Development of splay faults in the Nankai Accretionary prism

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Abstract

We have investigated the cause of splay fault developing in the eastern Nankai accretionary prism by means of finite element method (FEM). Simulation models are based on the geological cross-sections produced by Le Pichon et al. (1996) and Park et al. (2002). Using these cross-sections, we have investigated development pattern of the splay faults with changing displacement condition of megathrust and the inserted two types of thin layer (fully coupled and decoupled condition) in plate boundary. Results of our model are displayed in two form; the distribution of failure element and the displacement vector. Results indicate a little effect of the inserted thin layer. Splay faults are developed at high angle in all the simulated model.

1. Introduction

Nankai Trough is the plate boundary between the Eurasian plate and the Philippine Sea plate off Southwest Japan (Fig. 1). Nankai subduction zone is one of the important areas to study a seismicity and development of thrust system in accretionary prism. Recently, in Nankai Trough, many studies have been carried out in different aspects that are mainly concentrated to geological structures. For example, according to the historical literatures, the Nankai Trough has been ruptured every 100-200 years by one or two successive large earthquakes (Ando, 1975a, b; Nakanishi et al., 2002). The Nankai subduction zone has been of interest from viewpoints of seismic hazards and earthquake potential since last two large megathrust earthquakes, i.e., the most recent events, the 1944 Tonankai (M=8.1) and 1946 Nankaido (M=8.3) earthquakes, therefore is an important area to study large earthquakes because at present Nankai region is in an interseismic period (Ando 1975b).

Park et al. (1999) succeeded in imaging a subduction seamount, using a multi-channel seismic (MCS) reflection survey. This subducting seamount is thought to belong to the Kinan seamount chain in the Shikoku Basin. Moore et al. (2005) investigated the detail
structure of the Muroto Transect based on these new seismic reflection data. They subdivided the accretionary prism along the Muroto Transect into several tectonic domains. This area and Barbados subduction zone are well studied about accretionary prism (Kopf and Brown, 2003).

Baba et al. (2001) have studied deformation and fracture of the seamount during subduction process. They carried out a numerical simulation of deformation and stress distribution of a subducting seamount. They reveals stress condition around the seamount, and concluded that the faulting is due to shear stress near the flanks of the seamount. MCS reflection profile shows a “splay faults” in the rupture area of the 1944 Tonankai earthquake (Park et al., 2002). They suggest that the splay fault may partition some slip to the surface, where it can help generate a “Tsunami”. The branching portion of the splay fault in the seismic zone is coupled to the subduction zone and may help to generate large earthquakes along the plate boundary.

In this work, we have simulated the stress state of the eastern Nankai Trough section to understand cause of the splay fault development.

2. Geotectonic setting of the Nankai-Tokai area

2.1 Geological setting of the Nankai subduction zone (Nankai and Tokai segments)

The Nankai Trough is an active convergence boundary between the subducting Philippine Sea plate and overriding Eurasian plate (Fig.1). Subduction of the Shikoku Basin and sediment accretion subsequently led to the development of a broad accretionary
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prism at the Nankai Trough. The Nankai subduction zone can be divided into four discrete domains (Fig. 2, A-D) marked by the megathrust earthquake ruptures (Ando, 1975b).

Domains A and B are considered as western Nankai, whereas C and D are eastern Nankai which are stable over the historic earthquake cycles. The two discrete domains, C and D, of the eastern Nankai are often referred to as 'Tonankai' and 'Tokai' segments, respectively (Park et al., 2003). We select the eastern Nankai segment, because of the Tokai segment (domain D) has been considered a seismic gap since the 1854 Ansei earthquake (M=8.4) (Ando, 1975b) that ruptured the entire eastern Nankai region. This region is characterized by coseismic rupture area due to 1944 Tonankai earthquake. Recently, the Tokai segment has not been ruptured. In this context, a large earthquake may occur in the future along the Tokai segment (Ando, 1975a). The peculiarity of the eastern Nankai subduction zone is highlighted by the morphology of its accretionary prism, which is characterized by a slope steeper than that of the central Nankai prism. Le Pichon et al. (1996) revealed this feature by gravimetric modeling and magnetic cross-sections of the eastern Nankai area. They identified a large magnetic body adjacent to the prism backstop (see Fig. 3) that they interpreted as a subducted volcanic ridge and named as a paleo-Zenisu ridge.
2.2 Subduction mechanism in Tonankai and Tokai region

There have been few seismic reflection images, which clearly show the paleo-Zenisu ridge, and it was suggested that the ridge is presently located on the top of the main décollement immediately adjacent to the backstop. Subduction of paleo-Zenisu ridge below the Tokai margin (domain D) has led to a reorganization of the margin with a sequence of uplift, erosion and growth of new accretionary wedge (Le Pichon et al., 1996).

Recent MCS reflection profiles on line 4, 5 and 7 (Fig.2: Park et al., 2002) reveal "splay faults" around the updip end of the coseismic rupture area of the Tonankai earthquake (domain C). Park et al. (2003) pointed out the slope angle of the splay fault in the Tonankai segment becomes steeper in the ridge region than in the ridge-free region (Fig.3). Their study suggests that the ridge is located roughly at the seaward edge of the coseismic rupture zone of the 1944 Tonankai earthquake. This idea can indicate effect of existence of ridge and coupling condition. In this concept, it is not well understood that what factors control the development of splay fault having different dip angle in different segments of the eastern Nankai region. Therefore we speculate that frontal megathrust plays important role for analyzing development of splay fault. We perform modeling these two types of subducting situations, and find out the causes of different dip angle of splay fault.

![Fig.3: Schematic cross-sections showing the 'ridge region' and 'ridge-free region' (Park et al., 2003).](image-url)
3. Modeling

We have simulated the development of splay fault using 2D finite element method (FEM) under plane strain condition, supposing that the section along eastern Nankai area can be treated as elastic material.

3.1 Model Geometry

First, we have calculated "megathrust sliding model (Model A, B1 and B2)". These models do not include the area below megathrust zone. Model A (Fig.5) is divided into five layers (oceanic crust, paleo-Zenisu ridge, older indurated accretionary prism, accretionary prism and cover sediment). Model A (Fig.4) is base on the section by Le Pichon et al. (1996) and simulated regime is shown by black frame. Since the horizontal to vertical exaggeration is 1:2 in the cross-section (Fig.4), we simply expanded the horizontal length two times to recover its natural scale. The total length of the model is 82.77 km and thickness varies up to 13.75 km (Fig.5). Models B1 (Fig.7) and B2 (Fig.8) consist of an accretionary prism only (Fig.8). The difference between model B1 and B2 is

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**Fig.4:** Schematic interpretation of the Tokai segment section by Le Pichon et al. (1996).

**Fig.5:** Layer division and boundary condition of model A simplified from Figure 4.
that model B2 has the 10 km decoupling zone along bottom which we call "frontal part of megathrust", but model B1 has not. The length of these models is 72 km and maximum thickness is 12 km.

Second, we have used "subducting oceanic crust model (Fig.9; Model B3)". In contrast to previous models (Model A, B1 and B2), we have included the area below the megathrust zone. Model B3, which is formed by five layers (oceanic crust, thin layer 1,2,3 and accretionary prism) (Fig.6), and is derived from cross section given by Park et al. (2002). The length of the model is 70 km and maximum thickness is 14 km (Fig.9). Thin layer 1, 2 and 3 are distinguished by three coupling intensity from landward to oceanic
site, fully coupled, increasing coupling and decoupling zone, so that the effect of oceanic crust could be considered.

Finally, "thin layer inserted model (Models B4 and B5)" is simulated. These models (Fig.10) are remove the oceanic crust layer in Model B3 and are divided into four layers (accretionary prism and thin layer 1,2,3) of which length is 70 km and the maximum thickness is 12 km (Fig.10). Rock layer property of thin layer 2 and 3 is same in model B4, but that of thin layer 1 and 2 is same in model B5.

![Fig.9: Layer division and boundary condition of model B3.](image)

![Fig.10: Layer division and boundary condition of model B4, and B5.](image)

3.2 Boundary condition

We have imposed a convergence displacement from the right side of the models, which is adequate for the present day plate kinematics in the Nankai region. Left side of the model is free to move vertically but fixed in horizontal direction. Upper part is a surface in all models. The symbol of triangle indicates a fixed nodal point.

We have demonstrated two types of boundary condition. For the first set (Models A, B1, B2, B4 and B5), the displacement imposed along bottom decreases gradually toward continent side by which we realized the megathrust that moves toward ocean side (Figs. 5, 7, 8 and 10). The second type is applied to the oceanic crust sliding (Model B3), where nodes along oceanic bottom move horizontally with same displacement ranging from 0 m to 300 m.
3.3 Rock layer property

Reasonable rock layer properties used in the simulation models are shown in Figs. 11, 12, 13 and 14 and on Tables 1 to 5, which are based on the studies by Baba et al. (2001) and Takahashi et al. (2002). Rock layer properties of thin layer in Model B3, B4 and B5 are modified as shown in Tables 3 to 5.

Table 1: Rock layer properties of Model A.

<table>
<thead>
<tr>
<th></th>
<th>Poisson's ratio</th>
<th>Density (kg/m³)</th>
<th>Young's modulus (GPa)</th>
<th>Cohesion (MPa)</th>
<th>Friction angle (degree)</th>
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<td>Oceanic crust &amp; Paleo-Zenisu ridge</td>
<td>0.25</td>
<td>2800</td>
<td>105</td>
<td>170</td>
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<tr>
<td>Older indurated accretionary prism</td>
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<td>Accretionary Prism</td>
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<td>30</td>
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<td>Cover sediments</td>
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Table 2: Rock layer properties of Model B1 and B2.

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<th>Young's modulus (GPa)</th>
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Table 3: Rock layer properties of Model B3.

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<tr>
<td>Thin layer 1</td>
<td>0.37</td>
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<td>35</td>
</tr>
<tr>
<td>Thin layer 2</td>
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<tr>
<td>Thin layer 3</td>
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Table 4: Rock layer properties of Model B4.

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Table 5: Rock layer properties of Model B5.

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<th>young's modulus (GPa)</th>
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<tr>
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<tr>
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<tr>
<td>Thin layer 2</td>
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<td>2000</td>
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<td>35</td>
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<tr>
<td>Thin layer 3</td>
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<td>1.7</td>
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</tbody>
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4. Results

4.1 Megathrust sliding model

The failure analysis is carried out using Mohr- Coulomb failure criterion (Chamlagain and Hayashi 2004).

4.1.1 Model A

As there is no failure element under 140 m convergence displacement boundary condition, we have fixed the convergence displacement condition to be 140 m (Fig.15). The cluster of failure elements has moved vertically with increasing the inverse displacement, which is imposed to the reverse direction for the convergence.
Fig. 15: Distribution of failure elements in model A under 140 m convergence displacement with increasing inverse displacement along megathrust from 0 m to 140 m.

4.1.2 Model B1
As there is no failure element under the convergence displacement 120 m, we have used the constant convergence displacement 120 m (Fig. 16). When the inverse displacement increases, the swarm of failure element has moved vertically. This is almost the same as that of Model A.
Fig.16: Distribution of failure elements in model B1 under 120 m convergence displacement with increasing inverse displacement along megathrust from 0 m to 140 m.

4.1.3 Model B2

The nodal points along the frontal part of the megathrust, ranging from 40 km to 55 km from trough axis, can move horizontally to simulate decoupled area under the constant 120 m convergence displacement (Fig.6). Increasing the inverse displacement, the cluster of failure element distributes in wide area different from the results of Model A and B1 (Fig.17).
Fig. 17: Distribution of failure elements in model B2 under 120 m convergence displacement with increasing inverse displacement along megathrust from 0 m to 140 m.

4.2 Thin layer inserted model
4.2.1 Model B4

The convergence displacement is set up constant 80 m. Increasing the inverse displacement, firstly, failure elements occur at sea side of the fully coupled area (layer 1)
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Then the cluster of failure elements has developed at high angle to the megathrust plane (Fig. 18 (d) and (e)). Many failure elements are also observed at upper part of the fully coupled area (layer 1) (Fig. 18 (c), (d) and (e)). Regarding the displacement vector, displacement direction is almost horizontal along the fully coupled area (layer 1) as shown in Fig. 19. At the sea side of accretionary prism, displacement directions are landward, and the direction is changed at middle part of accretionary prism.

Fig. 18: Distribution of failure elements in model B4 under 80 m convergence displacement with increasing inverse displacement along megathrust from 0 m to 200 m.
4.2.2 Model B5

The convergence displacement is set up constant 80 m. At first, failure elements emerge along fully coupled area (Fig.20 (b)). Increasing the inverse displacement, the swarm of failure elements has developed at high angle (Fig.20 (d) and (e)). Concerning the displacement vector, the displacement direction near continent is downward but the vector direction is changed to upward at the junction between layer 1 and 2 as shown in Fig. 21. The vector direction is landward from the junction to ocean side.

Fig. 19: Distribution of displacement vector in model B4.

Fig. 20: Distribution of failure elements in model B5 under 80 m convergence displacement with increasing inverse displacement along megathrust from 0 m to 200 m.
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4.3 Subducting oceanic crust model (Model B3)

Failure elements are clustered around the fully coupled area (layer 1) as shown in Fig. 22 (b), (c) and (d).

Fig. 21: Distribution of displacement vector in model B5.

Fig. 22: Distribution of failure elements in model B3.
5. Discussions

5.1 Effect of plate boundary

In order to assess the effect of amount of boundary displacement, Model A, B1 and B2 are calculated by changing displacement. On Model A and B1, the cluster of failure elements is developing vertically, whereas in Model B2, the failure elements are distributed in wide area. The results suggest that frontal part of megathrust affects the shape of cluster. Thus, these models show that development of splay fault is controlled by the coupling of boundary between accretionary prism and oceanic crust.

As we have ignored the effect of oceanic crust in the models A, B1 and B2, the subducting oceanic plate is included in model B3. Results show that the number of failure elements increases around layer 1 (Fig.22). The model B3 shows stress concentration at the boundary. When we change the properties of thin layer, there is no shape change in the cluster of failure elements.

In case of Model B4 and B5, we investigate the effect of amount of displacement and thin layer properties. When property of thin layer 1 is same as accretionary prism (it implies fully-coupled), failure elements are observed at the frontal part of megathrust. Though the distribution of failure is almost the same in the model B4 and B5, there are some differences in the failure stress state. On the boundary between layer 1 and layer 2, maximum compressive stress (σ1) is horizontal as shown in model B4, whereas it is inclined in model B5. Results suggest that the initial failure occurs along layer 1, which is due to coupling strength.

5.2 Displacement of nodal point in accretionary prism

For Model B4 and B5, we obtained the different result for displacement direction. For Model B5 (Fig.21) the displacement vector is clearly oriented upward, which is consistent with the high angle splay fault. In contrast, the displacement vector in Model B4 is almost horizontal from landside end to the boundary point of layer 1 and 2. These indicate that coupling state (weak coupling or decoupled layer) controls kinematics around the boundary point. This displacement vector may control the angle of splay fault.

6. Conclusions

In the Nankai Trough area, the splay faults are developed depend on the magnitude of displacement along megathrust. Park et al. (2003) suggested that the subducted ridge might act as a seaward barrier inhibiting the 1944 Tonankai earthquake rupture from propagating farther seaward. It is known that paleo-Zenisu ridge is the cause of strong coupling in the Tokai region. However, simulation models in this study indicate that the angle of splay fault is also controlled by plate boundary coupling state, and presence of
7. References

Ando, M., 1975a, Possibility of a major earthquake in the Tokai district, Japan and its pre-estimated seismotectonic effects, Tectonophysics, 25, 69-85.

Ando, M., 1975b, Source mechanisms and tectonic significance of historical earthquakes along the Nankai Trough, Japan, Tectonophysics, 27, 119-140.


