

Relationship Between Major Eruptions and Large Earthquakes: A Comparative Study Between Japan and Indonesia

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Synopsis

Now a days eruptive activity and seismicity are increasing significantly, and in the volcanic belt, they are thought to be inter correlated. Japan and Indonesia are frequently affected by earthquakes and eruptions but occurring patterns are not similar in both the countries. The results of time series analysis indicate that the earthquakes follow strong non-stationary property for Indonesia but on the other hand, Japan has seasonal effect. By applying some time series tools ARIMA(3,1,2) and ARIMA(2,0,1)x(1,0,1) models has proposed for forecasting the earthquakes of Indonesia and Japan, respectively.

The criterion for occurrence of a large earthquake based on timing of volcanic eruptions has a time-distance relationship. The results of the analysis strongly suggest that time-distance relations may help to predict an earthquake before it strikes if the epicentral location can be identified in advance and if the activity of the volcanoes is well monitored for both Japan and Indonesia.

Keywords: Time series, Stationary, Seasonal effect, ARIMA, Time-distance relation.

1. Introduction

Currently, earthquake forecasting is similar to weather forecasting. Scientists can predict that an earthquake has a certain probability of occurring within a given time frame, but not one that will definitely take place. Knowledge of past earthquake patterns, the earthquake (foreshock or mainshock) magnitude and the seismic history of the fault on which it occurred are among the important factors that go into forecasting an earthquake. There are many reasons for causing of large earthquakes in the world but most of the reasons become unknown before strike. Although, temporarily we are suggesting volcanic activity is more influential element for causing of earthquakes in the volcanic belt but the problem is to find out the influential

volcanoes [2].

Reports of volcanic eruptions and earthquakes originating from volcanoes indicate that seismic activity preceding the eruption is related not only to eruption magnitude and structure of the volcano, but also to viscosity of the lava at the time of eruption [11]. If the eruptions are influenced by the regional tectonic stresses causing earthquakes, some spatial and temporal relations between large interplate earthquakes and eruptions can be expected along the island arc systems [14]. Tectonic strain accumulates in the lithosphere of the preseismic stage and is released by the shocks [9]. Earthquakes have the potential to increase the pressure in magma chambers even at large distances, and a premature eruption may result if a seismic wave accelerates the ascent of magma close to the

critical pressure state [7]. Simultaneous occurrence pattern between large inland earthquakes and the volcanic eruptions, just prior to the great earthquakes or just afterwards suggests that the temporal correlation among the volcanic eruptions, and the great earthquakes is not statistically negligible.

A probable relationship between volcanic activity and large earthquakes was first shown in the Kanto area when Oshima volcano was in active stage and a few years later the two earthquakes occurred concurrently in that region [8]. The space-time relationship among the volcanic eruptions, the large inland shallow earthquakes and the great earthquakes near the trench is useful for long-term earthquake prediction and volcanic eruption in the northern Honshu region [10]. Statistical analysis suggested that the criterion for occurrence of a great earthquake based on timing of volcanic eruptions has a time-distance relationship in Japan [1-3]. By examining the historical record of volcanic eruptions and earthquakes, a statistically significant correlation is found between large earthquakes and volcanic eruptions separated by a distance up to 750 km [6]. Recently, Barren volcano erupted lava and the Narcondum volcano emitted smoke and sand after the occurrence of mega earthquake in Indonesia (December, 2004) which support the interpretation and the hypothesis that the volcanic system is disturbed by earthquakes [12]. Many scientists have pointed out that there exists some physical relation between volcanic activity and tectonic seismicity [15, 17].

Most of the large earthquakes occurred before or after major eruptions in the volcanic belt. I have used here only the major eruptions that occurred before large earthquakes. Two regions (Japan and Indonesia) are selected to show the relationship between volcanic activity and seismicity in this article. Our goal is to develop (i) a time series model for forecasting the earthquake behavior, and (ii) to provide the relationship between major eruptions and large earthquakes in the world and then forecast the upcoming large earthquake depending on the relationship model.

2. METHODOLOGY

The goal of time series analysis is to find out a useful way (a model) to express a time-structured relationship. Such data may be collected at regular time intervals, such as daily, weekly, monthly, quarterly and annually etc that have a unique important place in the field of earthquake data analysis. Autoregressive integrated moving average (ARIMA) model is used for forecasting the earthquake behavior for Japan and Indonesia. This class of models has proved to be useful in representing both stationary and nonstationary time series data. A seasonal ARIMA model is classified as an $ARIMA(p,d,q) \times (P,D,Q)$ model, where P =number of seasonal autoregressive (SAR) terms, D =number of seasonal differences, Q =number of seasonal moving average (SMA) terms. In identifying a seasonal model, the first step is to determine whether or not a seasonal difference is needed, in addition to or perhaps instead of a non-seasonal difference [5].

Box-Jenkins forecasting models are based on statistical concepts and principles and are able to model a wide spectrum of time series behavior. There are both statistical tests for verifying model validity and statistical measures of forecast uncertainty. The objective of Box-Jenkins is to identify and estimate a statistical model [4].

Activity of the Oshima volcano is directly related to the occurrence of the great Kanto earthquake in 1923 and Bosooki earthquake in 1953 along the Sagami Trough which shows that time interval decreases as distance increases (Fig. 1). This occurs because variations of time intervals strongly suggest that the crustal strain migrates from the area where crustal rupture may appear in future; this was pointed out using all of the related eruptions and large earthquakes in central Japan [3]. Eruptions and earthquakes pattern in Kanto region are the basis for selection of data in this study.

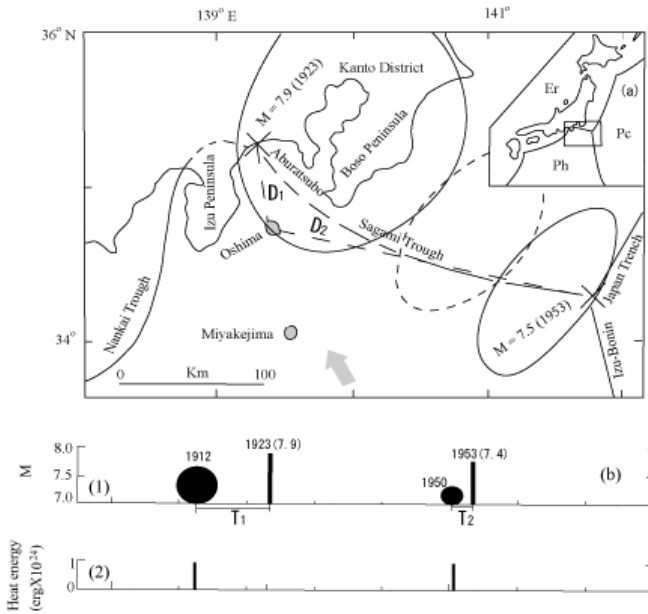


Fig. 1 (a) Large earthquakes (X = epicenter; solid and broken out lines show aftershock areas and seismicity gap) that have occurred along the Sagami Trough since 1880. Direction of slip of the northern Philippine Sea Plate (arrow), Sagami Trough (Sg), Nankai Trough (Nk), Japan Trance (Jp), Izu-Bonin Trenc (I-B), Oshima (Os), Miyakejima (My), Aburatsubo (Ab), Boso Peninsula (Bs), Izu Pensinula (Iz), Philippine Sea Plate (Ph), Pacific Plate (Pc) and Eurasian Plate (Er) are shown. D1 and D2 are the distance between the Oshima volcano and the earthquakes of 1923, and 1953.

(b) Relationship between large eruptions (bold circle) and large earthquakes (vertical bars) that have occurred along the Sagami Trough. (1) Record of large earthquakes and eruptions along Sagami Trough; (2) Heat energy discharged by large eruptions of Mihara-yama. T1 and T2 are the time intervals between the Oshima volcano and occurrence of the shocks of 1923 and 1953, respectively.

3D partial correlation coefficient can be written as $r_{xy.z} = \frac{r_{xy} - r_{xz}r_{yz}}{\sqrt{(1 - r_{xz}^2)(1 - r_{yz}^2)}}$, where r_{xy} , r_{xz} and r_{yz} are the respective 2D correlation coefficients between log of distance and time, log of distance and magnitude, respectively. $r_{xy.z}$ represents the correlation between log of distance and time when

the influence of magnitude is eliminated. Variables are selected according to their influences on the models that are used for regression analysis. Least squares method is used to estimate the parameters of the regression model,

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \varepsilon \quad (1)$$

where Y , X_1 and X_2 represent time, log of distance and magnitude respectively; $\beta_0, \beta_1, \beta_2$ are regression coefficients and ε is the error term. Different statistical testing procedures are applied to verify the adequacy of the model [13].

3. RESULTS AND DISCUSSION

Simple statistical tools and time series analysis are used for analyzing and comparing the earthquake effects between two countries Indonesia and Japan during 1980 to 2007. Earthquakes are classified into different class intervals depending on magnitude and time. Recently, earthquakes and eruptions are increasing significantly all over the world. Earthquakes are also monotonically increasing in both Japan and Indonesia since 1980. Duncan multiple range test suggests the number of occurrences in 2005 significantly differ from other years due to the occurrence of the mega earthquake in Indonesia (December, 2004). But maximum earthquakes occur in Japanese in 2001 though it is not statistically significant compare to other years, probably two large earthquakes ($M \geq 7.0$) and some eruptions occurred during this period [1].

3.1 Time series analysis

Stationarity has always played a major role in time series analysis and forecasting. To perform forecasting, most techniques require stationarity condition. Sample autocorrelation function (ACF) and Box-Ljung statistic are typical of a series which indicates that the magnitude of the earthquakes follows non-stationary for Indonesia. Autocorrelation plot function and partial autocorrelation function (PACF) indicates that both MA (moving average) and AR (autoregressive) models are appropriate [4]. There exist no unit roots

after first difference of autocorrelation function which is a sign of stationarity (Table 1). The Box-Pierce (Ljung-Box) Chi-square statistic and p-values are insignificance indicating that there exist no further ARIMA effects (Table 2). Finally, the out sample root mean sum of square error is less than the in sample root mean sum square error, thus the model ARIMA(3,1,2) is selected for Indonesian earthquake and the model can be written as

$$\Delta Y_t = 0.2865 + 0.1367\Delta Y_{t-1} + 0.1452\Delta Y_{t-2} + 0.3352\Delta Y_{t-3} + \varepsilon_t - 0.5996\varepsilon_{t-1} - 0.3935\varepsilon_{t-2} \dots \quad (2)$$

Table 1 Parameter estimation and their significance. Coef (coefficient), SD (standard error), T (test statistic), P (probability for significance).

Type	Coef	SD	T	P
AR1	0.1367	0.0590	2.32	0.021
AR2	0.1452	0.0562	2.59	0.010
AR3	0.3352	0.0567	5.91	0.000
MA1	0.5996	0.0250	23.98	0.000
MA2	0.3935	0.0133	29.68	0.000
Constant	0.2865	0.1049	2.73	0.007

Table 2 (Ljung-Box) Chi-Square Statistic. DF indicates degrees of freedom.

Lag	12	24	36	48
Chi-Square	11.1	25.8	27.8	30.4
DF	6	18	30	42
P-Value	0.085	0.105	0.582	0.907
Mean sum of square residual (MSSE) = 7652				

The ACF is typical of a series for Japanese earthquakes that follows both non-stationary and weakly seasonality which indicates that at least one order of differences is needed. Depending on the residual ACF and PACF, ARIMA(2,0,1)x(1,0,1) model is statistically significant for forecasting Japanese earthquakes (Table 3-4). The final model is selected as

$$(1 - 1.4134B^s + 0.42B^{2s})Y_t = (1 - 0.9557B^s)\varepsilon_t \quad (3)$$

Table 3 Parameter estimation and their significance

Type	Coef	SD	T	P
AR1	1.4134	0.0525	26.94	0.000
AR2	-0.4200	0.0523	-8.03	0.000
SAR12	0.9884	0.0538	18.39	0.000
MA1	0.9557	0.0127	75.08	0.000
SMA12	0.9437	0.0757	12.46	0.000

Table 4 Box-Pierce (Ljung-Box) Chi-Square statistic

Lag	12	24	36	48
Chi-Square	3.6	13.2	19.8	30.8
DF	9	21	33	45
P-Value	0.937	0.901	0.966	0.948
Mean sum of square residual (MSSE) = 7652				

3.2 Relationship between major eruptions and large earthquakes

The correlation coefficient ($r = -0.915$) between time and log of distance shows a highly significant negative correlation. Coefficient of determination (R^2) is approximately 0.928 indicating that 92.8% variability can be explained by the regression model for Japanese earthquakes and eruptions data. Analytical results ($P = 0.00$; exact value of $P < 10^{-7}$) suggest that the overall regression is highly significant indicating time may have relation to log of distance and/or magnitude (Table 5). To determine the influence of magnitude on time-distance relationship model, a partial parametric test on individual regression coefficient is applied and found that magnitude, or X_2 , contributes significantly ($P < 0.01$) to the model given that log of distance or X_1 , is in the model (Table 6). So the proposed model for Japan might be:

$$Y = 53.05 - 16.41X_1 - 0.91 X_2 \quad (4)$$

Table 5 Analysis of variance test. Table showing the mean squares of regression and residual along with F statistic for testing $H_0: \beta_1 = \beta_2 = \beta_3 = 0$. The P-value for the test for significance of regression is reported as $P=0.000$ (this is a rounded value; the actual $P\text{-value} < 10^{-7}$). Sum of Squares (SS), Degrees of Freedom (DF), Mean Sum of Square (MSS).

Source	SS	DF	MSS	F	P	R ²
Reg	2138.33	2	1069.16	490.6	0.0	0.928
Res	398.81	183	2.18			
Total	2537.14	185				

Table 6. Table shows the standard errors of the estimates and intercepts along with the t statistic for testing $H_0: \beta_0 = 0$, $H_0: \beta_1 = 0$ and $H_0: \beta_2 = 0$. The P-values for the test for significance of individual regression coefficients (distance and/or magnitude) are reported. Standard Error (SE), Test Statistic (t).

Predictor	Coefficients	SE	T	P
Constant	$\hat{\beta}_0 = 53.05$	2.97	17.88	0.00
Log distance	$\hat{\beta}_1 = -16.41$	0.52	-31.27	0.00
Magnitude	$\hat{\beta}_2 = -0.92$	0.35	-2.62	0.01

The negative value of the coefficient β_1 indicates that the eruption occurs prior to the concerned shock if the epicenter of the earthquake is nearer to the respective volcano/volcanoes (Fig. 2).

Scattered diagram (bold circle), fitted line (open circle), confidence interval for the mean response and prediction interval for the future observation are shown. The fitted model shows the negative association between time and log of distance, that is, time duration decreases as distance increases.

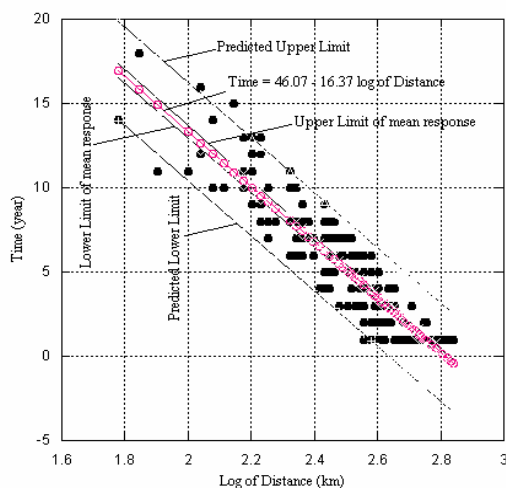


Fig. 2 Time - distance relationship between volcanic eruptions and large earthquakes in Japan.

R^2 is approximately 0.496 indicating that 49.6% variability can be explained by the regression model which is really difficult to make any comment for Indonesian data though the fitted model is almost similar to Japanese ($Y = 46.12 - 16.49 \log X$). Combination of both samples (Japan and Indonesia) and fitting provides a similar model like as Japan (Fig 3). For fitting the time-space relationship model for Japan, I have used the data from 1880 to 2007 but for Indonesia, I have only a data set from 1980 to 2007. Due to the lack of available data, I am unable to make any comment that the model (Fig 3.) is also fruitful for Indonesia. But the proposed model may able to show the primary relation between major eruptions and large earthquakes in Japan and Indonesia.

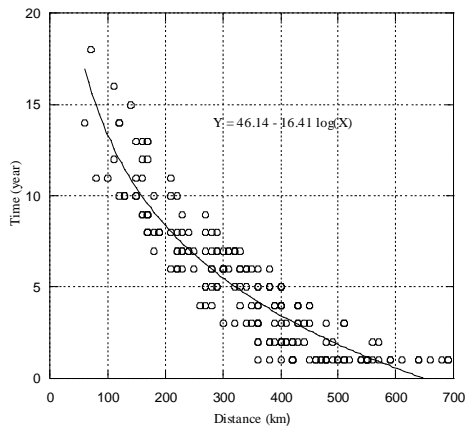
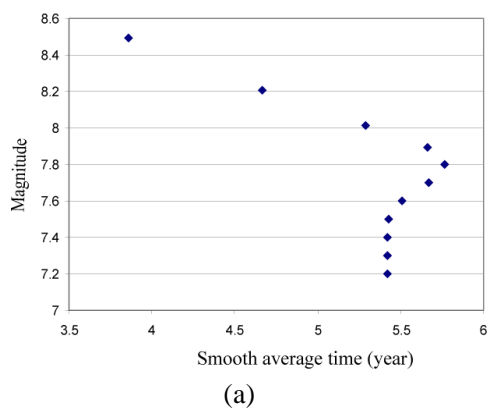
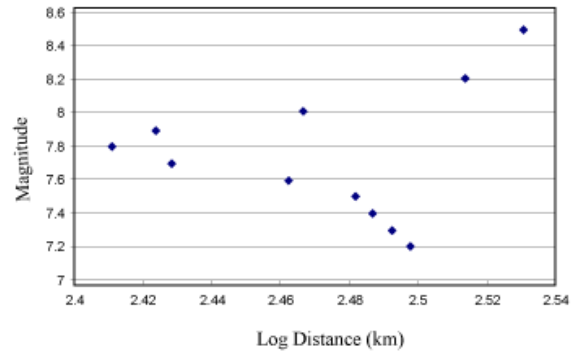


Fig. 3 Time - distance relationship between volcanic eruptions and large earthquakes in Japan and Indonesia.

The **4253H** method [16] indicates that if magnitude is less than or equal to 7.4, average time duration between eruptions and earthquakes remain unchanged. Average time duration between eruptions and earthquakes increase as magnitude increases until 7.8 then again average time duration decreases as magnitude increases which means that time duration between eruptions and earthquakes will be smaller for great earthquakes ($M > 7.8$) than that of large earthquakes ($M < 7.8$). That is strain migration will be faster for great earthquakes than that of large one (Fig. 4a).



(a)



(b)

Fig. 4. Robust nonlinear data smoothing pattern. (a) relation between smoothed magnitude and smoothed average time, and (b) smoothed magnitude and smoothed average log of distance.

The arrow shaped figure indicates that distance decreases for large earthquakes ($M < 7.8$) but increases for great earthquakes ($M > 7.8$). That is, strain migration region for large earthquakes are smaller than that of the great earthquakes (Fig. 4b). This decreasing and increasing pattern implies that there may involve some tectonic causes that are responsible for both the volcanic eruptions and earthquakes.

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火山噴火と大地震の関係：日本とインドネシアの比較研究

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要 旨

近年、地震活動、火山噴火活動が活発化の傾向にあり、火山帯においてそれらは相互相関していると考えられる。日本とインドネシアはたびたび地震や火山の影響を被ってきたが、その発生パターンには両国間に差異がある。時系列解析の結果、インドネシアでは地震は強い非定常性を示すのに対し、日本では季節性の変動を示す。時系列解析モデル $ARIMA(3, 1, 2)$ と $ARIMA(2, 0, 1) \times (1, 0, 1)$ を各々インドネシアと日本における地震予測に適用した。

火山噴火と大地震には時間と距離に依存した関係がある。インドネシア日本両国において震央位置が迅速に得られ、火山活動が十分モニターされるならば、この時間と距離の相関解析は地震の事前予測に役立つものであることが示唆される。

キーワード: 時系列, 定常, 季節性, ARIMA, 時間・距離相関