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Application of slip line analysis to the mechanical model of active accretionary wedge

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1. Introduction

An active accretionary wedge is formed from sediments accreted continuously at a continental margin by a subducting plate and mechanically characterized by a plane-strain compressive frictional flow throughout its entire volume (Figure 1). Continuous deformation induced by incoming sediments raises the distortional stress eventually leading to an ultimate condition known as a critical state. According to the critical taper theory (Davis et al., JGR, 1983), the angle of wedge increases as the incoming materials are accreted into the wedge until it reaches a critical value where the shear force on the basal detachment is in equilibrium with the basal friction. Under this concept, we applied the plastic slip-line theory for the computation of stress and velocity fields throughout the continuously deforming area of the wedge. For the simplicity, we assumed that the tapered wedge overlying a basal décollement fault is described by a perfectly plastic rheology complying with the Coulomb failure criterion and the associated flow rule. A complete description of soil rheology at the critical state requires the determination of stress tensors and velocity vectors at given points within the deforming region. For the boundary condition of stress, the effective normal and shear tractions on the upper surface of wedge are equal to zero, and thus the maximum principal stress acts parallel to the surface.

2. Conceptual model of accretionary wedge

Material path

Stress path

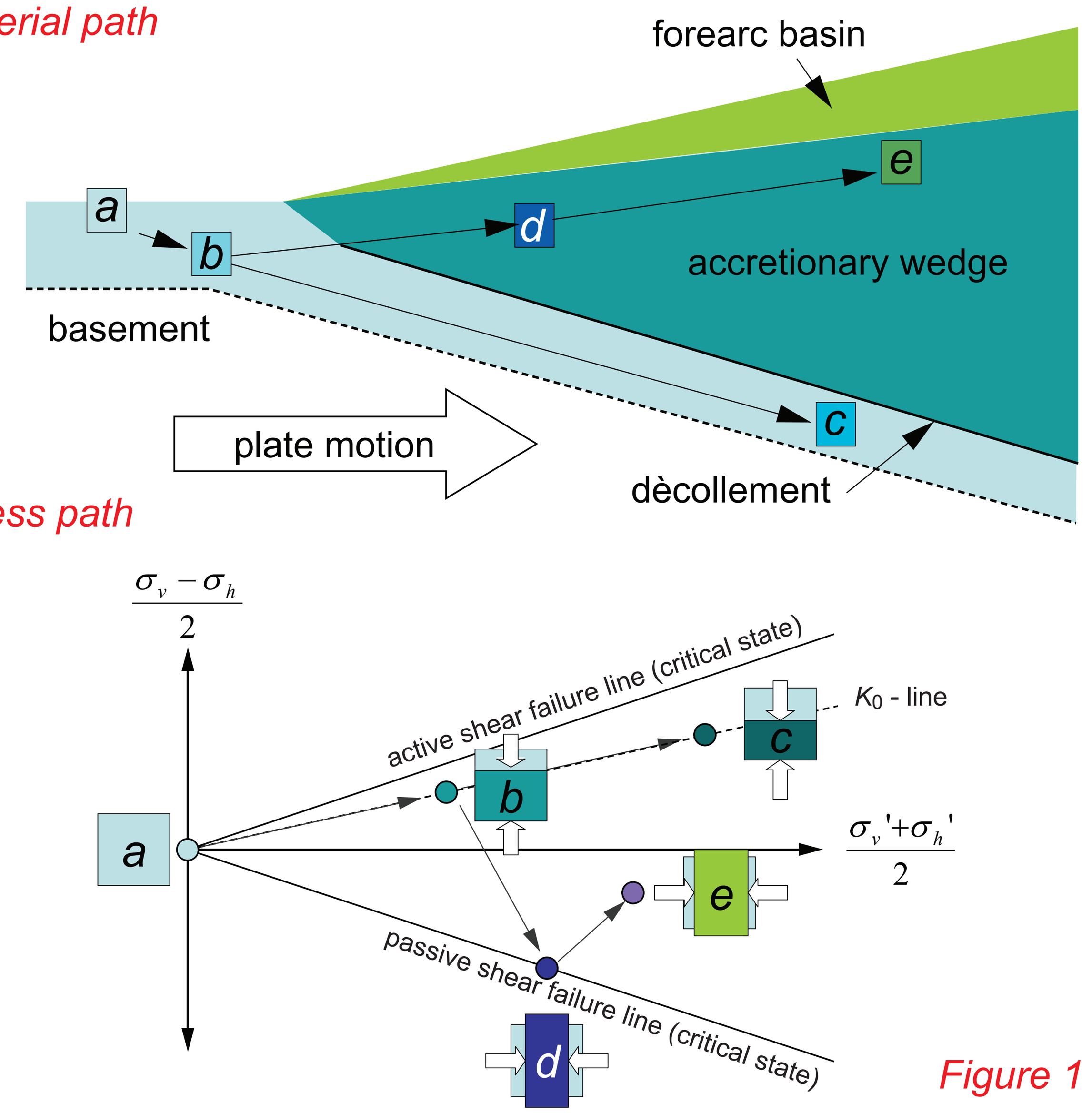


Figure 1

3. Governing equations

Equilibrium equations in x-y coordinate system

$$\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xy}}{\partial y} = \gamma_x - \frac{\partial p_f}{\partial x}$$
$$\frac{\partial \sigma_{xy}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} = \gamma_y - \frac{\partial p_f}{\partial y}$$

stress tensor: $\begin{bmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{xy} & \sigma_{yy} \end{bmatrix}$

unit weight vetor: $\begin{bmatrix} \gamma_x \\ \gamma_y \end{bmatrix}$

pore fluid pressure: p_f

Mohr-Coulomb failure criterion

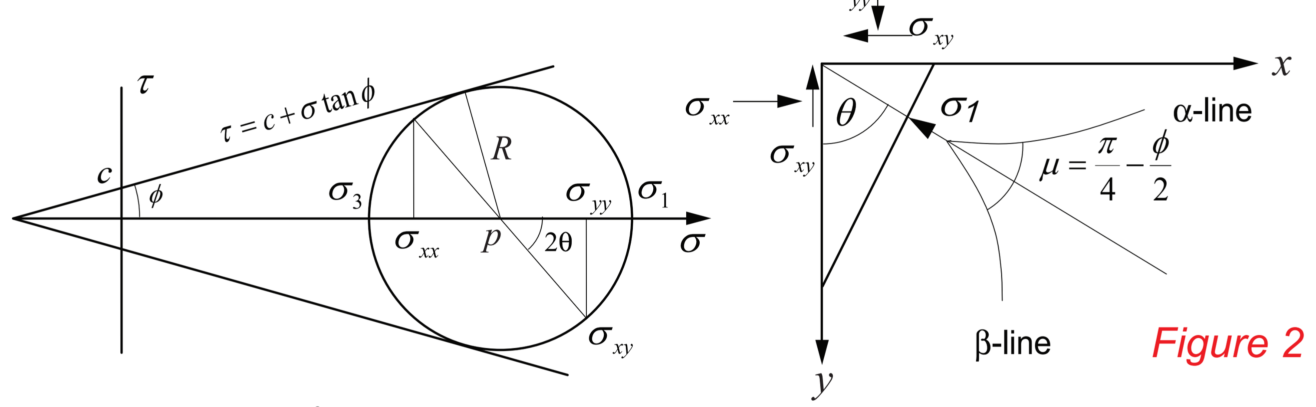


Figure 2

$$\sigma_{xx} = p - R\cos 2\theta$$
$$\sigma_{yy} = p + R\cos 2\theta$$
$$\sigma_{xy} = R\sin 2\theta$$

where

$$p = (\sigma_{xx} + \sigma_{yy})/2 = (\sigma_1 + \sigma_2)/2$$
$$R = (p + c\cot\phi)\sin\phi = c\cos\phi + p\sin\phi = (\sigma_1 - \sigma_2)/2$$

Equilibrium equations at critical state in terms of (p, θ)

$$(1 - \sin\phi\cos 2\theta)\frac{\partial p}{\partial x} + 2R\left(\sin 2\theta \frac{\partial \theta}{\partial x} + \cos 2\theta \frac{\partial \theta}{\partial y}\right) + \sin\phi \sin 2\theta \frac{\partial p}{\partial y} = \gamma_x - \frac{\partial p_f}{\partial x}$$
$$\sin\phi\sin 2\theta \frac{\partial p}{\partial x} - 2R\left(\sin 2\theta \frac{\partial \theta}{\partial y} - \cos 2\theta \frac{\partial \theta}{\partial x}\right) + (1 + \sin\phi\cos 2\theta)\frac{\partial p}{\partial y} = \gamma_y - \frac{\partial p_f}{\partial y}$$

4. Slip line analysis

Introduction to a new coordinates denoted by α and β with their directions that align the potential failure surfaces.Two characteristics (α, β) for the two equilibrium equations are defined by

$$\frac{dx}{dy} = \tan(\theta \pm \mu)$$

The two characteristics defined in the above equations represent the two failure planes on which the failure criterion is satisfied. This is why they arealso termed slip lines or shear lines.

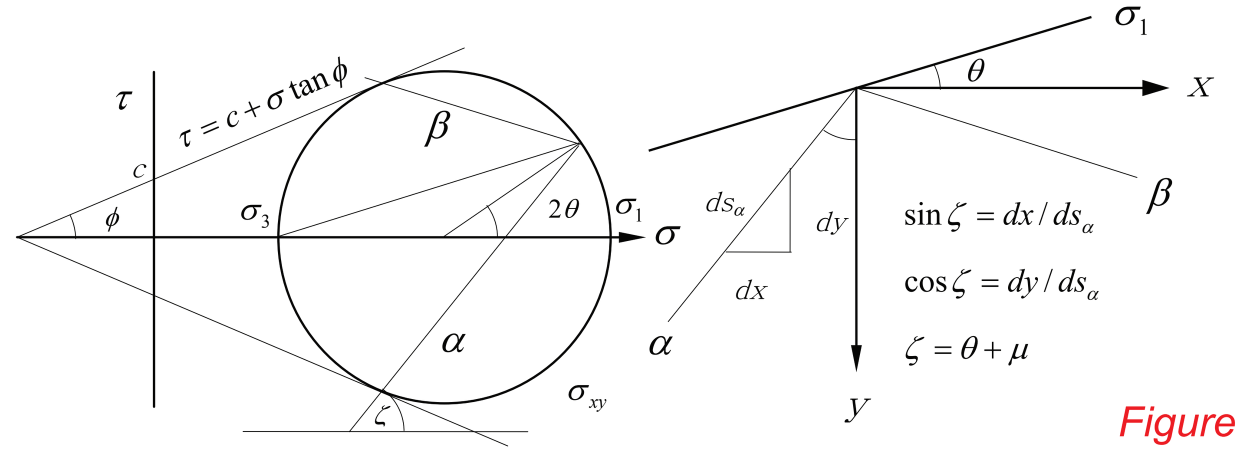


Figure 3

Stress fields

$$dp + \frac{2R}{\cos\phi} d\theta = \frac{F_x \cos(\theta - \mu) - F_y \sin(\theta - \mu)}{\cos\phi \cos(\theta + \mu)} dy \qquad \frac{dx}{dy} = \tan(\theta + \mu) \qquad \text{for } \alpha\text{–line}$$
$$dp - \frac{2R}{\cos\phi} d\theta = \frac{F_y \sin(\theta + \mu) - F_x \cos(\theta + \mu)}{\cos\phi \cos(\theta - \mu)} dy \qquad \frac{dx}{dy} = \tan(\theta - \mu) \qquad \text{for } \beta\text{–line}$$

Velocity fields

$$u_x = \frac{u_\beta \cos(\theta + \mu) - u_\alpha \cos(\theta - \mu)}{-\sin 2\mu} \qquad \cos\phi du_\alpha + (u_\beta - u_\alpha \sin\phi) d\theta = 0 \qquad \text{for } \alpha\text{–line}$$
$$u_y = \frac{u_\beta \sin(\theta + \mu) - u_\alpha \sin(\theta - \mu)}{\sin 2\mu} \qquad \cos\phi du_\beta + (u_\beta \sin\phi - u_\alpha) d\theta = 0 \qquad \text{for } \beta\text{–line}$$

5. Computation method

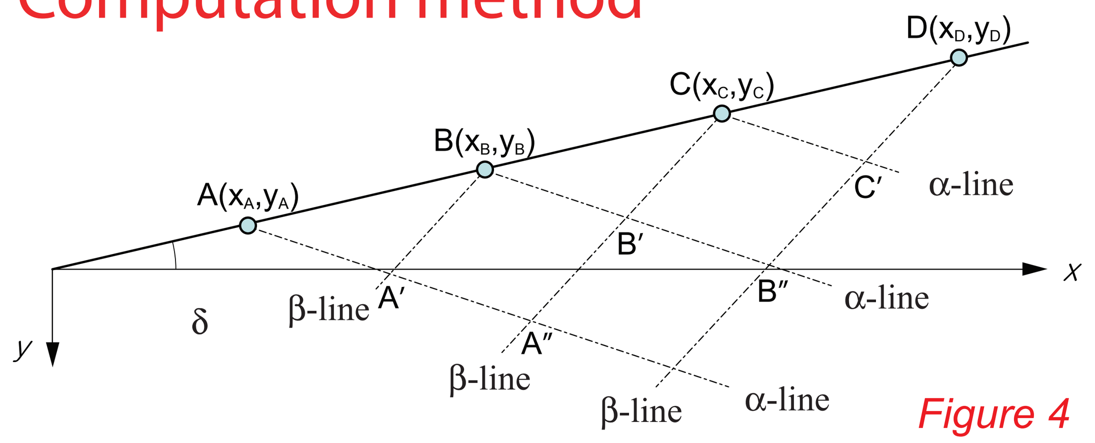


Figure 4

Stress boundary conditions at seafloor

$$p_{passive} = \frac{q(x,y) + c\cos\phi}{1 - \sin\phi}$$
$$\theta_{passive} = \pi/2 + \delta$$

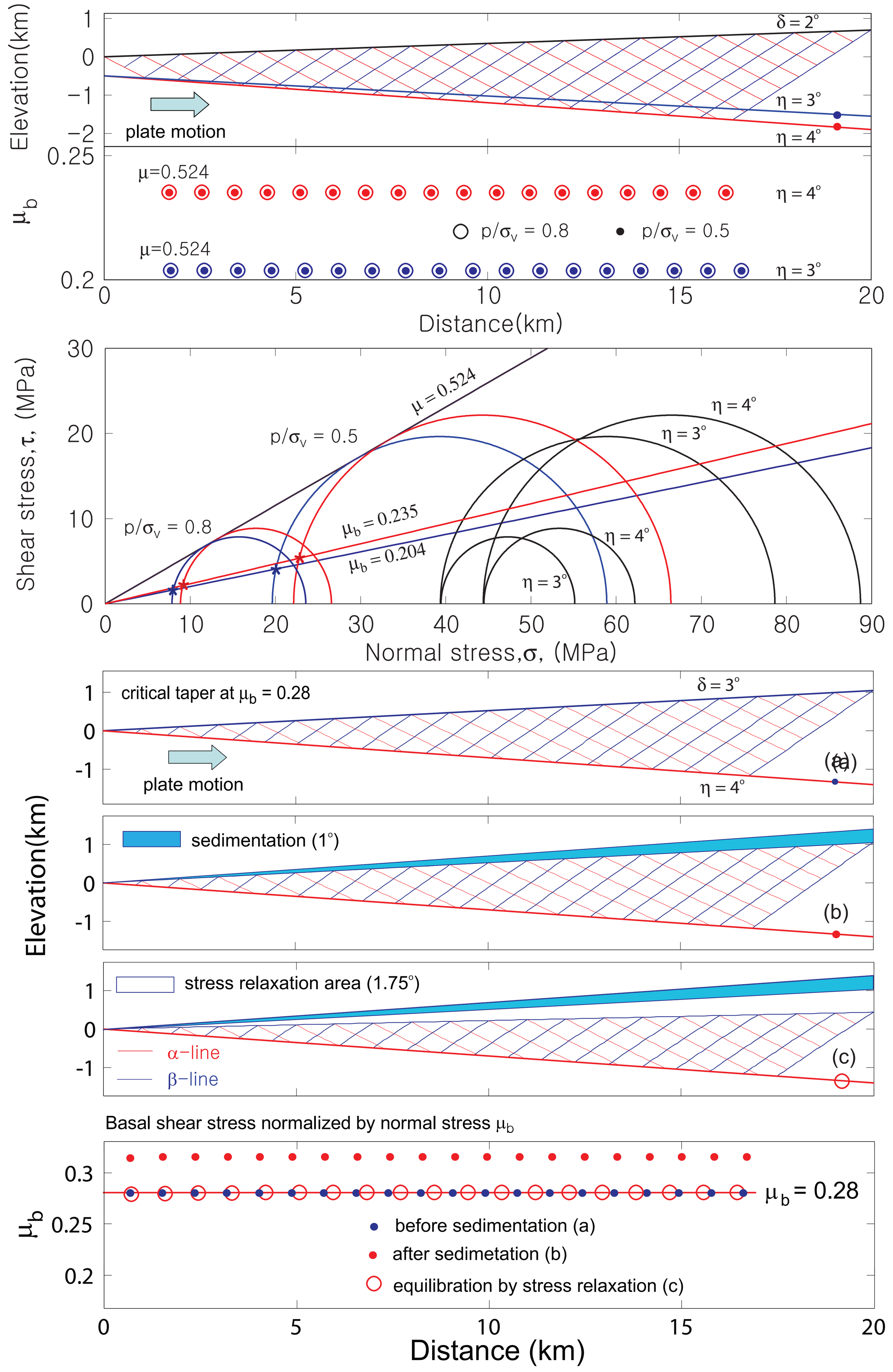
where $q(x,z) = p - R = \sigma_3 = 0$

Computation procedure

$$\mathbf{p}_A = [x_A, y_A, p_A', \theta_A]^t, \quad \mathbf{p}_B = [x_B, y_B, p_B', \theta_B]^t, \quad \mathbf{p}_C = [x_C, y_C, p_C', \theta_C]^t, \quad \mathbf{p}_C = [x_C, y_C, p_C', \theta_C]^t$$
$$\rightarrow \mathbf{p}_{A'} = [x_{A'}, y_{A'}, p_{A'}', \theta_{A'}]^t, \quad \mathbf{p}_{B'} = [x_{B'}, y_{B'}, p_{B'}', \theta_{B'}]^t, \quad \mathbf{p}_{A''} = [x_{A''}, y_{A''}, p_{A''}', \theta_{A''}]^t$$
$$\rightarrow \mathbf{p}_{A'} = [x_{A'}, y_{A'}, p_{A'}', \theta_{A'}]^t, \quad \mathbf{p}_{B'} = [x_{B'}, y_{B'}, p_{B'}', \theta_{B'}]^t$$

A complete stress vector at a point is defined as $p=[x, y, p', \theta]^T$. From the stress boundary conditions at the seafloor ($\sigma_3=0$ and $\theta=\delta+90^o$) and the Mohr-Coulomb criterion, we can determine the stress vectors at points A, B, C and D. As shown in Figure 4, new stress vectors at points A′, B′ and C′ can be determined by the intersections of the conjugate stress characteristics (α- and β-lines; potential slip lines) derived from the governing equations for stress fields. Using the same procedures, we can obtain the stress vectors at A″ and B″ and further points. After the stress solution is yielded at each intersection point, the velocity vectors can also be determined by the same procedure using the boundary condition of the velocity of incoming sediments obtained from the velocity of subducting plate or GPS data.

6. Results



The wedge angle (δ and η) is dependent both on the internal and sliding friction coefficients (μ and μ_b). The pore pressure within the wedge and the décollement fault has no effect on he accretionary wedge angle. The formation of sediment basin on top of the active accretionary wedge leads to the stress relaxation in the region below the basin.