Seismic hazard assessment (SHA) in Sabah using the international monitoring system (IMS) data of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO): The preliminary findings

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Abstract. Sabah is the most seismically active state in Malaysia where it has recorded higher number of moderate seismological activities for the past decades, as compared to other states in the country. The seismicity map of Sabah shows the presence of two zones of distinctive seismicity, which are Ranau in Kota Kinabalu and Lahad Datu in the southeast of Sabah. The International Monitoring System (IMS) network setup by the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) has successfully detected seismic events occurred in Sabah for the past decades. This paper aims at presenting the preliminary findings of seismic hazard assessment (SHA) in Sabah using the IMS data. This study utilised seismic data from the CTBTO International Data Centre and then analysed to identify the related seismicity parameters including magnitude, depth, and intensity. The Extreme Value Distribution Type-I has been applied to evaluate the maximum magnitude data, where the results of analysis have enabled the quantification of seismic hazard in Sabah in terms of recurrence periods and probabilities of occurrence of earthquake at any given magnitude. Consequently, the findings from this study could be to assess the impact of seismic events in Sabah as well as assist relevant entities in development planning and disaster management.

1. Introduction
Malaysia is situated on the southern edge of the Eurasian and considered to have low seismicity profile. It is closed to the most two seismically active plate boundaries, the inter plate boundary between the indo-Australian and Eurasian plates on the west and the inter-plate boundary between the Eurasian and Philippines plates on the east [1]. Different with Peninsular Malaysia which is classified as a seismically stable, the region of Sabah is known as prone to earthquake activities compared to other parts of Malaysia. The region has suffered several earthquakes of moderate magnitude, where of these events have caused
structural damage to buildings and other infrastructures and injuries to humans [2]. In 1976, one of the worst earthquakes occurred in Sabah when a 5.8 magnitude on Richter scale earthquake shocked Lahad Datu. Later in 1991, an earthquake of magnitude 4.5 on Richter scale shook Ranau, resulting in structural damage to a school. Eastern Sabah is also exposed to tremors caused by earthquakes originated in the southern Philippines and the Straits of Macassar, Sulu Sea and Celebes Sea. Figure 1 shows the epicenter of felt earthquakes ever recorded in East Malaysia, majority in Sabah [2].

Based on the above facts, seismic hazard assessment (SHA) for Sabah is essential in order to mitigate the effects of potential large earthquake that may occur in the future. One important measure in mitigating the earthquake hazard is to design and build structures using appropriate engineering practices, so that these structures exhibit sufficient resistant against earthquake [3]. This paper presents a preliminary study regarding SHA for Sabah utilizing seismic data of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO). The analysis was performed using statistical theory of extreme values, where the results have enabled the quantification of seismic hazard in Sabah in terms of recurrence periods and probabilities of occurrence of earthquake at any given magnitude.

2. Earthquake data
Seismic technology is one of three waveform technologies which are part of the International Monitoring System (IMS) of the Comprehensive Nuclear Test Ban Treaty (CTBT). The IMS consists of 337 monitoring stations and laboratories that include 50 primary and 120 auxiliary seismic stations, installed world-wide and transmitting data to the International Data Centre (IDC) in Vienna [4]. Since June 1999, the IDC began routine automatic and interactive processing of seismic data, where the detected and located events are systematically included in the Reviewed Event Bulletin (REB) [5].

The analysis of seismic hazard assessment requires data recorded from earthquake events that occurred around the site of interest and observed for a specific time interval. For this study, the data of earthquake events occurred around Sabah region (bounded by 3.95°N to 7.16°N latitude and 115.4°E to 119.3°E longitude) from January 2002 to June 2020 have been taken from the CTBTO’s REB. In order to study the earthquake risk, probability of occurrence and return periods, the earthquake data distributed over 19 years periods has been divided into one year time interval such as at least one event in each year duration is observed. To ensure the continuity of the data, for a few years that no events were reported for Sabah region in the REB, the event with magnitude Mw 4 has been assumed for the year of 2011, 2013 and 2018. Table 1 shows the list of earthquake events in Sabah recorded by the CTBTO seismic stations from the year 2002 to 2020. In term of depth, it is observe that depth of most of the events are fixed at 0 km as the IMS is looking for explosions signature (manmade activities), which is generally shallow (depth less than 5 km) in seismology. This 0-km depth classification is telling us that the sources of these earthquakes are deep in the upper mantle to the surface [6].

3. Method of analysis
Various statistical models have been proposed for the analyses of earthquake occurrence with different degrees of success [7]. The earthquakes occurrence in space and time can be explained using mathematical models of a given physical system change in accordance with the laws of probability [8]. These models have usually incorporated the Poisson distribution, or extended to clustering of events using Markovian models of non-independent events. Calculations obtained are often unconvincing because of incompleteness in the data sets or inherent uncertainties in the distributed parameters [9].

However, the method of Extreme Value Distribution Type-I, which is also known as Gumbel’s Type I, has certain clear and advantages as far as the requisite data are concerned [10]. If compared with other methods requiring the whole data set, and rarely completely reported, the Gumbel’s need only part of the event data, such as, the largest earthquakes i.e. extremes. The CTBTO IMS data represent a continuous and
complete set of annual maximum magnitude events, thus, it is very useful to apply such method for the
calculation process of this study. The results obtained are useful to determine a variety of statistics including
average recurrence periods of annual maximum magnitude earthquakes and probabilistic seismic hazard
assessment of the region. Results also are informative for seismic threat and related earthquake engineering
determinations that usually require estimation of return periods or probabilities of exceedance of specific
levels of design load criteria or external safety conditions.

Figure 1. Epicenter of felt earthquakes in East Malaysia.

Table 1. 2002-2020 Earthquake events in the region of Sabah recorded by the IMS network.
| YEAR | Event ID | Date       | Time      | Latitude  | Longitude | Magnitude | Depth (KM) |
|------|----------|------------|-----------|-----------|-----------|-----------|------------|
| 2020 | 18767431 | 14/04/2020 | 20:04:22  | 5.0212    | 118.9558  | mb 3.6    | 0          |
| 2019 | 17680942 | 03/08/2019 | 15:31:06  | 6.2831    | 117.2185  | mb 3.6    | 0          |
| 2018 | 15530461 | 08/03/2018 | 13:06:10  | 5.8856    | 116.5306  | mb 4.4    | 0          |
|      | 15848813 | 27/05/2018 | 7:53:42   | 5.2794    | 119.0089  | mb 3.8    | 0          |
|      | 15916404 | 16/06/2018 | 7:47:58   | 1.0666    | 111.3856  | mb 3.8    | 0          |
| 2017 | 14228945 | 26/03/2017 | 9:30:49   | 4.7966    | 118.7287  | mb 3.7    | 53         |
|      | 1488716  | 24/09/2017 | 0:25:23   | 5.9464    | 118.3581  | mb 3.5    | 0          |
| 2016 | 13497338 | 26/08/2016 | 1:39:32   | 6.4172    | 117.3407  | mb 3.6    | 0          |
| 2015 | 11783042 | 19/03/2015 | 21:56:00  | 5.4795    | 118.3777  | mb 3.8    | 0          |
|      | 11997735 | 14/05/2015 | 10:25:07  | 1.8141    | 110.5797  | mb 3.6    | 0          |
|      | 12047012 | 04/06/2015 | 23:15:42  | 6.039     | 116.6377  | mb 5.2    | 0          |
|      | 12048513 | 05/06/2015 | 13:12:14  | 6.6386    | 117.191   | mb 3.7    | 0          |
|      | 12048801 | 05/06/2015 | 15:13:32  | 6.0524    | 116.6861  | mb 3.9    | 0          |
|      | 12050340 | 06/06/2015 | 5:45:13   | 6.2528    | 116.8675  | mb 4.1    | 0          |
|      | 12068968 | 12/06/2015 | 18:25:34  | 6.4085    | 117.3888  | mb 3.4    | 0          |
|      | 12068970 | 12/06/2015 | 18:29:24  | 6.0878    | 116.8661  | mb 4.4    | 75         |
|      | 12098600 | 23/06/2015 | 9:32:34   | 5.9739    | 116.5596  | mb 3.7    | 49         |
|      | 12199515 | 26/07/2015 | 10:04:9   | 6.2731    | 117.0466  | mb 3.9    | 0          |
| 2014 | 10715051 | 14/04/2014 | 20:42:03  | 4.5645    | 117.7927  | mb 3.4    | 0          |
|      | 10471451 | 01/02/2014 | 9:15:08   | 6.095     | 116.6187  | mb 4.1    | 0          |
| 2013 | 10099555 | 19/09/2013 | 21:50:37  | 5.6921    | 116.223   | mb 3.6    | 0          |
|      | 9440838  | 29/01/2013 | 1:04:30   | 5.1358    | 118.7193  | mb 4.0    | 0          |
| 2012 | 8726575  | 28/05/2012 | 16:44:08  | 4.7371    | 118.3378  | mb 4.1    | 0          |
| 2011 | -        | -          | -         | -         | -         | -         | 0          |
| 2010 | 6607825  | 21/08/2010 | 19:43:27  | 5.4801    | 118.5899  | mb 3.5    | 0          |
| 2009 | -        | -          | -         | -         | -         | -         | 0          |
| 2008 | 4536681  | 10/01/2008 | 13:18:35  | 4.2583    | 116.5442  | mb 3.6    | 0          |
| 2007 | 4428540  | 23/10/2007 | 20:34:39  | 5.6865    | 119.2532  | mb 4.3    | 0          |
| 2006 | 3550325  | 06/02/2006 | 14:54:07  | 5.1248    | 118.8151  | mb 3.6    | 0          |
|      | 3674353  | 22/04/2006 | 2:01:25   | 6.0392    | 117.5982  | mb 3.7    | 0          |
|      | 3859855  | 28/09/2006 | 15:11:34  | 6.4085    | 118.0916  | mb 3.7    | 0          |
| 2005 | 3249883  | 23/05/2005 | 19:58:12  | 6.2446    | 117.713   | mb 4.3    | 0          |
| 2004 | -        | -          | -         | -         | -         | -         | 0          |
| 2003 | 1978643  | 02/11/2003 | 8:43:19   | 6.2718    | 117.5447  | mb 3.5    | 0          |
|      | 1852956  | 22/08/2003 | 18:01:00  | 5.8225    | 119.2862  | mb 3.3    | 0          |
| 2002 | 1328028  | 06/10/2002 | 21:03:24  | 5.9584    | 117.8815  | mb 3.8    | 0          |
Gumbel’s extreme value theory postulates that if the earthquake magnitude is unlimited, if the number of earthquakes per year decreases with their increase in size, and if individual events are unrelated, then the largest annual earthquake magnitude is distributed by cumulative distribution function $G(m)$, where, [11]:

$$G(m; \alpha, \beta) = \exp \left(-\alpha \exp(-\beta m) \right); \quad m \geq 0$$  \hspace{1cm} (1)

where $\alpha$ is the average number of earthquakes with magnitude $> 0$ per year, $\beta$ is the inverse of the average magnitude of earthquakes under the considered region, and $m$ is the maximum annual earthquake magnitude. The probability integral transformation theorem and manipulation of equation (1) gives the relation:

$$-\ln[-\ln(p_m)] = \beta m_i - \ln(\alpha)$$  \hspace{1cm} (2)

where $p_m$ represents the plotting position. The mean frequency of $i$-th observation in the ordered set of extremes may be represented as:

$$p_m = \frac{i}{N+1}$$  \hspace{1cm} (3)

where $N$ is the total number of observed data. The relationship between Gumbel parameters $\alpha$ and $\beta$ and Gutenberg-Richter parameters $a$ and $b$ can be given by the expression

$$b = \beta \log_{10} e$$  \hspace{1cm} (4)

and

$$a = \log_{10} \alpha$$  \hspace{1cm} (5)

The expected number of earthquakes, $N_m$, in a given year having magnitude exceeding $M$ can be expressed by the Gutenberg- Richter seismicity relation as

$$\log_{10} N_m = a - bM$$  \hspace{1cm} (6)

where, $aa$ and $bb$ are constants. From equation (6),

$$\log_{10} N_m = a - bM$$  \hspace{1cm} (7)

the probability of at least one earthquake of magnitude $\geq M$ occurring within one year is given by the Poisson process as:

$$p = 1 - e^{-N_m} = 1 - e^{-10^{a-bM}}$$

$$= 1 - e^{-\ln_{10} \alpha - bM}$$  \hspace{1cm} (8)

After derivation, Equation (8) becomes,
where \( p \) lies in the interval \((0,1)\). The probability of at least one earthquake of magnitude \( \geq M \) within \( t \) years can be given by the equation:

\[
p = 1 - e^{-Nt} = 1 - e^{-(10^\alpha - bM)\cdot t}
\]

(10)

The expected number of earthquakes in a given year which have magnitude exceeding \( m \) can be found using Equation (11):

\[
\ln N_m = \ln \alpha - \beta m
\]

(11)

and the return period of earthquakes having magnitude greater than \( m \) is given by:

\[
T_m = \frac{1}{N_m} = \exp (\beta m) / \alpha
\]

(12)

4. Results and Discussion

As method of Extreme Value Distribution Type-1 is applied for this study, the annual maximum magnitudes of seismic events recorded in the region of Sabah from 2002 to 2020 are need to be rearranged in rank order so that a variety of statistics can be determined using the Equations (1), (2) and (3) as described above. These 19 years of annual maximum magnitudes and the subsequent statistics are shown in Table 2. The values of cumulative frequency probability are calculated using Equation (3), while the Gumbel’s extreme Type I reduced variant is calculated as per Equation (2). Figure 2 shows the variation of maximum magnitude with years, which indicates that the maximum magnitude increases with time in the considered region. Figure 3 demonstrates the mean Line of Expected Extreme (LEE) to study the probability of largest extreme magnitude in Sabah.

The values of estimated Gumbel’s parameters \( \alpha \) and \( \beta \) are then estimated from a least-square fit to the Reduced Linear Variation Equation, as described in Figure 4. These values of \( \alpha \) and \( \beta \) are summarized in Table 3.
Table 2. Calculations of Gumbel's Annual Maximum Distributions

| Extremes | Rank (j) | Plotting Position G(m) | Reduced Statistics ln (-ln(G(m))) |
|----------|----------|------------------------|----------------------------------|
| 3.5      | 1        | 0.05000                | 1.09719                          |
| 3.5      | 2        | 0.10000                | 0.83403                          |
| 3.6      | 3        | 0.15000                | 0.64034                          |
| 3.6      | 4        | 0.20000                | 0.47588                          |
| 3.6      | 5        | 0.25000                | 0.32663                          |
| 3.7      | 6        | 0.30000                | 0.18563                          |
| 3.7      | 7        | 0.35000                | 0.04862                          |
| 3.7      | 8        | 0.40000                | -0.08742                         |
| 3.8      | 9        | 0.45000                | -0.22501                         |
| 4        | 10       | 0.50000                | -0.36651                         |
| 4        | 11       | 0.55000                | -0.51444                         |
| 4        | 12       | 0.60000                | -0.67173                         |
| 4        | 13       | 0.65000                | -0.84215                         |
| 4.1      | 14       | 0.70000                | -1.03093                         |
| 4.1      | 15       | 0.75000                | -1.24590                         |
| 4.3      | 16       | 0.80000                | -1.49994                         |
| 4.4      | 17       | 0.85000                | -1.81696                         |
| 4.4      | 18       | 0.90000                | -2.25037                         |
| 5.2      | 19       | 0.95000                | -2.97020                         |

Figure 2. Variation of maximum magnitude with year

Figure 3. Variation of extreme magnitude with probability
Figure 4. Display Reduced Variant with extreme magnitudes to estimate $\alpha$ and $\beta$ using linear regression of data

Table 3. Estimated Gumbel’s Parameters $\alpha$ and $\beta$

| Statistics         | Value   |
|--------------------|---------|
| Slope(-$\beta$)    | -2.5039 |
| $\beta$            | 2.504   |
| Intercept(ln($\alpha$)) | 9.3885  |
| $\alpha$           | 11950.16|

Risk analysis that involves a detailed consideration, includes of hazards and uncertainties is important from the economic and safety point of view, prior to any decision made to embark on development and investment in the region. Seismic threat and related earthquake engineering determinations usually require estimation of return periods, probabilities of exceedance of specific levels of design load criteria, and external safety conditions. Assessment of seismic hazard has become one of major problems in the field of earthquake engineering.

The earthquake yearly numbers and their return period for different magnitude expected in Sabah region are calculated and summarized in Table 4. These indicate that as return period increases, frequency of earthquake occurrences decreases. For quantifying the earthquake hazard $H_t(m)$ in Sabah, which is the probability of occurrence of earthquake of magnitude $m$ within a period of $t$ year, the following equation is considered:

$$H_t(m) = 1 - \exp \left( -\alpha t e^{-\beta m} \right)$$

(13)
From the histories of maximum earthquake magnitude recorded, earthquake hazard probabilities for different magnitudes with time are calculated for 10, 20, 30, 50, 75 and 100 years periods. The results are summarized in Table 5. The relation between these yearly numbers of earthquakes, their return periods and the calculated earthquake hazard is further illustrated in Figure 5 and Figure 6. The observations suggest that within hundred year period the probability of occurrence of larger magnitude earthquakes decrease with time. The general interpretation of this curve reveals that the probability of an earthquake of magnitude 4.1 occurring in the considered region with 20-years period is estimated to be 0.999. This means that at least one earthquake of magnitude 4.1 is predicted to occur within that period of time. However, probability of such particular event is never absolutely certain.

Table 4. Predicted yearly number of earthquakes and their return periods.

| Magnitude | Nm         | Tm         |
|-----------|------------|------------|
| 3.5       | 1.867965642| 0.535341752|
| 3.5       | 1.867965642| 0.535341752|
| 3.6       | 1.454205854| 0.687660552|
| 3.6       | 1.454205854| 0.687660552|
| 3.7       | 1.132095054| 0.883318054|
| 3.7       | 1.132095054| 0.883318054|
| 3.8       | 0.881332728| 1.134645257|
| 4         | 0.53413853 | 1.872173497|
| 4         | 0.53413853 | 1.872173497|
| 4         | 0.53413853 | 1.872173497|
| 4         | 0.53413853 | 1.872173497|
| 4.1       | 0.415825302| 2.404856065|
| 4.1       | 0.415825302| 2.404856065|
| 4.3       | 0.252014147| 3.968031205|
| 4.4       | 0.196192285| 5.097040379|
| 4.4       | 0.196192285| 5.097040379|
| 5.2       | 0.026469026| 37.78000723 |
| 6         | **0.003571034** | **280.039278** |
| 6.5       | **0.001021125** | **979.311774** |
| 7         | **0.000291987** | **3424.805818** |
| 7.5       | **8.34928E-05** | **11977.07941** |
| 8         | **2.38745E-05** | **41885.71234** |
Table 5. Most probable largest earthquake hazard $H_t$ (m) for Different Magnitudes and Time Periods ($t$=10, 20, 30, 50, 75 and 100 years).

| Magnitude (m) | $H_{10}$ (m) | $H_{20}$ (m) | $H_{30}$ (m) | $H_{50}$ (m) | $H_{75}$ (m) | $H_{100}$ (m) |
|--------------|--------------|--------------|--------------|-------------|--------------|--------------|
| 3.5          | 0.9999999992 | 1            | 1            | 1           | 1            | 1            |
| 3.5          | 0.9999999992 | 1            | 1            | 1           | 1            | 1            |
| 3.6          | 0.9999999516 | 1            | 1            | 1           | 1            | 1            |
| 3.6          | 0.9999999516 | 1            | 1            | 1           | 1            | 1            |
| 3.7          | 0.999987884  | 1            | 1            | 1           | 1            | 1            |
| 3.7          | 0.999987884  | 1            | 1            | 1           | 1            | 1            |
| 3.8          | 0.999851262  | 0.999999978  | 1            | 1           | 1            | 1            |
| 4            | 0.995210768  | 0.999977063  | 1            | 1           | 1            | 1            |
| 4            | 0.995210768  | 0.999977063  | 1            | 1           | 1            | 1            |
| 4.1          | 0.984365152  | 0.99755552   | 0.999996     | 1           | 1            | 1            |
| 4.1          | 0.984365152  | 0.99755552   | 0.999996     | 1           | 1            | 1            |
| 4.3          | 0.919551775  | 0.993528083  | 0.999479     | 0.99997     | 1            | 1            |
| 4.4          | 0.859412169  | 0.980235062  | 0.997221     | 0.999945    | 1            | 1            |
| 4.4          | 0.859412169  | 0.980235062  | 0.997221     | 0.999945    | 1            | 1            |
| 5.2          | 0.23255638   | 0.41103029   | 0.547999     | 0.733785    | 0.862644     | 0.92913      |

Figure 5. Variation of probability with year.
As for probabilistic seismic hazard assessment in the region, the probability $P(t \geq T)$ that the recurrence period of the design earthquake of magnitude $m$ exceeds a random recurrence period of $T$ years is given by [12]:

$$P(t \geq T) = \exp\left(-\frac{T}{T_m}\right) \quad (14)$$

Therefore, the probability of recurrence period being less than random time $T$ is given by:

$$P(t \leq T) = 1 - \exp\left(-\frac{T}{T_m}\right) \quad (15)$$

where, one can deduce that period $T$ within which at least one earthquake of magnitude $m$ will occur with probability $P$ express as:

$$T = -T_m \ln (1-P) \quad (16)$$

In this regard, one can estimate expected period within which at least one earthquake of any given magnitude will occur with any specified probability. For example, recurrence period for at least one earthquake of magnitude $m$ within a probability of 90% is given by:

$$T_{90} = -T_m \ln (1-0.90) \quad (17)$$

From Table 4, the design earthquake recurrence period with 90% probability is calculated and the values are presented in Table 6. The 90% probability recurrence period could be understood that in Sabah region, there is 90% probability in 29 years period that at least one earthquake of magnitude 4.5 or greater will occur and conversely that 10% probability an earthquake of the same magnitude or more will not occur.
Table 6. Design earthquake Recurrence Period with 90% probability.

| Magnitude (m) | Return Period (years) | Recurrence Period (years) |
|---------------|------------------------|---------------------------|
| 3             | 0.153                  | 0.69                      |
| 3.5           | 0.535                  | 2.40                      |
| 4             | 1.872                  | 8.40                      |
| 4.5           | 6.547                  | 29.39                     |
| 5             | 22.897                 | 102.78                    |
| 5.5           | 80.074                 | 359.42                    |
| 6             | 280.031                | 1256.96                   |
| 6.5           | 979.312                | 4395.77                   |
| 7             | 3424.806               | 15372.71                  |
| 8             | 41885.712              | 188009.73                 |

Subsequently, the findings from this study could be useful in order to assess the impact of seismic events in Sabah, which is one of the important elements that could assist the relevant entities in the planning for infrastructural development and activities in the region. As the study is useful for engineering investigations at particular site, the predicted values are also useful and important for decision making and planning with regards to disaster management of the site of interest.

5. Conclusion

The study has managed to produce the preliminary findings of seismic hazard assessment in Sabah using the IMS data of the CTBTO. The results of analysis have enabled the quantification of seismic hazard in terms of recurrence periods and probabilities of occurrence of earthquake at any given magnitude. Generally, it can be summarized that the methodology of the Gumbel’s Type I extreme distribution could provide future seismic and hazard status of the region, and the availability of CTBTO’s IMS complete earthquake data sets leads to reliable results that the study aimed for. The results demonstrate a clear consistency with the stability postulate from which distributions of extremes are deduced and provides further confidence in the application of such method.

6. References

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