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A DESCRIPTIVE STATISTICAL STUDY OF THE SEISMIC PROPERTIES IN TAIWAN

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Abstract

The purpose of this paper is to use descriptive statistics to study the properties of earthquakes in Taiwan from January 1995 to February 2021, i.e. 26.17 years or 314 months. The data used in the analysis are subtracted from the seismic archive of the Central Weather Bureau (CWB) of Taiwan. 11,965 earthquakes occurred during that 314 months, and among them, 3,454 are labeled with numbers, but the rest 8,511 are unlabeled local small-scaled ones. The statistical seismic properties evaluated in this paper include: yearly numbers, mean times per year, mean depth (km), maximum magnitude (M_L), mean interval of time between two earthquakes, energy released ratio, and energy equivalent to the number of atomic bombs in each city and county. These properties are plotted as diagrams to facilitate reading. The properties of the total 11,965 earthquakes are scrutinized, but the labeled ones are used only for comparison. The data used are summarized in appendices A, B, and C.

The energy released by an earthquake is huge, in this study, the energy of earthquakes is "normalized" by the atomic bomb dropped at Hiroshima, Japan closed to the end of WWII with codename Little Boy, which release 6.3E+20 ergs.

There are 20 municipal areas in Taiwan. Yilan, Hualien, and Taitung are on the east coast where 77.3% of earthquakes occurred. Hualien has the highest frequency (5,399), the shortest period between two earthquakes (1.8 days), and the highest energy released (193.7 atomic bombs) place in Taiwan. Most of the earthquakes in Taiwan's twenty municipal areas are categorized to be shallow (<70km), except Keelung, which has an average depth of hypocenters at 114.9 km (intermediate-depth). Maybe it is because the hypocenters of Keelung are in the submerged tectonic plate. In the past 314 months (January 1995 to February 2021) the strongest magnitude (Richter magnitude scale, ML) is 7.3, which happened on September 21, 1999, and killed 2,415 people.

The regression equation of intensity with independent variables, such as magnitude, and depth of hypocenters is proposed in this paper, which shows that the intensity of Taiwan increases with increasing magnitude, and decreases with increasing depth. The coefficient of determination $R^2_{(adj)}$ is 91.49%, which shows the dependent variable, intensity, is highly explained through the knowledge of the variability in the independent variables.

Keywords: CWB Seismic Archive, Coefficient of Determination, Hypocenter

1. Introduction

Taiwan is on the Circum-Pacific seismic belt; therefore, earthquakes occur from time to time. How to systematically study the properties is important for the people on this island because it is unavoidable to escape the influence of earthquakes as long as they live in Taiwan.

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The Central Weather Bureau (CWB) [1] records the longitude, latitude, magnitude, depth, occurring time, and intensity of each earthquake. And such a treasured record becomes the source to glimpse the mystery of the movement of plate tectonics. The archive of the Central Weather Bureau (CWB) [1] of Taiwan has two kinds of earthquake records, labeled and unlabeled. The labeled ones have a stronger impact on several areas, and unlabeled ones only have records but without numbers given, usually less severe than the labeled ones. Each year, the labeled earthquake always starts from number one. In the CWB archive, the author finds that not until May 2000 did the CWB begin to put unlabeled earthquakes into its archive. These unlabeled earthquakes may amend the knowledge one lacks if many aftershocks of a strong earthquake are neglected.

From January 1995 to February 2021, there were 3,454 labeled and 11,965 total (labeled plus unlabeled) earthquakes occurring in 26.17 years (314 months). The total and labeled number of earthquakes differ more than three times (3.46). The difference of seismic properties between labeled and total earthquakes will increase with the increase of time. If only study labeled ones may neglect the contribution of these so-called “small earthquakes”, hence, this paper is focused on the properties of the total earthquakes, and the labeled ones will be used in the necessary comparison only.

2. Number of earthquakes in Taiwan and their statistical properties

11,965 earthquakes were occurring from January 1995 to February 2021, but only 3,454 were labeled due to their relatively significant impact on Taiwan. As long as the magnitude of an earthquake is larger than Richter scale magnitude scale 4.0 and its intensity measured by one seismometer is over 4.0 (or intensity over 3.0 recorded by two seismometers in different stations) the earthquake will be labeled [1]. This study covers the seismic records of the past 314 months or 26.17 years. After tedious data manipulation and arrangement, the number of earthquakes in each city and county is summarized in Appendix A (for total earthquakes), Appendix B (for labeled earthquakes), and Appendix C (for energy calculation and the equivalent number of atomic bombs). In the following subsections, each property of these tables will be presented by graphs to facilitate reading. The author uses well-known Minitab software for statistical analysis and graphing.

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2.1 Number of earthquakes per year in Taiwan

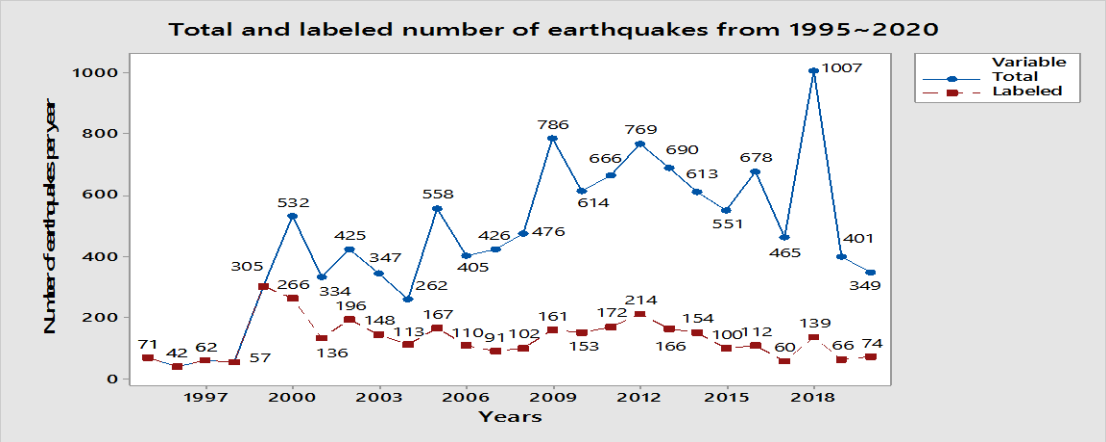

Figure 1: Number of the total (labeled and unlabeled) and labeled earthquakes per year from 1995 to 2020

From the above figure, one finds the total earthquakes (11,965) are about 3.46 times more than the labeled (3,454) ones. After the year 2000, the two records begin to separate because not until May 2000 did the CWB begin to put small-scaled earthquakes into the archive. In 2018 there were 1,007 earthquakes occurred in Taiwan, which very extraordinary.

2.1.1 Number of total earthquakes per year in Taiwan

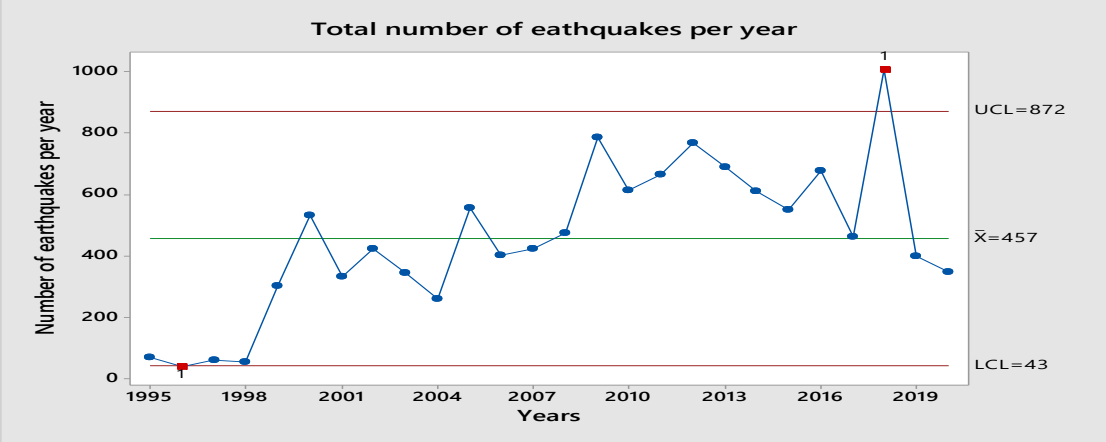

Figure 2: Number of total earthquakes per year from 1995 to 2020 in Taiwan

From the above figure, one finds there are an average 457 of total earthquakes in one year. Years 1996 has only 42 earthquake records, which is three standard errors below the mean, on the contrary, in 2018 (1,007) has a point above three standard errors of the mean. From 1995 to 1998, the records are extremely low, the accumulation of energy may contribute tremendously to the 921 earthquake, which is 7.3 magnitude by the Richter scale.

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2.1.2 Number of labeled earthquakes per year in Taiwan

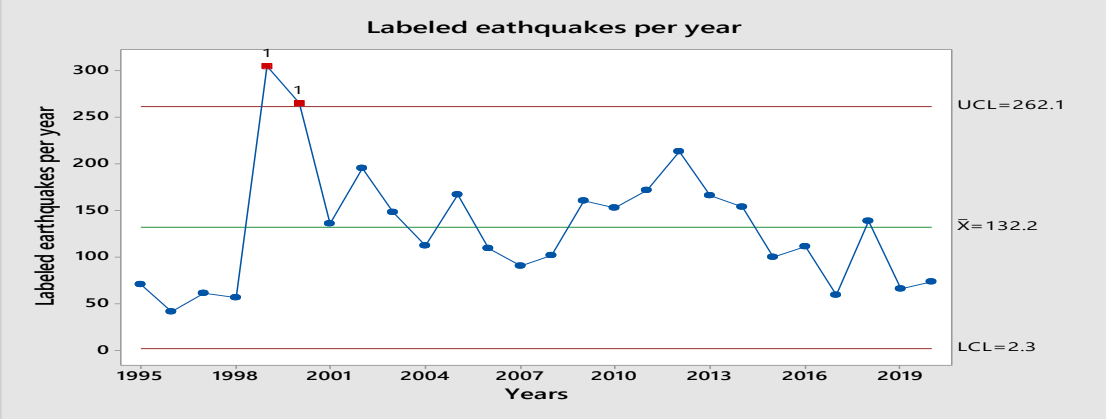

Figure 3: Number of labeled earthquakes per year from 1995 to 2020 in Taiwan

From the above figure, one finds the average number of earthquakes per year is 132.2 times. The year 1999 has an extraordinarily high number of records due to the horrible 921 earthquake, which registered with a magnitude of 7.3 on the Richter scale. The 921 Nantou earthquake took away 2,415 lives as well as injured 11,305 people [4]. Note that from 1995 to 1998, the yearly number of earthquakes is two standard errors below the mean. The energy accumulated during these (and previous) periods seemed to be finally released in the year 1999.

2.2 Number of total earthquakes in each city and county

This subsection is used to find the earthquake frequencies of each city and county in Taiwan for the past 26.17 years (314 months) from January 1995 to February 2021. Both bar and pie charts are used to identify the number and percentage (%) of earthquakes in each locality.

2.2.1 Number of total earthquakes in each city and county

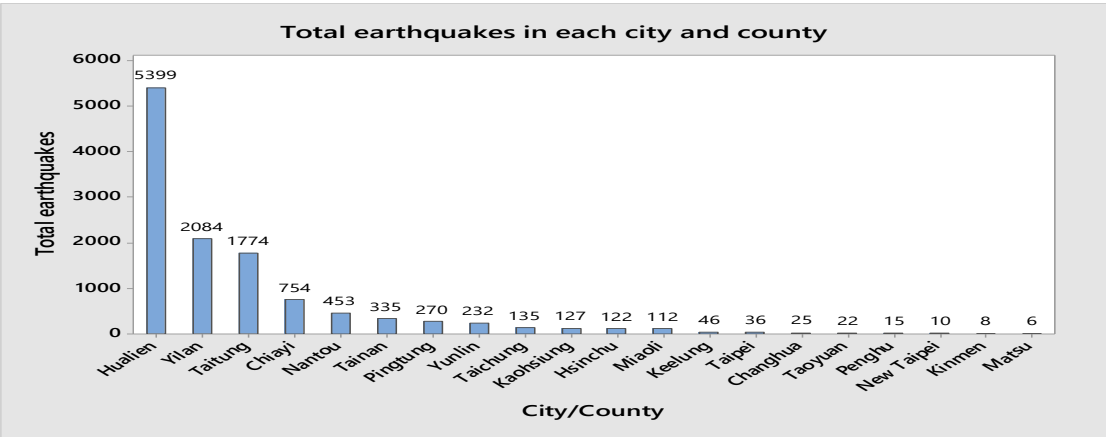

Figure 4: Number of earthquakes in each city and county from January 1995 to February 2021

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From the above figure, one finds Hualien is the county with the highest earthquake occurring frequency. There are 5,399 earthquakes in the past 314 months. Yilan and Taitung have the second and third highest frequency with numbers of 2,084 and 1,774 respectively.

2.2.2 Ratio of total earthquakes distribution in each city and county

To express the number of earthquakes in each city and county as the percentage to the total numbers can make readers understand the distribution of earthquakes in the whole of Taiwan.

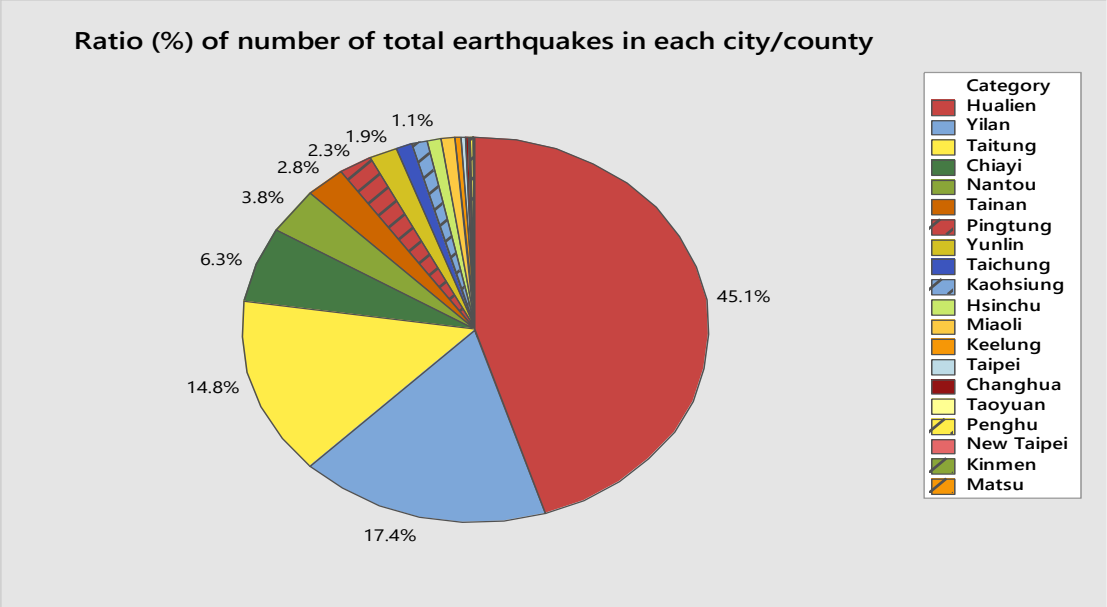

Figure 5: Percentage (%) of the total earthquakes in each city and county

From the above pie chart, 45.1% of earthquakes are occurring in Hualien, 17.4% in Yilan, and 14.8% in Taitung. Sum together ratios these three counties is 77.3%, and it means that more than 77% of earthquakes occurred on the east coast of Taiwan.

2.3 Magnitude of earthquakes (Richter scale, M_L) in each city and county

The magnitude of an earthquake represents its energy released. The energy measurement equation is proposed by Gutenberg and Richter [2] with formula as:

$$\log E = 11.8 + 1.5 M_s \qquad (1)$$

Where E is energy with unit ergs, and M_s is shear-wave magnitude.

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2.3.1 Maximum magnitude (Richter scale, M_L) of total earthquakes in each city and county

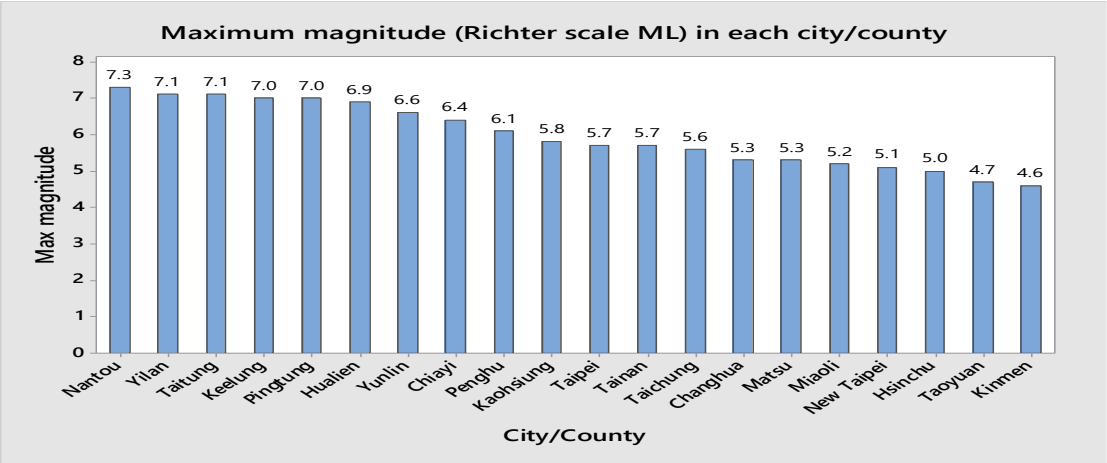

Figure 6: Maximum magnitude of total earthquakes in each city and county

The maximum magnitude earthquake in the past 26.17 years is 7.3, which occurred in Nantou on September 21, 1999. Totally 2,415 people died and 11,305 were injured in that earthquake [4]. Although the maximum magnitude of Yilan, Taitung, Keelung, and Pingtung is 7.0 or above, the epicenters of them are off Taiwan, hence much less damage was observed.

2.3.2 Mean magnitude (Richter scale, M_L) of total earthquakes in each city and county

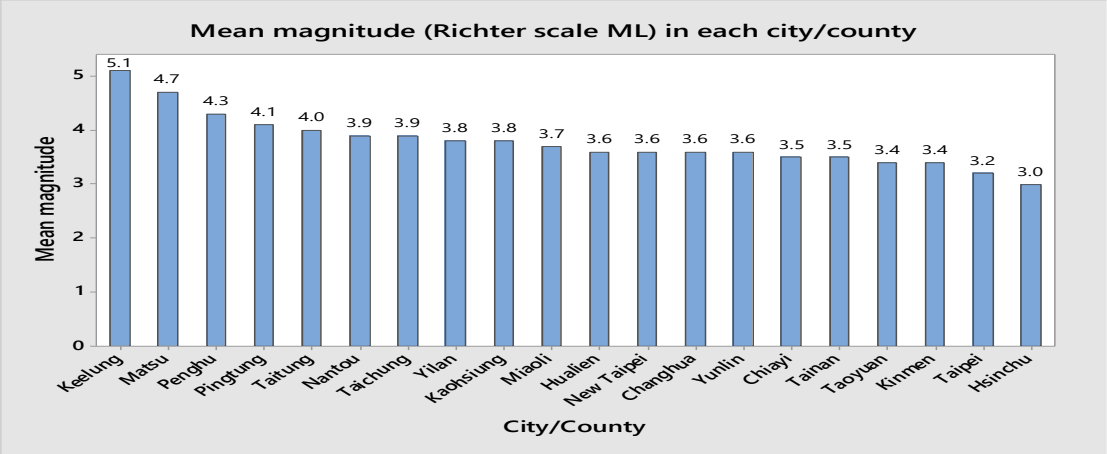

Figure 7: The mean magnitude of earthquakes in each city and county

The largest mean value of earthquakes in the past 23.5 years is 5.1 on Keelung. The serious damage of earthquakes was rarely observed in that area because the depth of hypocenters is deeper than any locality in Taiwan. The wave of earthquakes dissipates its energy when reaching the surface, so does its power of damage.

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2.4 Energy distribution of total earthquakes

The energy released by earthquakes is huge and difficult to manipulate with computer programs. In this study, the author "normalized" the energy accumulated in the past 26.17 years energy in each city and county using the energy generated by the atomic bomb detonated over Hiroshima, Japan. The energy produced by the atomic bomb with the codename Little Boy was 6.3E+20 ergs [5].

2.4.1 Energy distribution of total earthquakes in each city and county

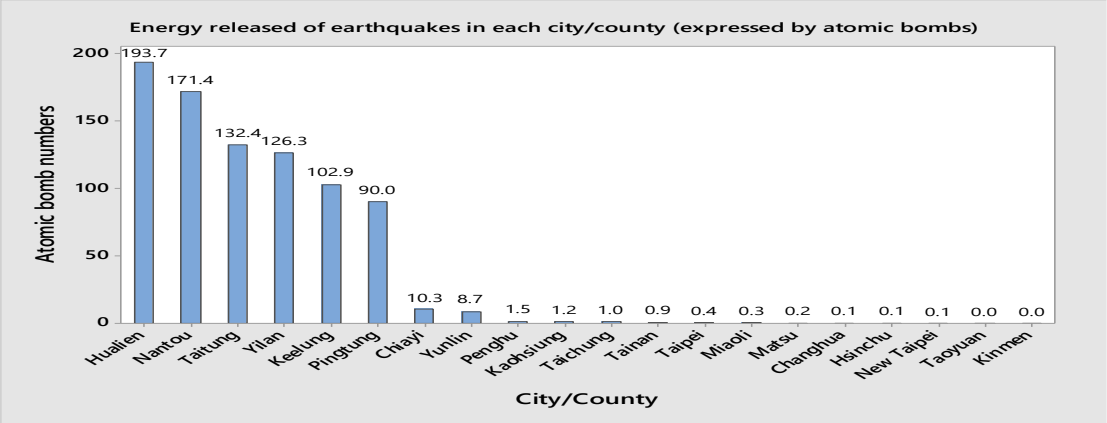

Figure 8: Energy released by earthquakes and expressed by the equivalent atomic bomb numbers from January 1995 to February 2021

In the past 26.17 years, the earthquakes in Hualien generated energy equivalent to 193.7 atomic bombs. Nantou is the second-highest, with the number of 171.4 bombs, and the third is Taitung, with 132.4 atomic bombs.

2.4.2 Energy distribution in percentage (%) for earthquakes in each city and county

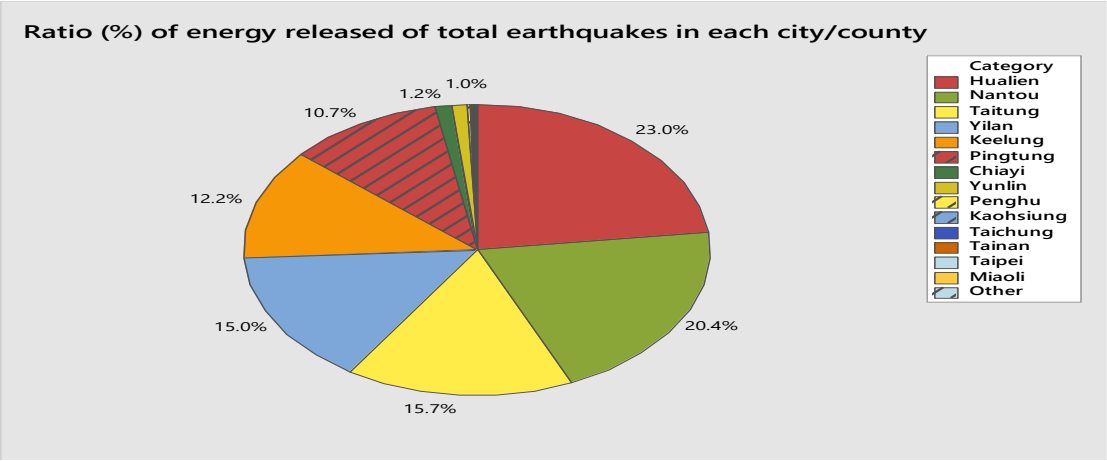

Figure 9: The percentage (%) distribution of energy issued by earthquakes

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In the past 314 months, Hualien accounts for up to 23.0% of total energy generated by all the earthquakes occurring in Taiwan. Nantou, Taitung, and Yilan share 20.4%, 15.7%, and 15.0% respectively. Sum up energy released from total earthquakes in these four counties is 74.1%, almost three-quarters of the energy released by the total earthquakes in Taiwan.

2.5 Average depth (km) of hypocenters of total earthquakes

This subsection is used to find the average depth of earthquakes in each city and county.

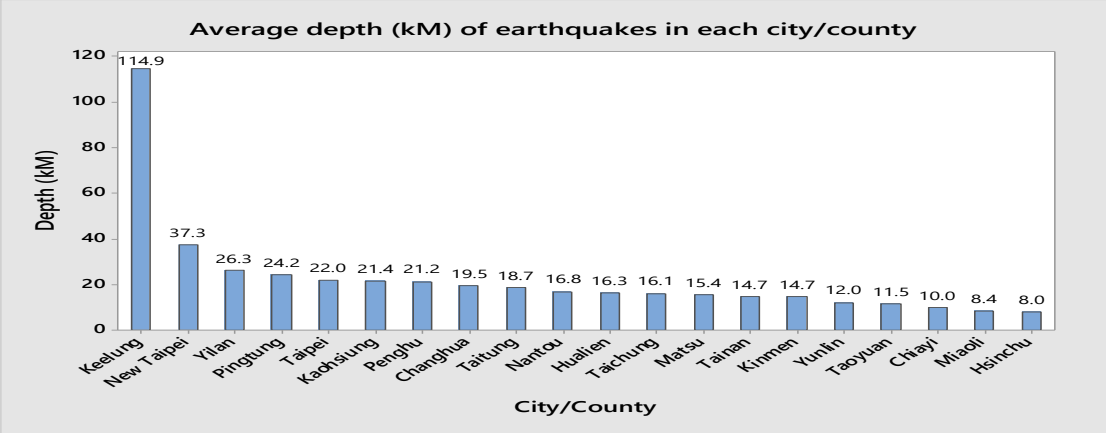

Figure 10: The average depth (km) of earthquakes in each city and county

The average depth of earthquakes in Keelung is 114.9 km (intermediate-depth), which is the deepest for all areas in Taiwan. The depths of earthquakes in other places are smaller than 70km and are categorized as "shallow" [1]. The average depth of earthquakes in Hsinchu is 8.0 km, and it is the shallowest in Taiwan.

2.6 Average interval (days) between two earthquakes

This subsection is used to find the interval of occurring two earthquakes in each city and county in Taiwan.

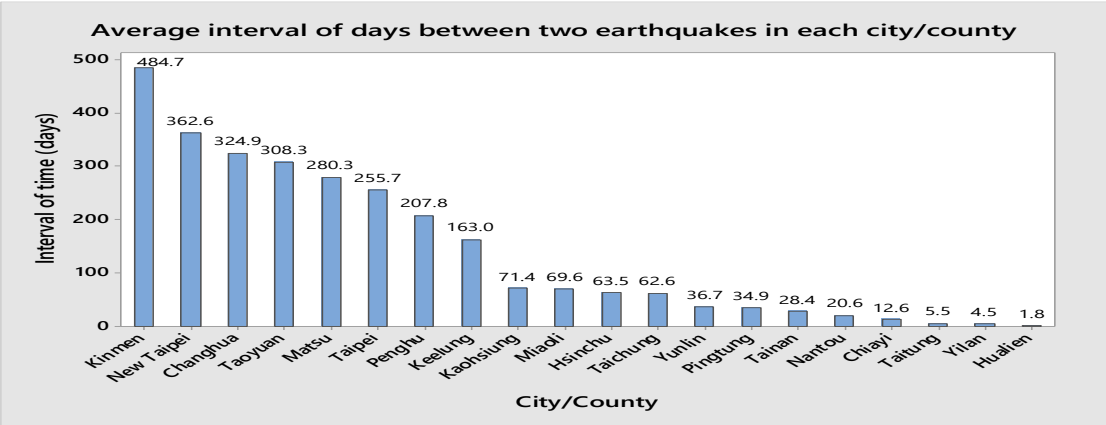

Figure 11: The average interval of time (days) between two earthquakes

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Hualien has the most frequent earthquakes and the shortest gap time (days) between two earthquakes. Averagely speaking, for every 1.8 days, Hualien will have an earthquake. Kinmen, in the end, enjoys the longest interval between two earthquakes, 484.7 days.

3. Regression analysis of the intensity of earthquakes

The purpose of this section is to try to use an equation to represent the intensity on the surface of the ground and its relationship with the magnitude and hypocenter depth (km) of earthquakes. From geophysics, one can be expected the intensity measured on the surface of the earth may increase with the increasing of magnitude and decrease with the increasing depth of hypocenters.

3.1 Regression between intensity, magnitude (M_L), and depth (km) of earthquakes

For all the earthquakes from January 1995 to February 2021, a total of 11,965 records are used in the regression analysis. As long as variables such as magnitude and depth of an earthquake are observed, and substituted into the regression equation, the intensity on the surface of the ground can be obtained. The regression equation of the relationship between intensity and two aforementioned variables is:

$$\begin{aligned} &Intensity = 0.826\, M_L - 0.020\, Depth \\ &(t\text{-}value) \quad (275.71) \quad (-48.48) \\ &(p\text{-}value) \quad (0.00) \quad (0.00) \\ &\text{And } R^2_{(adj)} = 91.49\% \end{aligned} \tag{2}$$

The interesting observation of the above equation is that the intensity of an earthquake increases with the increasing magnitude, and decreases with the increasing depth of hypocenter (*kM*). The *t-value* of each parameter is big, which means the corresponding *p-value* is smaller than the 5% level of significance. In other words, the hypothesis H_0*: parameter =0* is rejected, and each parameter in the above equation is not zero. The adjusted coefficient of determination $R^2_{(adj)}$ is as high as 91.49%, which means that the dependent variable (intensity) can be highly explained by the independent variables on the right-hand side of the regression equation [6, 7].

Table 1: The intensity regression equation of earthquakes in Taiwan

Regression equation	Coefficient of determination $R^2_{(adj)}$
Intensity = 0.826 M_L - 0.020 Depth	*91.49%*

4. Conclusions

After analyzing seismic data in Taiwan from January 1995 to February 2021 and scrutinizing the major characters of earthquakes in all twenty municipal areas in Taiwan, the following statistical conclusions can be summarized as follows:

(1) Hualien is the most active place for earthquakes in Taiwan. There are 5,399 earthquakes in Hualien out of a total of 11,965 earthquakes in Taiwan, and the frequency ratio is 45.1%.

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Yilan takes second place, occurring 2,084 times with a ratio of 17.4%. Taitung with 1,794 times is the third, with a ratio of 14.8%.

(2) In each year, on average, 457 earthquakes will occur in Taiwan.

(3) Almost all the mean depths of hypocenters of earthquakes in Taiwan are shallow (<70 km), except Keelung (114.9 km), which is classified as intermediate-depth. Maybe it is because earthquakes in Keelung are in the submerged tectonic plate. The shallowest depth of earthquakes is in Hsinchu, 8.0 km.

(4) The maximum magnitude of earthquakes in Taiwan for the past 26.17 years is 7.3 (Richter scale, ML) in Nantou on September 21, 1999.

(5) In Hualien, the average interval of two earthquakes in 1.8 days. In Kinmen, the interval between two earthquakes takes 484.7 days, which is the longest in Taiwan.

(6) The total energy released from all earthquakes in the past 26.17 years is 5.3E+23 ergs. Hualien is accounted for 23.0% of it and is the place where earthquakes released the most energy.

(7) From January 1995 to February 2021 there was energy equivalent to 841.4 atomic bombs generated in Taiwan. No doubt, Hualien was the most intense area with an equivalent of 193.7 bombs. Nantou (171.4 bombs) was the second, followed by Taitung (132.4 bombs).

(8) The regression equation between intensity, magnitude, and depth (km) has been proposed. The determination of the coefficient $R^2_{(adj)}$ is 91.49%, which means that the dependent variable can be highly explained through the knowledge of variability in the independent variables.

5. References

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6 Appendices:

There are three appendices with data of total (labeled plus unlabeled) earthquakes (Appendix A), labeled earthquakes (Appendix B), and energy released from earthquakes (Appendix C). These three tables provide the backbone for this paper.

6.1 Appendix A:

Table A1: Data of the total earthquakes for cities in Taiwan (From January 1995 to February 2021)

City/County	Numbers of earthquakes	Mean times per month	Mean times per year	Number of Earthquakes /Total Earthquakes (%)	Mean Depth (km)	Magnitude (Richter M_L)		Total Energy Released (ergs)	Mean dTime (days)
						Mean	Max		
Yilan	2084	6.60	79.60	17.40	26.3	3.8	7.1	7.95E+22	4.5
Hualien	5399	17.19	206.29	45.13	16.3	3.6	6.9	1.22E+23	1.8
Taitung	1774	5.65	67.80	14.83	18.7	4.0	7.1	8.34E+22	5.5
Nantou	453	1.44	17.31	3.79	16.8	3.9	7.3	1.08E+23	20.6
Keelung	46	0.15	1.76	0.38	114.9	5.1	7	6.48E+22	163.0
Taipei	36	0.11	1.38	0.30	22.0	3.2	5.7	2.61E+20	255.7
New Taipei	10	0.03	0.38	0.08	37.3	3.6	5.1	3.17E+19	362.6
Taoyuan	22	0.07	0.84	0.18	11.5	3.4	4.7	1.60E+19	308.3
Hsinchu	122	0.39	4.66	1.02	8.0	3.0	5	4.23E+19	63.5
Miaoli	112	0.35	4.24	0.93	8.4	3.7	5.2	2.13E+20	69.6
Taichung	135	0.43	5.16	1.13	16.1	3.9	5.6	6.37E+20	62.6
Changhua	25	0.08	0.96	0.21	19.5	3.6	5.3	7.83E+19	324.9
Yunlin	232	0.74	8.87	1.94	12.0	3.6	6.6	5.45E+21	36.7
Chiayi	754	2.40	28.82	6.30	10.0	3.5	6.4	6.48E+21	12.6
Tainan	335	1.07	12.80	2.80	14.7	3.5	5.7	5.83E+20	28.4
Kaohsiung	127	0.40	4.85	1.06	21.4	3.8	5.8	7.73E+20	71.4
Pingtung	270	0.86	10.32	2.26	24.2	4.1	7	5.67E+22	34.9
Penghu	15	0.05	0.57	0.13	21.2	4.3	6.1	9.32E+20	207.8
Kinmen	8	0.03	0.31	0.07	14.7	3.4	4.6	6.48E+18	484.7
Matsu	6	0.02	0.23	0.05	15.4	4.7	5.3	1.01E+20	280.3
Total	11,965	1.90	22.86	100.00	22.47	3.79	5.975	5.30E+23	139.97
Energy (ergs)	$\log_{10}E=11.8+1.5M_S$								
Average dTime (days)	The average days between two earthquakes.								

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6.2 Appendix B:

Table B1: Data of the labeled earthquakes for cities in Taiwan (From January 1995 to February 2021)

City/County	Numbers of earthquakes	Mean times per month	Mean times per year	Earthquake percentage (%)	Depth (km)	Magnitude (Richter M_L)		Total Energy Released (ergs)	Average dTime (days)
						Mean	Max		
Yilan	586	1.87	22.39	16.97	37.9	4.5	7.1	7.61E+22	16.1
Hualien	1407	4.48	53.77	40.74	16.6	4.3	6.9	1.17E+23	6.7
Taitung	485	1.54	18.54	14.04	19.8	4.6	7.1	6.97E+22	19.6
Nantou	208	0.66	7.95	6.02	16.0	4.5	7.3	1.08E+23	43.7
Keelung	19	0.06	0.73	0.55	103.6	5.5	7	6.24E+22	358.2
Taipei	13	0.04	0.50	0.38	35.6	3.7	5.7	2.59E+20	647.2
New Taipei	3	0.01	0.11	0.09	50.6	3.7	5.1	2.82E+19	964.1
Taoyuan	9	0.03	0.34	0.26	11.8	3.9	4.7	1.54E+19	615.0
Hsinchu	14	0.04	0.54	0.41	7.6	3.9	5.0	3.70E+19	437.7
Miaoli	35	0.11	1.34	1.01	8.9	4.4	5.2	1.96E+20	171.1
Taichung	63	0.20	2.41	1.82	16.6	4.3	5.6	6.17E+20	134.1
Changhua	8	0.03	0.31	0.23	13.3	4.3	5.3	7.44E+19	769.9
Yunlin	108	0.34	4.13	3.13	11.8	4.1	6.6	5.44E+21	72.3
Chiayi	264	0.84	10.09	7.64	10.4	4.1	6.4	6.43E+21	34.5
Tainan	98	0.31	3.75	2.84	15.2	4.0	5.6	4.73E+20	95.9
Kaohsiung	39	0.12	1.49	1.13	30.0	4.2	5.8	7.39E+20	231.4
Pingtung	92	0.29	3.52	2.66	26.4	4.7	7	5.64E+22	98.6
Penghu	3	0.01	0.11	0.09	29.0	5.0	6.1	9.00E+20	618.3
Kinmen	0	0.00	0.00	0.00	N.A.	N.A.	N.A.	0	N.A.
Matsu	0	0.00	0.00	0.00	N.A.	N.A.	N.A.	0	N.A.
Total	3,454	0.55	6.60	100	N.A.	N.A.	N.A.	5.05E+23	N.A.
Energy (ergs)	$\log_{10}E=11.8+1.5M_S$								
Average d Time (days)	The average days between two earthquakes.								

In the above table, the released energy of earthquakes is based on the equation, $\log_{10}E=11.8+1.5M_S$, given by Gutenberg and Richter [2]. Many variations of M_S (shear-wave magnitude) formulas take into account the effects of specific geographic regions so that the final computed magnitude is reasonably consistent with Richter's original definition of M_L [3]. In this study, the author does not distinguish these two magnitudes. During the energy calculation, M_S was substituted by M_L.

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6.3 Appendix C:

Table C1: Energy released of earthquakes from January 1995 to February 2021 in Taiwan

City/County	The energy released of labeled earthquakes and equivalent to atomic bomb numbers		The energy released of total earthquakes and equivalent to atomic bomb numbers	
	Energy released (ergs)	Equivalent atomic bomb numbers	Energy released (ergs)	Equivalent atomic bomb numbers
Yilan	7.61E+22	120.8	7.95E+22	126.2
Hualien	1.17E+23	185.7	1.22E+23	193.7
Taitung	6.97E+22	110.6	8.34E+22	132.4
Nantou	1.08E+23	171.4	1.08E+23	171.4
Keelung	6.24E+22	99.0	6.48E+22	102.9
Taipei	2.59E+20	0.4	2.61E+20	0.4
New Taipei	2.82E+19	0.0	3.17E+19	0.1
Taoyuan	1.54E+19	0.0	1.60E+19	0.0
Hsinchu	3.70E+19	0.1	4.23E+19	0.1
Miaoli	1.96E+20	0.3	2.13E+20	0.3
Taichung	6.17E+20	1.0	6.37E+20	1.0
Changhua	7.44E+19	0.1	7.83E+19	0.1
Yunlin	5.44E+21	8.6	5.45E+21	8.7
Chiayi	6.43E+21	10.2	6.48E+21	10.3
Tainan	4.73E+20	0.8	5.83E+20	0.9
Kaohsiung	7.39E+20	1.2	7.73E+20	1.2
Pingtung	5.64E+22	89.5	5.67E+22	90.0
Penghu	9.00E+20	1.4	9.32E+20	1.5
Kinmen	0.00E+00	0.0	6.48E+18	0.0
Matsu	0.00E+00	0.0	1.01E+20	0.2
Total	5.05E+23	801.3	5.30E+23	841.3

Note: The released energy of an atomic bomb dropped in Hiroshima is about 63TJ or equivalent to 6.30E+20 ergs (codename: Little Boy)

From the above table, one finds that the negligence of unlabeled earthquakes may under-estimate the released energy up to 2.5E+22 ergs, or more graphically speaking, equivalent to 39.7 atomic bombs dropped in Hiroshima, Japan during WWII.