

### 3. Landforms made by wave and current

#### 3.2 Rocky coast

Dominant geomorphic processes at rocky coasts are downward erosion of sea floor and lateral erosion of sea cliff by wave action. Sediments produced by the wave erosion are carried away from the coastal areas and rocky coasts are maintained. The rate of sea floor lowering ( $dz/dt$ ) is given by the following exponential function of water depth :

$$\frac{dz}{dt} = Ae^{-Bz} \quad (3.10)$$

where  $z$  is relative height from sea level,  $A$  is erosion rate at shoreline,  $t$  is time and  $B$  is a constant. The value of  $A$  is  $10^0 \sim 10^1$  mm/year at Tertiary mud stone. Because the critical water depth of wave action (wave base) is  $10 \sim 15$ m, the value of  $B$  is  $0.25 \sim 0.3$ . When sea level changes, (3.10) is rewritten as

$$\frac{dz}{dt} = Ae^{-Bz} + u \quad (3.11)$$

where  $u$  is the rate of sea level rise or fall.

The change in the location of shoreline ( $x$ ) with time is simplified to be proportional to time as follows:

$$\frac{dx}{dt} = R \quad (3.12)$$

where  $R$  is the rate of sea cliff retreat. The value  $R$  is about  $10^{-1}$ m/year at Tertiary mud stone.

From (3.11) and (3.12),

$$z = -\frac{1}{B} \log \frac{ue^{-Bux/R}}{u + A(1 - e^{-Bux/R})} \quad (3.13)$$

is derived. When  $u$  does not change,

$$z = \frac{1}{B} \log \left( \frac{AB}{R} x + 1 \right) \quad (3.14)$$

is obtained.

By using (3.11) and (3.12), evolution of rocky coast profiles has been simulated for various values of  $u$  and  $R$ . The grid interval for digital simulation is 1 meter, and time interval is 1 year. Initial profiles are given as a line with the gradient of  $1/50$ .

When  $u$  is constant, profiles are represented by (3.14) as shown in Fig.3.9. When sea level rise is relatively slow, sea cliff is formed in spite of sea level rise (Fig.3.10). When sea level falls and sea cliff retreat is very rapid, landward shoreline migration occurs in spite of sea level fall.

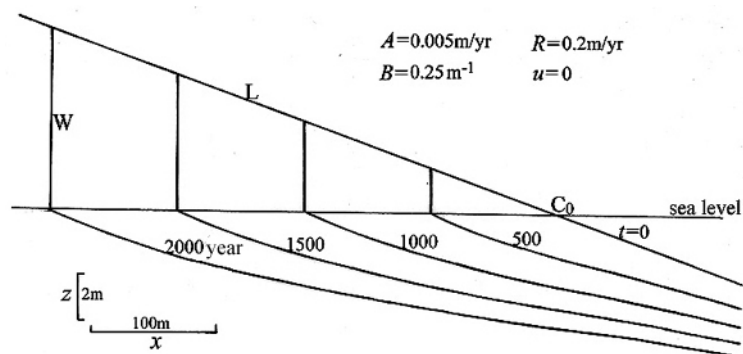


Fig.3.9 Simulation of the evolution of rocky coast profile when sea level is constant  
L:initial profile, W:sea cliff,  $C_0$ :initial shoreline

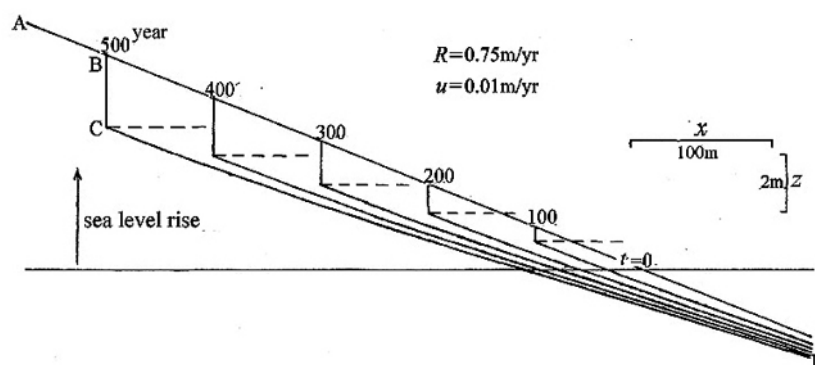


Fig.3.10 Simulated evolution of rocky coast profile when sea level rises and sea cliff retreat is relatively rapid ( $u/R > S$   $u$ :rate of sea level rise,  $R$ :rate of sea cliff retreat,  $S$ :gradient of land surface)  
The profile at 500 year is A - B - C - D. A sea cliff develops.

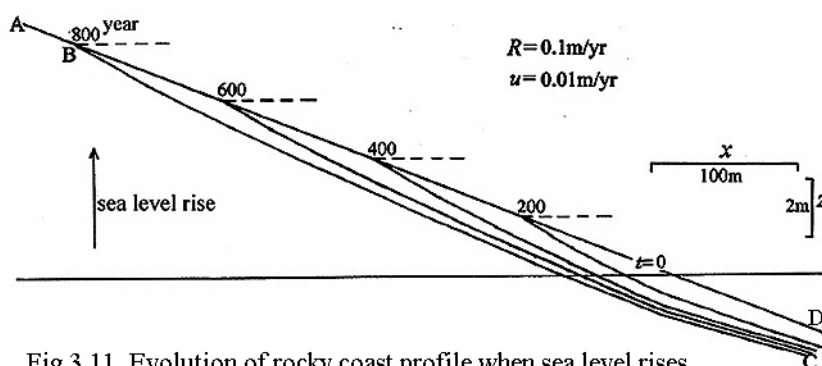


Fig.3.11 Evolution of rocky coast profile when sea level rises and sea cliff retreat is relatively slow ( $u/R < S$ )  
A - D :initial profile, A - B - C :profile at  $t=800$ . Sea cliff does not develop.



$$E_x = \frac{1}{16} c_g \rho g H^2 \sin 2\alpha \quad (3.15)$$

where  $c_g$  is wave velocity,  $\rho$  is density of sea water,  $g$  is gravity acceleration,  $H$  is wave height and  $\alpha$  is angle of wave incidence. Sediment flux  $Q_x$  is proportional to wave energy flux:

$$Q_x = aE_x \quad (3.16)$$

When  $\alpha = 45^\circ$ ,  $Q_x$  has maximum amount.

Equation of continuity of sediment in one dimension is given by

$$\frac{\partial y}{\partial t} + \frac{1}{D} \frac{\partial Q_x}{\partial x} = 0 \quad (3.17)$$

where  $y$  is distance normal to shoreline,  $x$  is distance along shoreline, and  $D$  is water depth at outer margin of sediment drift zone.

Digital simulation of delta evolution has been conducted on the grid shown in Fig.3.21.

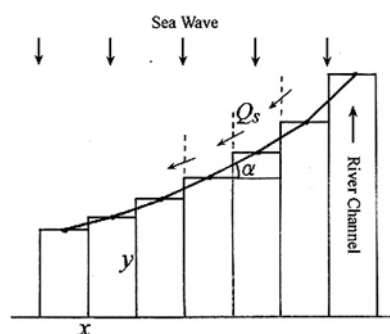


Fig.3.21  
Grid for delta simulation

In the case when  $\alpha$  in Fig.3.21 does not exceed 45 degrees, sediments are transported along shoreline away from river mouth, and consequently a caspate delt develops (Fig.3.22). When it exceeds 45 degrees, long shore sediment transport away from river decreases, and river mouth prolongs to offshore, resulting in the development of birdfoot-like landform. (Fig.3.23). When the condition that  $a$  of (3.15) increases with the distance from shoreline, arcuate delta can be simulated (Fig.3.24).

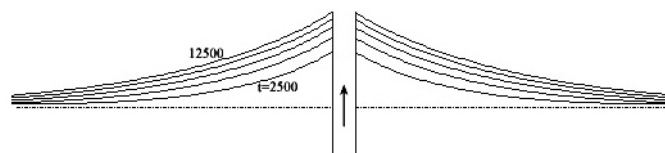


Fig.3.22 Simulation of caspate delta  
When  $\alpha$  of (3.15) does not exceed 45 degrees

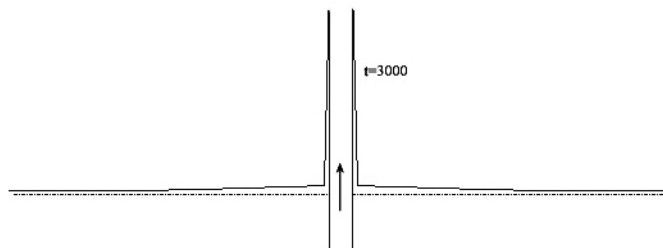


Fig.2.23 Development of bird-foot delta  
When  $\alpha$  of (3.15) exceeds 45 degrees

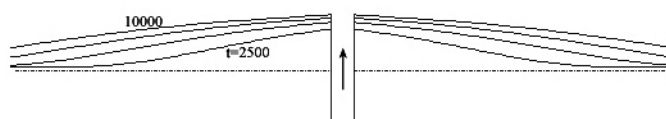


Fig.3.24 Development of arcuate delta

## (2) Delta profile evolution

Now, we consider the evolution of delta profile formed at the river mouth area shown in Fig.3.26. A river transporting sediments flows into shallow sea at P, where deposition of sediments occurs because of sudden decrease in the transporting force by the sudden decrease in flow velocity. The flow velocity  $u$  is simplified as flow discharge divided by flow depth ( $Q/h$ ). Initial profile of river floor and sea floor is given by a continuous straight line.

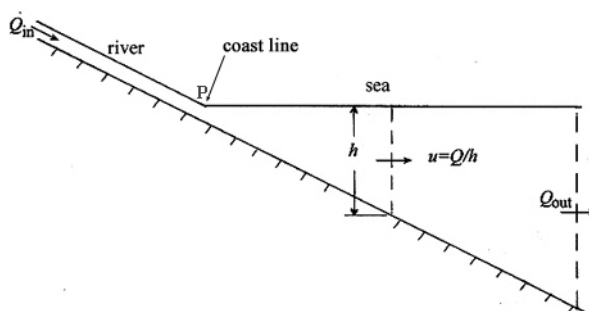


Fig.3.26 Simulation field for delta profile evolution

Equation of motion of water flow and continuity equation in one dimension are given by

$$\frac{\partial M}{\partial t} + \frac{\partial(uM)}{\partial x} = -gh \frac{\partial(h+z)}{\partial x} - gn^2 \frac{u|u|}{h^{1/3}} \quad (3.18)$$

$$\frac{\partial h}{\partial t} + \frac{\partial M}{\partial x} = 0 \quad (3.19)$$

where  $M$  is discharge,  $u$  is flow velocity,  $h$  is water depth,  $z$  is altitude and  $n$  is Manning's coefficient of roughness.

Sediment flux  $q_s$  is given by the following simplified equation:

$$q_s = a \left( \frac{M}{h} \right)^2 + bS \quad (3.20)$$

where  $S$  is slope gradient. The first term of the right hand side represents suspension load, which is given by the second power of mean flow velocity ( $M/h$ ). The second term represents tractional load, which is very small in quantity. Continuity equation for sediments is represented by

$$\frac{\partial z}{\partial t} + \frac{\partial q_s}{\partial x} = 0 \quad (3.21)$$

Sediments are provided from the upper end of the river continuously. When the angle of deposition surface exceeds an angle of repose in water, the excess amount of sediments are distributed on the front of deposits. Thus forest bed evolves and proceeds forwards. A small amount is transported further, making bottom-set beds. On the deposition surface top-set beds evolves. Deposition also proceeds upstream. Fig.3.27 is the result of simulation conducted under the condition of constant sea level. Angle of repose for deposition in water is set at 20 degrees.

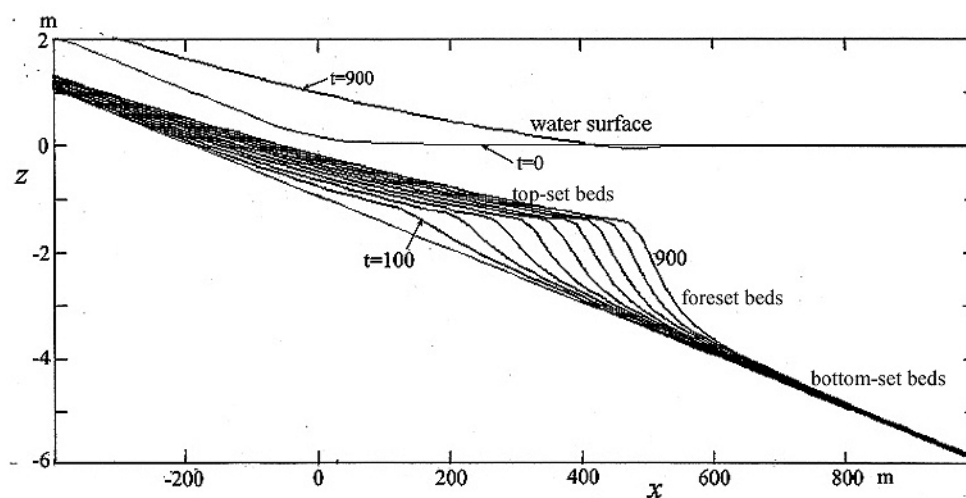


Fig.3.27 Simulation of delta profile evolution in the case of constant sea level

When sea level falls, forward progress of fore-set beds is faster and the upper surface is slightly eroded (Fig.3.29). Faster the rate of sea level fall, larger the speed of forward progress of forest beds. Fig.3.31 shows the evolution of delta profile when sea level falls until  $t=900$  and thereafter sea level rises. When sea level changes to rise, forward progress of front decreases rapidly and soon it almost stops. On the other hand evolution of top-set beds become significant.

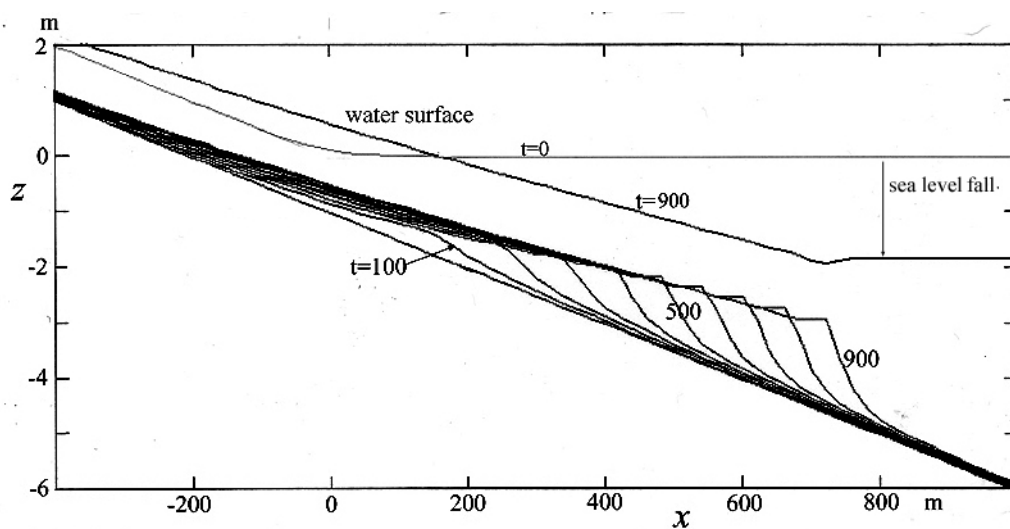


Fig.3.29 Simulated delta profile in the case when sea level falls

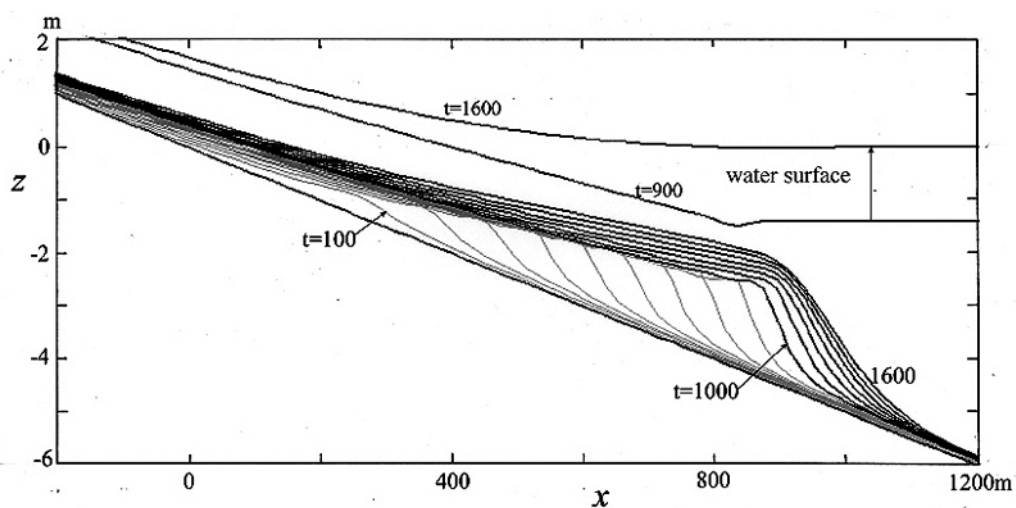


Fig.3.31 Simulated delta profiles when sea level falls until  $t=900$  and after then sea level rises