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<td>Morishita, Tadayoshi; Hayashi, Daigoro</td>
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Simulation of role of decollement slope and surface slope angles to the stress field in accretionary wedge

Tadayoshi Morishita* and Daigoro Hayashi*

*Department of Physics and Earth Sciences, University of the Ryukyus,
Nishihara, Okinawa, 903-0213, Japan

Abstract

The purpose of this study is to estimate the effect of surface slope-angle (α), decollement slope-angle (β) and boundary condition to the stress field within accretionary wedge by using finite element method (FEM). We impose four types of boundary conditions along the base of four types of models. These boundary conditions are expressed by linear, quadratic (convex and concave) and cubic function. Four types of models have different decollement slope and surface slope.

Comparing with two models (models B and C) which have different decollement slope-angle (β), the decollement slope-angle (β) affect weakly to stress field. On the other hand, comparing with the other two models (models A and C) which have different surface slope-angle (α), the surface slope-angle (α) affects fairly to stress field. Failure area propagates wider to the tip of model as the surface slope-angle (α) becomes gentler. However the more effective factor to decide the propagation of failure area is the difference of boundary conditions. Each boundary condition has different tendency of propagation of failure area. The most widely spread failure area is calculated under the boundary condition 3 and followed in the order of boundary condition 2, 1 and 4.

Introduction

Finite element method (FEM) is one of the sophisticated methods to solve structural problem. In FEM, an equilibrium equation is changed to an discrete equation. Although such a general idea of FEM existed from earlier time, numerical code was developed through the innovation of computer from 1950. At first, FEM was applied to the aeronautical engineering. Since end of 1960, FEM has been applied to the field of structural geology and tectonics.

In our simulation of simplified plate subduction zone, displacement boundary condition is imposed along the base of an overriding wedge shaped plate, and the value of the displacement is a function of the distance from the origin. Boundary conditions are adopted so that they prevent unnatural stresses from the calculation of stress within the plate.

To investigate the influence of variety of boundary condition to the stress calculation, four types of boundary condition are considered. Displacements of linear (condition 1), quadratic (condition 2 and 4) and cubic function (condition 3) are imposed with gradual
change along the base of model as four displacement boundary conditions.

In addition, to evaluate the influence of the shape of accretionary wedge, four different accretionary wedge models having different surface slope-angle ($\alpha$) and decollement slope-angle ($\beta$) are examined for each boundary condition. Surface slope-angle ($\alpha$) and decollement slope-angle ($\beta$) are shown in the schematic cross section of plate subduction zone (Fig.1).

![Fig 1. Schematic cross section of plate subduction zone.](image)

**Simulation**

In this study, 2D elastic finite element method is used to estimate in plane strain state.

**Preparing models**

A cross section of an accretionary wedge model is divided into a number of finite elements using several softwares as follows (Fig.2).
(1) A software *grid* produces a file where x and y coordinates and a table which connects element number and nodal point number. The file is called as "grid model".

(2) A software *net.func* is used for drawing a newly produced grid model figure and for saving the figure in postscript format as *modeleps*.

(3) The grid model (*model.eps*) will be deformed into another shape (*modeleps2*) with some commercial softwares where we used *Adobe Illustrator*.

(4) Modified x-y coordinate of nodal points is extracted from the postscript file (*modeleps2*) with a software *xget*.

**Models**

We adopt the values of the surface slope-angle ($\alpha$) and decollement slope-angle ($\beta$) from the typical accretionary wedge models proposed by Davis et al. (1983) as shown in Fig.3. To investigate the effect of surface slope-angle ($\alpha$) and decollement slope-angle ($\beta$) for stress field, next four models are used.
Fig 3. Relation between surface slope and decollement slope modified from Davis et al. (1983).
Model A

The model is characterized by steep surface slope-angle (5.7°) and gentle decollement slope-angle (2.5°), which is named Guatemala type (Fig. 3 and 4a).

Fig 4. Four models for simulation. (a) Model A is Guatemala type model. (b) Model B is Barbados type model. (c) Model C is Makran type model. (d) Model D is Japan type model.
Model B
The model is characterized by gentle surface slope-angle (1.0°) and steep decollement slope-angle (8.0°), which is named Barbados type (Fig.3 and 4b).

Model C
The model is characterized by gentle angle of inclination both surface slope-angle (1.6°) and decollement slope-angle (2.0°), which is named Makran type (Fig.3 and 4c).

Model D
The model is characterized by intermediate angle of inclination both surface slope-angle (4.5°) and decollement slope-angle (5.4°), which is named Japan type (Fig.3 and 4d).

To compare stress field among those models, the model length is adjusted to the same length (200 km). All these models are composed of 369 nodal points and 640 elements.

Boundary condition
Considering the geometry of the subducting plate, we define the boundary conditions as follows (Fig.5a): (1) nodal points are movable along the left side AD and fixed at point A; (2) right side BC is displaced for 500 meters to the left.

Along the decollement slope AB, the next four displacement boundary conditions are imposed.

(1) Displacement is proportional to the distance from the point A. Thus the relation between displacement and distance is shown a straight line in Figs.5a and 5e.

(2) Displacement along AB is expressed by a concave quadratic function of the distance from point A in Figs.5b and 5e.

(3) Displacement along AB is expressed by a cubic function of the distance from point A in Figs.5c and 5e.

(4) Displacement along AB is shown by a convex quadratic function of the distance from point A in Figs.5d and 5e.

Physical property of model
We consider that the overriding accretionary wedge is composed of granite. Because the real component of accretionary wedge is complex and because the study aims to estimate the influence of the decollement slope-angle (\(\beta\)) and surface slope-angle (\(\alpha\)) to the stress field, we simplified the component of the accretionary wedge into granite. The physical property of the granite is listed in Table 1 (Farhad and Hayashi, 2003).

Coulomb-Mohr criterion
After the calculation of stress values, Coulomb-Mohr criterion (Fig.6) is applied for all models.

In Coulomb-Mohr criterion, cohesion (C) and internal friction angle (\(\phi\)) are used for drawing a failure line in the normal stress - shear stress diagram. In the Mohr's stress circle, \(\sigma_1\) is the maximum compressive stress and \(\sigma_2\) minimum compressive stress.

When Mohr's stress circle touches the failure line, failure will occur.

Although the calculated result includes only two principal stresses on the section
Fig 5. Four types boundary condition ((a)–(d)). Nodes along left boundary (AD) move vertically. Node A is fixed. Displacement 500 meters to left is imposed at the right boundary (BC). Along the base of model (AB), displacement boundary condition is imposed. All arrows indicate the direction and magnitude of displacement. (e) Each displacement along the base of model is shown in the graph.
Table 1. Physical property of granite

<table>
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<tr>
<th>Rock species</th>
<th>Young's Modulus (GPa)</th>
<th>Poisson's Ratio</th>
<th>Density (kg/m³)</th>
<th>Friction angle (degree)</th>
<th>Cohesion (MPa)</th>
</tr>
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<tbody>
<tr>
<td>granite</td>
<td>80</td>
<td>0.3</td>
<td>2800</td>
<td>45</td>
<td>300</td>
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Fig 6. Coulomb-Mohr criterion. When Mohr’s stress circle touches the failure line, failure occurs.

plane, the third principal stress is obtained from the theory of plane strain as

\[ \sigma^* = \nu (\sigma_1 + \sigma_2) \]

where \( \nu \) is Poisson's ratio (Timoshenko and Goodier, 1970; Hayashi and Kizaki, 1972). Comparing three stress magnitudes, we can define three dimensional principal stresses \( \sigma_1, \sigma_2 \) and \( \sigma_3 \), and then apply newly defined principal stresses \( \sigma_1 \) and \( \sigma_3 \) to the Coulomb-Mohr criterion.

**Results and discussion**

Stress field of each model is shown in Fig.7a to 14a. The figures 7b to 14b show \( \sigma_1 \) trajectory of each model. Comparing the figures, following results are found.
Fig 7. Boundary condition 1 is imposed in model A. (a) stress field; (b) $\sigma$, trajectory; (c) failure area. "500 MPa" indicates stress scale of 500 MPa in each figures.
model A under boundary condition 2

(a)

(b)

(c)

Fig 8. Boundary condition 2 is imposed in model A. (a) stress field; (b) $\sigma$ trajectory; (c) failure area.
Fig 9. Boundary condition 1 is imposed in model B. (a) stress field; (b) $\sigma_1$ trajectory; (c) failure area.
model B under boundary condition 2

Fig 10. Boundary condition 2 is imposed in model B. (a) stress field; (b) σ1 trajectory; (c) failure area.
model B under boundary condition 3

(a)

(b)

(c)

Fig 11. Boundary condition 3 is imposed in model B. (a) stress field; (b) $\sigma_1$ trajectory; (c) failure area.
model B under boundary condition 4

(a)

(b)

(c)

Fig 12. Boundary condition 4 is imposed in model B. (a) stress field; (b) \(\sigma_1\) trajectory; (c) failure area.
Fig 13. Boundary condition 1 is imposed in model C. (a) stress field; (b) $\sigma_1$ trajectory; (c) failure area.
Fig 14. Boundary condition 1 is imposed in model D. (a) stress field; (b) $\sigma_1$ trajectory; (c) failure area.
Influence of decollement slope-angle (β)

To estimate the influence of decollement slope-angle (β) to stress field, the model B (Barbados type) which has a steepest decollement slope-angle (β), and the model C (Makran type) which has a gentlest decollement slope-angle (β), are compared under the boundary condition 1.

Because both models have different thickness, it is impossible to compare simply. For that reason, the whole part of model C and the upper part of model B are suitable portion for comparison of stress state difference.

These results indicate that the decollement slope-angle (β) does not have much effect on stress field in both models. Figures 9a and 13a show similar tendency of stress field, and figures 9b and 13b show similar stress trajectory for both models.

Comparing with the failure area of both models, figures 9c and 13c show similar distribution of failure area. While, in the lower part of tip of model B, narrow failure area is exceptionally recognized.

Influence of surface slope-angle (α)

To estimate the influence of surface slope-angle (α) to stress field, the model A (Guatemala type) which has the steepest surface slope-angle (α), and the model C (Makran type) which has a gentler surface slope-angle (α), are compared under the boundary condition 1. Although the model B has the gentlest surface slope-angle (α), it is better to compare the model C to model A. Because the models A and C have a similar decollement slope-angle (α), while the models A and B have quite different decollement slope-angles (β).

In the shallow part of the models A and C, σ₁ trajectory is almost parallel to the surface slope as shown in Fig.7b and 13b. Thus σ₁ direction is fairly defined by the surface slope-angle (α).

In the model C, the failure area distributes more widely than that in the model A (Fig.7c and 13c). Thus the distribution of failure area becomes wider as the surface slope-angle (α) becomes gentler.

Influence of boundary condition

To estimate the influence of each boundary condition to σ₁ trajectory, we consider the model B as a typical model.

Under the boundary condition 1, σ₁ trajectory rotates clockwise in the whole area of model B as the depth increases (Fig.9b).

With regards to the boundary condition 2, σ₁ trajectory rotates anticlockwise in the right part of model B and it rotates irregularly in the left part of model B (Fig.10b). Concerning to the failure area, the boundary condition 2 produces more concentrated failure area on the tip of model B compared with boundary condition 1 (Fig.10c, 9c).

In reference to the boundary condition 3, σ₁ trajectory rotates clockwise in the left part of model B and anticlockwise in the right part of model B as the depth increases (Fig.11b).
Failure areas are more concentrated on the tip of model B than under the boundary condition 2 (Fig.11c).

With respect to the boundary condition 4, \( \sigma_1 \) trajectory rotates clockwise in the whole area of model B (Fig.12b) which is the same direction under the boundary condition 1. The rate of rotation is more gradual under the boundary condition 4 than under the boundary condition 1 as the depth increases (Fig.12b, 9b). Failure area distributes sparsely on the tip of model B under the boundary condition 4 (Fig.12c) than under the boundary condition 1 (Fig.9c).

**Two types of stress trajectory**

Almost all of the stress fields are characterized by the rotation of \( \sigma_1 \) trajectory. In shallow part, \( \sigma_1 \) trajectory is parallel to the surface slope. As the depth increases, \( \sigma_1 \) trajectory is rotating. Thus we can classify the simulated results into two types according to the rotation of \( \sigma_1 \) trajectory. The first type is that \( \sigma_1 \) rotates clockwise in the whole domain of models A, B, C and D (Figs.7b, 9b, 12b, 13b and 14b). The second type is that \( \sigma_1 \) rotates clockwise in the left side part, and rotates anticlockwise in the right side part of model B (Figs.10b and 11b).

The rotation of \( \sigma_1 \) trajectory under the boundary conditions 1 and 4 belongs to the first type, while that of under the boundary conditions 2 and 3 to the second type. The second type boundary conditions induce more wider failure area at the tip of model B.

**Conclusions**

1. The decollment slope-angle (\( \beta \)) affects weakly to stress field in this study.
2. \( \sigma_1 \) trajectory has a tendency to be parallel to the surface slope-angle (\( \alpha \)) in shallow area of the models A, B, C and D. The distribution of failure area becomes wider as the surface slope-angle (\( \alpha \)) becomes gentler in models A and C.
3. Under the boundary conditions 1 and 4, \( \sigma_1 \) trajectory rotates clockwise as the depth increase. But the rate of rotation is more gradual under the boundary condition 4 than under the boundary condition 1. With regards to the boundary condition 2, \( \sigma_1 \) rotates anticlockwise as the depth increases. In reference to the boundary condition 3, \( \sigma_1 \) rotates clockwise in the left part of model B and anticlockwise in the right part of model B.
4. Failure area becomes wider as the boundary condition is changing from the boundary condition 3 to 2, from 2 to 1 and from 1 to 4.

**Future problems**

1. One component material
   
   To investigate the effect of the boundary condition and geometry to stress field, we assumed that all the models are composed of one component material in this study. It is necessary to consider another type of model which is composed of plural materials to investigate more natural stress states.
(2) Elastic finite element method

The simulation using Coulomb-Mohr criterion shows that failure occurs within accretionary wedge. Once the failure occurred, the failed part is as highly deformed as it exceeds elastic limit. Therefore the elastoplastic finite element method should be used for more detailed study.

Acknowledgment

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References


