 0.2*". Hence, for this case, $M = 6.855$ could be used as the parametric trigger for the earthquake CAT Bond; and $t = 5$ years could be used as the period to maturity of the earthquake CAT Bond. For this case, the expected number of years until an earthquake with moment magnitude of at least 6.855, given a moment magnitude threshold of 5.6, occurs for the first time in the region, is approximately 22 to 23 years.The trigger magnitudes for different periods to maturity of the CAT Bonds and for the probability of exceedance of 10% and 20%, are given in Table 3.2.

3. This paper also give examples of the values of the premium ρ based on different values of λ and for a probability of exceedance of 10% and 20%. Using Table 3.2 and 4.1, different scenarios may be simulated which may be used as an aid in decision making, either by the investors based on their risk appetite (the risk-averse and the risk-taker); or by the issuer of the CAT Bond.

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