A Statistical Model of Temporal Variation of Seismicity in the Inner Zone of Southwest Japan Related to the Great Interplate Earthquakes along the Nankai Trough

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To evaluate the temporal variation of seismicity in the Inner Zone of Southwest Japan before and after the Nankai trough events, we introduced a statistical model and estimated the value of the model parameters. We used the data of disastrous earthquakes to estimate them. Because of the lack of spatially sufficient data, we used data from the 9th century in the case of the northern Kinki region, and in the case of the whole Inner Zone of Southwest Japan only data after the 17th century. The results show that for the northern Kinki region the seismicity has a peak before the Nankai trough events, although there is no significant change before them in the whole Inner Zone of Southwest Japan. The seismicity in the Inner Zone of Southwest Japan increases just after the Nankai trough events. We compared the obtained intensity functions with the recent JMA data from 1885 to 1995. The seismicity seems to have increased in the last 30 years. Using data from this period, we estimated the occurrence time of the next Nankai trough event. Our results show that it will occur in the 2030's.

1. Introduction

The region, we investigate in this paper, is located in the eastern margin of the Eurasian plate and roughly corresponds to the tectonic province called the Inner Zone of Southwest Japan (Fig.1). The southern and the eastern margins of this province are the Median Tectonic Line (MTL) and the Itoigawa-Shizuoka Tectonic Line (ISTL), respectively. To the south of MTL, the Philippine Sea plate is moving relatively northwestward and is subducting beneath the Eurasian plate. This part of the boundary between these two plates is called the Nankai trough. Along this boundary, great interplate earthquakes have occurred repeatedly (Ando, 1975). We refer to these interplate earthquakes as Nankai trough events in this paper. Two Nankai trough events often occur successively in short time intervals in an adjacent area. We treat these successive events as a couple and use the occurrence time of the first event as the time for the couple of events.

There are many active faults in the eastern half of the Inner Zone of Southwest Japan (Fig. 1b) and many disastrous earthquakes, including the 1995 Hyogo-ken Nanbu earthquake, have occurred in this region. According to the historical earthquake data, disastrous earthquakes frequently occurred there around the same time as the Nankai trough events (Utsu, 1974a, b; Shimazaki, 1976; Seno, 1979; Mogi, 1981). The average rate of their occurrence in the period from 50 years before to 10 years after the Nankai trough events is about four times higher than in the other periods (Utsu, 1974a). A period of low seismicity for several decades follows a period of high seismicity around the occurrence time of each Nankai trough event.

In this paper, we introduce a statistical model in order to quantitatively treat the temporal variation of seismicity in the Inner Zone of Southwest Japan before and after Nankai trough events. We use the data of disastrous earthquakes to estimate the value of the parameters in the statistical model. We apply this model to the data of recent earthquakes.

2. Data

2.1 Disastrous earthquakes

We used the data of disastrous earthquakes...
(\(M \geq 5.8\)) for estimating the values of the parameters in the statistical model introduced later. The disastrous earthquake data cover a long period of more than 1,000 years, in which eight couples of Nankai trough events are included. Therefore, we can obtain the “average” temporal variation in seismicity around the occurrence times of the Nankai trough events.

The data is taken from “the list of disastrous earthquakes in Japan” in the Rika nenpyo (Chronological Scientific Tables) published in 1995. In this list, there are some events for which magnitude, epicenter or both are not given. However, we can roughly determine them from the distribution of damage described in this list.

We estimated the value of the statistical model parameters for two regions, as shown in Fig. 1. One is the large region which roughly corresponds to the Inner Zone of Southwest Japan. The other is the northern Kinki region which has an especially dense distribution of the active faults. The eastern part of the northern Kinki region corresponds to the Kinki Triangle (Huzita, 1962). We concentrated on this small region since we can reliably use the historical data covering about 1,000 years in this region.

Fig. 1. (a) Index map of plates in and around Japan. EUR, Eurasian plate; PHS, Philippine Sea plate; NA, North American plate; PAC, Pacific plate. The polygon shows the area drawn in (b) and (c). (b) Distribution of active faults in and around southwest Japan after Matsuda (1981). ISTL, MTL and RA indicate Itoigawa–Shizuoka Tectonic Line, Median Tectonic Line and Rokko–Awaji Faults, respectively. Shaded zone indicates the Kinki Triangle (Huzita, 1962). Solid circle indicates Kyoto City. (c) Epicentral distribution of disastrous earthquakes in the period from 800 to January, 1995. The polygons indicate the regions treated in this paper. Solid circle indicates the 1995 Hyogo-ken Nanbu earthquake.
Statistical Model of Temporal Variation of Seismicity

Fig. 2. Space-time distribution of the epicenters in the Inner Zone of Southwest Japan. Each open circle indicates the earthquake whose epicenter and magnitude are given in Rika nenpyo (1995). Each solid circle indicates the event whose epicenter we roughly determine from the distribution of damage.

Fig. 3. Cumulative number of disastrous earthquakes in the northern Kinki region. This figure indicates that the increasing rate of the cumulative number of the earthquakes ($M \geq 5.8$) has been almost constant for about 1,000 years.

Fig. 4. Magnitude-time plot in the northern Kinki region. The shaded belts indicate the periods from 50 years before to 10 years after the Nankai trough events in 887, 1096, 1360, 1498, 1605, 1707, 1854 and 1944. The shaded part with "?" mark indicates the periods before and after the possible Nankai trough events in the 10-11th and 12-13th centuries (Sangawa, 1992).

Fig. 5. Magnitude-time plot in the Inner Zone of Southwest Japan. The shaded zones indicate the periods from 50 years before to 10 years after the Nankai trough events in 1605, 1707, 1854 and 1944.

Figure 2 shows the space-time distribution of the disastrous earthquakes in the Inner Zone of southwest Japan. In this figure, however, before the 17th century most of the epicenters are plotted only in and around Kyoto, where old capitals of Japan had been located for about twelve centuries. Therefore, we used only the data from the 17th century for the whole Inner Zone of Southwest Japan and used the data from the 9th century for the northern Kinki region. Figure 3 shows the cumulative numbers of earthquakes in the northern Kinki region. This figure indicates that the increasing rate of the cumulative number of the earthquakes ($M \geq 5.8$) has been almost constant for about 1,000 years.

In the northern Kinki region, high seismic periods roughly correspond to the periods from 50 years before to 10 years after the Nankai trough events, as shown in Fig. 4. A similar pattern can be seen in the Inner Zone of Southwest Japan (Fig. 5). The Nankai trough events may have occurred in the 10-11th and in the 12-13th centuries, respectively (Sangawa, 1992), as shown in Fig. 4. If this is the case, almost all of the events in the northern Kinki region may have occurred during the period from 50 years before to 10 years after the Nankai trough events. But presently we do not use this information in our analyses.

In order to see the average temporal variation of seismicity before and after the Nankai trough events, we superimposed the time series of earthquakes for the periods from 80 years before to 40
Table 1. Minimum magnitude and b-values used for modifying the intensity functions.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum magnitude</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>b-Value</td>
<td>0.88</td>
<td>0.86</td>
</tr>
</tbody>
</table>

Fig. 6. Histogram of the number of the disastrous earthquakes in the northern Kinki region. The origin of the horizontal axis corresponds to the occurrence times of the Nankai trough events in 887, 1096, 1360, 1498, 1605, 1707, 1854 and 1944.

Fig. 7. Histogram of the number of disastrous earthquakes in the Inner Zone of Southwest Japan. The origin of the horizontal axis corresponds to the occurrence times of the Nankai trough events in 1707, 1854 and 1944.

The Nankai trough events, although most of the earthquakes have magnitude smaller than 6.8 (Seno, 1979). We used these superposed data to estimate the value of the parameters of the statistical model.

2.2 JMA data
We applied the obtained statistical model to the data reported by JMA, and estimated the occurrence time of the next Nankai trough event. We took this data from the data of the SEIS-PC system (Ishikawa et al., 1985). This data includes the earthquakes occurring in the period from 1885 to the middle of 1995. We used the events whose depths were shallower than 30 km. Table 1 shows the periods of data used here and their magnitude thresholds.

3. Statistical Analyses
3.1 A statistical model of temporal variation of seismicity
We assumed that the superposition of the time series of the disastrous earthquakes were distributed according to a stationary or a non-stationary Poisson process. This assumption is appropriate because the data used here includes few aftershocks and so the earthquakes occurred independently of each other.

To evaluate the temporal variation in seismicity, we used the statistical model introduced by Ogata and Katsura (1985). We modify the intensity function $\lambda$ of this model as follows,

model 1:

$$\lambda(t') = \exp \left[ \sum_{k=0}^{m-1} a_k t'^k \right],$$

for $-80 \leq t' \leq -80 < 40$,

model 2:

$$\lambda_{tr}(t') = \exp \left[ \sum_{k=0}^{m-1} b_k t'^k \right],$$

for $-80 \leq t' < -80 < 0$. 

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\[ \lambda_{\text{ref}}(t') = \exp \left[ \sum_{k=0}^{l} c_k(t' - 80)^k \right], \]

for \( 0 \leq t' - 80 \leq 40, \)

where \( t' - 80 = t - t_i, \) \( \{t_i| i = 1, 2, \ldots, N\}. \) \( t_i \) and \( N \)

are the occurrence times of each Nankai trough event and the number of couples of Nankai trough events, respectively. \( n, m, \) and \( l \) are the number of parameters \( \{a_k\}, \{b_k\} \) and \( \{c_k\}, \) respectively.

We estimated the value of the parameters by using the maximum likelihood method and we calculated the maximum likelihood estimates (MLE) of the parameters for \( n, m, \) and \( l = 1, \ldots, 4. \) We used AIC (Akaike, 1974) to select the order of the polynomial in each intensity function. The intensity function whose AIC is larger, is considered to be the worse one for the data. We selected the lower order of polynomial if the difference of the values of AIC was smaller than 1.0. We also used AIC to compare the two models. AIC of model 2 is calculated by \( \text{AIC}_{\text{total}} = \text{AIC}_{\text{before}} + \text{AIC}_{\text{after}} \) (Kitagawa and Akaike, 1978). If AIC of model 2 was considerably smaller than that of model 1, the difference between the seismicity before and after the Nankai trough events was significant.

The approximate simultaneous distribution of the error of MLE is given by \( N(0, J^{-1}) \), where the matrix \( J \) is called by the Fisher information matrix (Ogata, 1983). We calculated the standard deviation \( \sigma \) of the probability density function \( \sum_k^l t^k e_k \), where \( e_k \) is the standard deviation of each probability density function for the error of each MLE. We will show each intensity function \( \lambda \) with the functions \( \exp(\pm \sigma) \cdot \lambda \) in order to indicate the error of estimation of its parameters.

### 3.2 Estimation of the value of the model parameters

We estimated the value of the model parameters in the two cases of \( M \geq 5.8 \) and \( M \geq 6.8 \) for each region. The values of AIC for the number of parameters of each intensity function are listed in Table 2. The values of AIC for the two models are also listed in this table. This table indicates that the temporal variation of seismicity is significant in all cases, except in the case of \( M \geq 6.8 \) for the Inner Zone of Southwest Japan. We show the estimated value of the parameters and their errors in Table 3.

For the northern Kinki region, model 1 was selected as shown in Table 2. We obtained the intensity function of the earthquakes \( (M \geq 6.8) \) as shown in Fig. 8. It has a peak before the occurrence times of the Nankai trough events. This trend also appears in the case of \( M \geq 5.8. \)

The intensity function for the Inner Zone of Southwest Japan in the case of \( M \geq 5.8 \) is shown in Fig. 9. In this case, model 2 was selected. This indicates that the seismicity changes significantly just after the Nankai trough events. In this region, however, no temporal variation was found before the events, unlike the northern Kinki region.

### 3.3 Application of the model to JMA data

We applied the model obtained above to the recent data of JMA and estimated the occurrence time of the next Nankai trough event. We used the model for the northern Kinki region, because this shows a significant temporal variation of seismicity before the Nankai trough events. We used the data of disastrous earthquakes to obtain the model, so we can only apply this model directly to JMA data that includes smaller earthquakes. We assumed that the Gutenberg and Richter's formula could be applied. We multiplied the intensity function by the factor \( C = 10^{-b(M_J - M_D)} \), where \( b, M_J, \) and \( M_D \) are

<table>
<thead>
<tr>
<th>Inner Zone of Southwest Japan</th>
<th>( M )</th>
<th>Model</th>
<th>( n = 1 )</th>
<th>( n = 2 )</th>
<th>( n = 3 )</th>
<th>( n = 4 )</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.8</td>
<td>1</td>
<td>Before</td>
<td>194.6</td>
<td>195.0</td>
<td>191.5</td>
<td>192.9</td>
<td>191.5</td>
</tr>
<tr>
<td>After</td>
<td>73.5</td>
<td>65.5</td>
<td>64.8</td>
<td>66.4</td>
<td>186.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.8</td>
<td>1</td>
<td>Before</td>
<td>117.2</td>
<td>117.0</td>
<td>117.8</td>
<td>119.7</td>
<td>117.2</td>
</tr>
<tr>
<td>After</td>
<td>49.7</td>
<td>49.9</td>
<td>50.0</td>
<td>50.2</td>
<td>117.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Northern Kinki region</th>
<th>( M )</th>
<th>Model</th>
<th>( n = 1 )</th>
<th>( n = 2 )</th>
<th>( n = 3 )</th>
<th>( n = 4 )</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.8</td>
<td>1</td>
<td>Before</td>
<td>172.1</td>
<td>174.0</td>
<td>157.7</td>
<td>158.4</td>
<td>157.7</td>
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<tr>
<td>After</td>
<td>46.9</td>
<td>41.1</td>
<td>42.4</td>
<td>44.2</td>
<td>157.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.8</td>
<td>1</td>
<td>Before</td>
<td>94.4</td>
<td>96.4</td>
<td>91.9</td>
<td>93.9</td>
<td>91.9</td>
</tr>
<tr>
<td>After</td>
<td>23.5</td>
<td>24.3</td>
<td>22.8</td>
<td>24.8</td>
<td>117.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

"Total" is AIC for each model. The underlined values indicate the selected models.
Fig. 8. The intensity function estimated using the data \( (M \geq 6.8) \) of the northern Kinki region shown in Fig. 6. Broken curves indicate the error band of the intensity function. These functions are divided by "8": the number of superposed couples of the Nankai trough events.

Fig. 9. The intensity function estimated using the data \( (M \geq 5.8) \) of the Inner Zone of Southwest Japan shown in Fig. 7. Broken curves indicate the error band of the intensity function. These functions are divided by "3": the number of superposed couples of the Nankai trough events.

Fig. 10. The lines show the expectation of the number of earthquakes every ten years calculated from the modified intensity functions for the northern Kinki region. The histograms are obtained from JMA data in the corresponding period.

Using the data of the last 30 years, we estimated the occurrence time of the next Nankai trough event by calculating MLE of \( t_0 \) in the following intensity function,

\[
\lambda(t; t_0) = \frac{C}{8} \exp \left[ \sum_{k=0}^{2} \hat{a}_k (t - t_0 + 80)^k \right],
\]

where \( \{ \hat{a}_k \} \) are MLE for the data of the northern Kinki region. We use the model of \( M \geq 6.8 \) \( (M_D = 6.75) \) because the Gutenberg and Richter's formula cannot be applied in the case of \( M \geq 5.8 \). That is, all the shallow earthquakes of \( M \geq 5.8 \) occurred in the northern Kinki region will not necessarily cause damages.

We compared the expectations calculated from the modified intensity function and JMA data (Fig. 10). This figure indicates that, before the Nankai trough event in 1944, the seismicity was much higher than expected compared with the average seismicity seen over a long time. The occurrence rate after the event, however, is comparable with the expectation. In the last 30 years, the seismicity is higher than the expectations and seems to increase. This trend possibly indicates a beginning of the increase of the seismicity before the next Nankai trough event.

Table 4 shows the estimates of the occurrence time of the next Nankai trough event by using the data of JMA \( (M \geq 5.0 \) and \( 6.0) \) in the period from 1965.5 to 1995.5. This table shows that the next Nankai trough event will occur in the early 21st century. In both cases, the occurrence times are earlier than the one obtained from the mean recurrence time (Rikitake, 1976) and roughly correspond to that from the time-predictable model (Shimazaki and Nakata, 1980). Figure 11 shows the modified intensity function for \( M \geq 6.0 \). This figure indicates

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Table 3. Estimated values of parameters of the selected intensity functions and the standard deviation of errors calculated from the variance-covariance matrix of the error distribution.

The Inner Zone of Southwest Japan

<table>
<thead>
<tr>
<th>$M\geq6.8$</th>
<th>Estimates</th>
<th>Errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_0$</td>
<td>-1.743</td>
<td>0.218</td>
</tr>
<tr>
<td>$b_0$</td>
<td>-0.981</td>
<td>0.182</td>
</tr>
<tr>
<td>$c_0$</td>
<td>0.432</td>
<td>0.333</td>
</tr>
<tr>
<td>$c_1$</td>
<td>0.0612</td>
<td>0.0207</td>
</tr>
</tbody>
</table>

The northern Kinki region

<table>
<thead>
<tr>
<th>$M\geq6.8$</th>
<th>Estimates</th>
<th>Errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_0$</td>
<td>-4.25</td>
<td>1.31</td>
</tr>
<tr>
<td>$a_1$</td>
<td>0.0945</td>
<td>0.0453</td>
</tr>
<tr>
<td>$a_2$</td>
<td>-0.000788</td>
<td>0.000366</td>
</tr>
</tbody>
</table>

Table 4. Estimated occurrence time of the next Nankai trough event.

<table>
<thead>
<tr>
<th>Method</th>
<th>Estimated time</th>
</tr>
</thead>
<tbody>
<tr>
<td>This study ($M\geq5.0$)</td>
<td>2,036</td>
</tr>
<tr>
<td>($M\geq6.0$)</td>
<td>2,037</td>
</tr>
<tr>
<td>Mean recurrence time</td>
<td>2,061±35</td>
</tr>
<tr>
<td>Time-predictable model</td>
<td>2,040.4</td>
</tr>
</tbody>
</table>

that the northern Kinki region is now in the period of high seismicity before the next Nankai trough event and the 1995 Hyogo-ken Nanbu earthquake is the first great intraplate earthquake in this period.

In order to evaluate the error of the occurrence time of the next Nankai trough event obtained above, we estimated the occurrence of the Nankai trough event in 1944 by using the same method. We use the JMA data of $M\geq6.0$ in the periods from 1885 to 1944. We calculate $t_0$ for each data set whose time interval is 30 years. The result shows that maximum, minimum and average errors are 25.9, 6.8 and 13.8 years, respectively.

4. Discussion

The statistical models show the significant temporal variations of seismicity both in the Inner Zone of Southwest Japan and in the northern Kinki region around the occurrence time of the Nankai trough events, although the patterns of the variations are different from each other.

In the Inner Zone of Southwest Japan, the intensity function for $M\geq5.8$ is constant before the Nankai trough events and has a peak just after them. This peak may be caused by the stress changes due to the occurrence of the Nankai trough events (for example Yoshioka and Hashimoto, 1989). We used, however, only the data after the 17th century and had only three couples of the Nankai trough events in this period. So it is not obvious that this significant temporal variation is a characteristic pattern of the seismicity in this region.

In the northern Kinki region, the intensity functions for both $M\geq5.8$ and 6.8 have a peak before the Nankai trough events. In the 7 out of 8 couples of the Nankai trough events, disastrous earthquakes occurred in this region within 40 years preceding them. So we can conclude that the high seismicity
before the Nankai trough events is a general characteristic of seismicity in this region. The physical process of this phenomenon is not yet revealed. There are two possibilities. One is that the temporal variation of seismicity corresponds to the appearance of a change in the tectonic stress field in the Inner Zone of Southwest Japan caused by space-time variations of interplate coupling along the Nankai trough. The other is that the Nankai trough events are made to occur earlier by the change in interplate coupling along the Nankai trough caused by the occurrence of successive intraplate earthquakes in the Inner Zone of Southwest Japan. To estimate these effects quantitatively, simulations of the stress field in and around this region are necessary.

5. Conclusion

We estimated the value of the parameters of the intensity functions by using the data of previous disastrous earthquakes in order to evaluate the temporal variation of seismicity around the occurrence time of the Nankai trough events. The obtained intensity functions for the northern Kinki region show that the seismicity has a peak before the Nankai trough events. The model of the Inner Zone of Southwest Japan for $M \geq 5.8$ shows that the seismicity has a clear peak just after the Nankai trough events, although no significant temporal variation is found before the events.

The recent seismicity in the northern Kinki region shows a significant increase, when compared with the expectation calculated from the modified intensity function. The estimated occurrence time of the next Nankai trough event is in the 2030's. These factors indicate that this region is now in the active period before the next Nankai trough event.

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