Block-spring simulation of earthquake cycle along the Nankai trough

Noa Mistui and Kazuro Hirahara

Graduate School of Environmental Studies, Nagoya University, Furo-cho, Chikusa-ku, Nagoya-city, Aichi, Japan (e-mail: mitsui@eps.nagoya-u.ac.jp; phone: +81-52-789-3036, hirahara@eps.nagoya-u.ac.jp; phone: +81-52-789-3651).

Abstract

Large earthquakes at the subduction zone along the Nankai trough occur repeatedly. Based on the rate and state friction law, we simulate the features of an earthquake cycle on five segments, A-E from west to east along the Nankai trough. We use a block-spring model to investigate the mechanism of the earthquake cycle. Considering the actual fault parameters for the five segments, we calculate the model parameters for the corresponding blocks in the simulation. The following features of the observed earthquake cycle are reproduced with the chosen fault parameters: (1) stick-slip periods are the same (more than 150 yrs) for non-interacting blocks, (2) different pairs of a_i-b_i and D_{ci} can produce Tonankai earthquakes followed by Nankai earthquakes, with different features of failure for each segment, (3) interactions between segments are strong.

Introduction

Along the Nankai trough, in southwest Japan, large earthquakes occur repeatedly (Fig.1). The earthquakes are named Nankai, Tonankai, and Tokai and the rupture zone is divided into five segments, A-E from west to east. The features of the earthquakes are as follows.

1. The recurrence times are from 90 to 150yrs.
2. All segments slip within a few years of each other.
3. Nankai earthquakes (segments A, B) tend to follow Tonankai earthquakes (C, D).
4. Tokai earthquakes (segment E) don't always occur.
5. The epicenters of the 1944 Tonankai and 1946 Nankai earthquakes are off the Kii peninsula (i.e., the earthquakes start at segments B and C). Moreover, segments B and C have more rapid slip rates than A and D [e.g., Tanioka and Satake, 2001].

We numerically simulate the earthquake cycle along the Nankai trough using a block-spring model, in order to understand the mechanism as simply as possible.

Model

We use the block-spring model shown in figure 2. Five blocks with connecting springs represent the five segments along the Nankai trough and the interaction between the segments. The floor velocity, V_{pi}, corresponds to the subduction of the Philippine Sea Plate in the ith segment of the Nankai trough.

The equation of motion of block i is

$$M_i(dV_{mi}/d_t)=-k^l_i u_i - k_{i,i-1}(u_{i-1}-u_i)-k_{i,i+1}(u_{i+1}-u_i)+\mu_i F^n_i \; (i=1\text{-}5). \tag{1}$$

M_i: mass of ith block $\quad$ V_{mi}: the ith block velocity
k^l_i: spring stiffness which combines the ith block with the wall
u_i: displacements of the ith block $\quad$ μ_i: coefficient of friction
$k_{i,i-1}$: spring stiffness connecting the ith and i-1th blocks
F^n_i: normal force on the contact surface

We apply a rate- and state-dependent friction law [Dieterich, 1979] on each contact surface.

$$\mu_i = \mu_{0i} + a_i \ln(V_i/V_0) + b_i \ln(V_0\theta_i/D_{ci}) \tag{2a}$$

$$d\theta_i/dt = 1 - V_i\theta_i / D_{ci} \tag{2b}$$

μ_{0i}: constant appropriate for steady-state slip at a reference velocity V_0
V_i: frictional slip velocity $\quad$ θ_i: state variable
D_{ci}: characteristic slip distance $\quad$ a_i, b_i: empirical constants

In the case a_i- b_i <0, the frictional response shows velocity weakening which leads to stick-slip motion, while the case a_i- b_i >0, shows velocity strengthening, leading to stable sliding. In the friction law, we set $V_i = V_{pi} - V_{mi}$ and $V_0 = V_{pi}$.
The model parameters are determined by considering the actual geometry of the fault segments (Table 1).

M_i: Mass of the volume above the contact
V_{pi}: subduction rate of the Philippine Sea Plate
k^l_i: stress increase at the contact surface when the plate subducts by 1m
$F^n_i = Mg\cos\delta_i$ (Normal force acting on the contact surface)

We integrate eqs. (1), (2a) and (2b) numerically.

1-block simulation –relation between slip velocity and Dc-

We investigate the effect of the frictional parameters, a_i- b_i and D_{ci} on the stick-slip period using a 1-block model. Different pairs of a_i- b_i and D_{ci} produce the same recurrence period, while the slip behaviors are different. The smaller D_{ci} is, the larger the coseismic velocity and the shorter the duration of the event. When D_{ci} is larger and the absolute value of a_i- b_i is smaller, the block behavior changes from stick-slip to stable sliding. We use this result to simulate the earthquake cycle along the Nankai trough.

2-block simulation –interaction between blocks-

We simulate the block behaviors using the 2-block model to examine the effects of the frictional properties of the blocks and the strength of the interaction between blocks.

In the case with weak interaction, blocks have constant recurrence intervals and time lags. In the case with strong interaction, the blocks perturb each other, which produces varying recurrence times.

In addition, when two blocks have different frictional features and the interaction between the blocks is strong, the block that slips more slowly is always perturbed strongly. The strongly perturbed block is forced to slip by the block that slips more rapidly. We suggest that the model behavior corresponds to the coseismic slips at segments B and C when two blocks have the same frictional characteristics. This also corresponds to the characteristics at segments A and B. When the frictional characteristics of the 2 blocks are different this corresponds to segments D and C.

Results of 5-block simulation

We simulate the behavior of each fault segment using a 5-block model, to reproduce the characteristics of the earthquake cycle along the Nankai trough. These characteristics are

1. Recurrence times from 90 to 150 years.

2. Segments slip at the same time.

3. Nankai earthquakes tend to follow Tonankai earthquakes.

We set the D_c value for blocks B, C and E smaller than the D_c value for blocks A and D so that A and D have more rapid slip. The values of a_i- b_i are set such that the stick-slip period for blocks A-D, without interaction between the blocks, is 150 yrs and the period of E is about 300 yrs. It is difficult to set the stiffness of the connecting springs between the blocks, $k_{i,i-1}$ and $k_{i,i+1}$. Therefore we examine block behaviors by changing the fault parameters, and choose the values that reproduce the features of the earthquakes along the Nankai Trough. We simulate the cases with each stiffness small ($k_{i,i-1}=k_{i,i+1}=0.05k^l_i$), and those with each stiffness large ($k_{i,i-1}=k_{i,i+1}=k^l_i$) (Fig.3). For the case with large stiffness values, two patterns of the block behaviors are shown. In the first pattern all blocks slip at the same time (Fig.3 pattern A), in the second pattern blocks A and B, and blocks C and D slip alternately (Fig.3 pattern B). Pattern A reproduces the features of the earthquake cycle along the Nankai Trough discussed in the next section.

Discussion

We discuss how we reproduce the earthquake cycle along the Nankai trough as follows.

1. The recurrence time of 90 to 150 yrs.

2. All segments slip at the same time.

3. Nankai earthquakes tend to follow Tonankai earthquakes.

4. Tokai earthquakes (segment E) often don't occur.

5. Each segment shows different failure features.

In this simulation, the recurrence times are from 60 to 120yrs. Though they are shorter than that of earthquakes along the Nankai trough, longer recurrences will be produced if the stick-slip periods without interaction between the blocks are set longer. Thus feature one can be reproduced using the model parameters that produce the same stick-slip period (more than 150 yrs) for blocks A-D without interaction between the blocks, and using strong interaction ($k_{i,i-1}=k_{i,i+1}=k^{l}_{i}$).

All segments slip in one year for 80% of the events in pattern A in Figure 3, hence feature two is well reproduced by using this model. Block C slips first in 40% of the earthquakes. Thus it doesn't reproduce feature three. Feature three will be reproduced if different frictional parameters, a_i- b_i and D_{ci} are set for blocks B and C, (e.g., block B has the lower value of D_{ci} than that of C).

The velocities of blocks B, C, and E are large, and those of A and D are small. Thus the different combinations of a_i- b_i and D_{ci} produce features three and five. If the same frictional parameters are used, behaviors of the blocks are similar to each other. In this case, the different slip features can't be seen and it is difficult to control which block slips first.

At segment E, the plate convergence rate along the Nankai trough is about half that of the other segments. This reproduces feature four.

Conclusion

We get the features of earthquakes along the Nankai trough from observations, shown as follows,

1. The plate convergence rate along the Nankai trough is 2-6 cm/yr from east to west. Thus at segment E, it is about half that of the other segments.

2. Segments B and C have more rapid slips than A and D.

The features of recurrence time from 90 to 150 years, all segments slipping at the same time, the order of earthquake occurrences, and the different failure features of each segment, are reproduced with the parameters as follows,

1. The stick-slip periods are the same (more than 150yrs) for blocks A-D without interaction between the blocks, and less than 300yrs for block E.

2. Larger D_cs, are set near the borderline which separates stable and unstable regions for segments A and D than for segments B, C and E so that they slip slowly.

3. The interactions between segments are strong.

Acknowledgments

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References

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	A	B	C	D	E
block number (i)	1	2	3	4	5
fault length L_i (km)	150	150	150	100	100
dip angle δ	9	10	11	10	15
M_i ($X10^{17}$) (kg)	6.7	6.0	5.5	4.0	2.6
k^l_i ($X10^{15}$) (N/m)	7.8	7.8	7.7	5.5	5.0
F^n_i ($X10^{18}$) (N)	6.6	5.9	5.3	3.9	2.5
V_{pi} (cm/yr)	6.0	5.5	5.0	4.5	2.0
a_i ($X10^{-3}$)	1.0	1.0	1.0	1.0	1.0
b_i ($X10^{-3}$)	1.23	1.26	1.26	1.19	1.23
D_{ci} (m)	0.16	0.01	0.01	0.12	0.10

Table 1: The fault parameters and resulting calculated model parameters

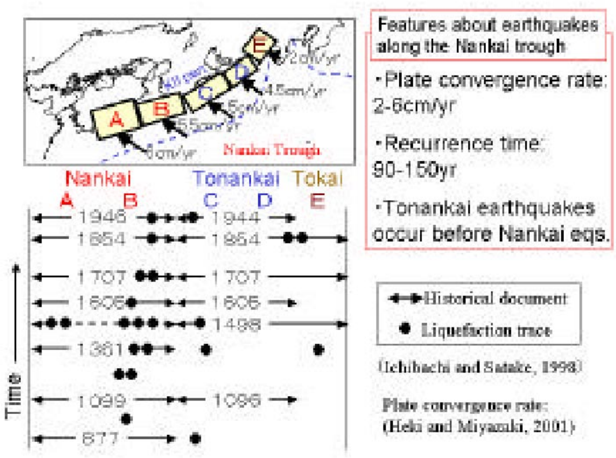

Figure 1: Space-time distribution of great earthquakes along the Nankai trough.

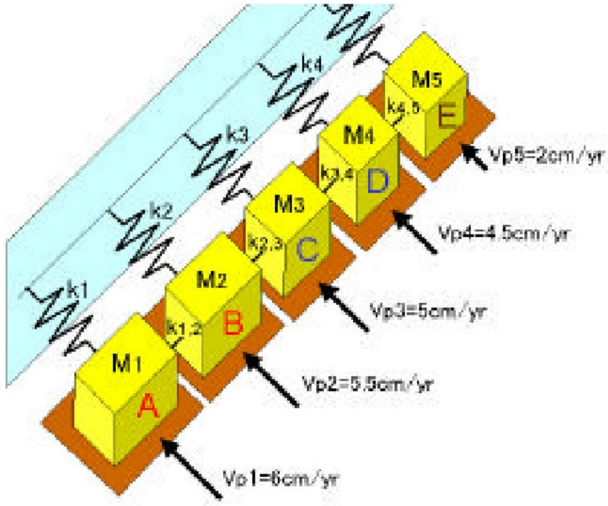

Figure 2: Block-spring model. Five blocks represent fault segments along the Nankai trough.

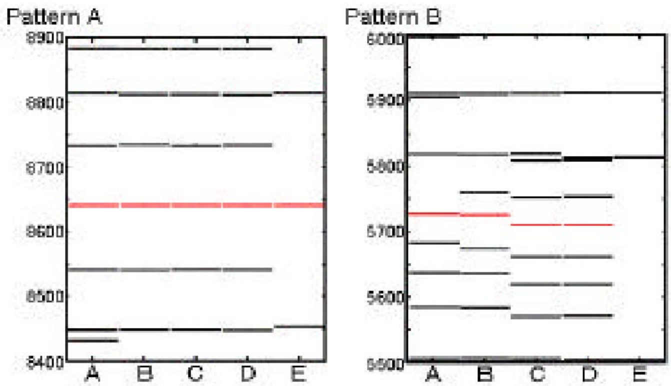

Figure 3: Block behavior patterns, showing the time of slip, for large stiffness values.