SEDIMENT TRANSPORT ACCOMPANIED BY THE SHOREWARD MOVEMENT OF LAKE ICE

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INTRODUCTION

Onshore thermal movement of lake ice, landing of ice sheets, and beach nourishment from lake ice transport of shore materials are observed in many inland lakes. Ice-made ramparts formed on the shores of these lakes derive sediment supply from the area near the shorelines and gradually grow in size. Alestalo and Häikiö (1979) carried out the field surveys on the formation of ice ridges and ice-made ramparts in many lakes located in the central part of Finland. On the basis of the investigation results, they classified the profiles of ice-surface forms and the profiles of ice-push shore forms. Although some field observations on thermal movements of lake ice were also done (Hamberg, 1919; Zumberge and Wilson, 1953; Wagner, 1970), the results obtained have not been fully utilized to explain the process of sediment supply to ice-made ramparts.

In the present study, the critical height (the maximum elevation above the lake ice surface) of sediment transport accompanied by the shoreward movement of lake ice is examined by paying attention to the difference in landing types of lake ice. Based on the examination results, the conditions of sediment supply to the ice-made ramparts developed on the shores of Lake Kussharo are also investigated.

SEDIMENT TRANSPORT IN EACH LANDING TYPE OF LAKE ICE

Alestalo and Häikiö (1979) classified the landing types of lake ice in three groups (Figure 1); (1) overthrust (an ice plate or a frozen soil slab thrusts up onto the shore); (2) horizontal thrust (an ice plate or a frozen soil slab horizontally thrusts against the shore in the same direction as its surface); (3) intrusion (an ice plate or a frozen soil slab intrudes into the shore). Those landing types of lake ice have also been confirmed by the author in the field surveys in Lake Kussharo and then their classification is adopted in this examination on the sediment transport accompanied by the shoreward movement of lake ice.

Overthrust:

Let us suppose that a frozen soil slab or an ice plate is thrust up onto the shore with an incline of θ degrees. The critical height of sediment transport (y) is obtained using

$$y = x \cdot \sin\theta \qquad (1)$$

where x is the distance of lake ice movement. Substitution of each value of θ ($\theta = 10°, 20°, 30°, 45°, 60°$) into equation (1) gives each critical height of sediment transport. Each function of x is plotted in Figure 2. This figure indicates that the larger the value of θ grows, the higher the critical height

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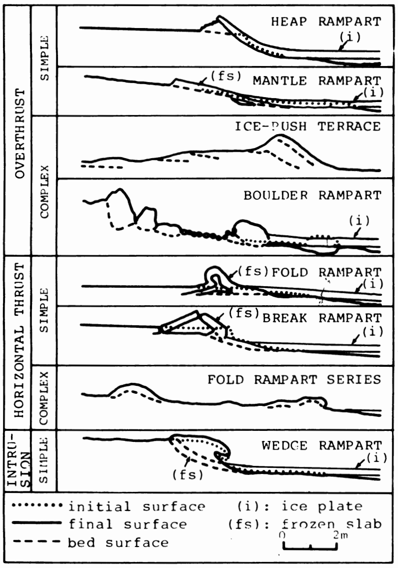

Figure 1 Ice - thrust shore morphology. (After Alestalo and Häikiö (1979))

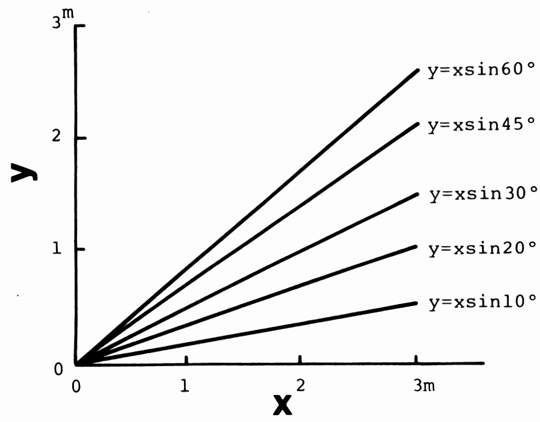

Figure 2 The critical height of sediment transport accompanied by the shoreward movement of lake ice (overthrust type).

of sediment transport becomes.

Horizontal thrust:

Figure 3 denotes that owing to the shoreward movement of lake ice, the frozen soil slabs or the ice plates ($\overline{AE}$ and $\overline{DE}$) divided by the fracture buckle upwards into the crest (Point E). The critical height of sediment transport (y) is obtained using

$$x = (s+r) - \sqrt{(s^2-y^2)} + \sqrt{(r^2-y^2)} \tag{2}$$

where x is the distance of lake ice movement and both s and r are the length of frozen soil slabs or ice plates.

Rearranging equation (2) results in

$$y = \frac{\sqrt{-(s+r-x)^4 + 2(s^2+r^2)(s+r-x)^2 - (s^2-r^2)^2}}{2(s+r-x)} \tag{3}$$

Let us now examine equation (3) for some special cases, namely for the cases of $s=r$, $s>r>0$, and $r>s>0$.

(a) $s=r$. equation (3) becomes

$$y = \frac{\sqrt{4s^2 - (2s-x)^2}}{2} \tag{4}$$

The graph of equation (4) is illustrated in Figure 4. This figure shows that the greatest value of y is s when x is 2s. In other words, the critical height of sediment transport is 0.5 when the distance of landward movement of lake ice is unit distance 1.

(b) $s>r>0$. We can improve equation (3) and obtain

$$y = \frac{\sqrt{-t^2 + 2(s^2+r^2)t - (s^2-r^2)^2}}{2\sqrt{t}} \tag{5}$$

having replaced

$$(s+r-x)^2 = t \tag{6}$$

where $\quad t > 0$ (7)

If we square both sides of equation (5), we obtain

$$y^2 = -\frac{1}{4}t + \frac{1}{2}(s^2+r^2) - \frac{1}{4t}(s^2-r^2)^2 \tag{8}$$

Examining the behaviour of the curve of equation (8), we find that the greatest value of y^2 is r^2 when $t=s^2-r^2$. That is, the greatest value of y is r when x satisfies the following condition.

$$x = s+r-\sqrt{s^2-r^2} \tag{9}$$

Let us now substitute $x=1$ (unit distance) in equation (9) and solve the equation for s we obtain

$$s = -r - \frac{1}{2(r-1)} \tag{10}$$

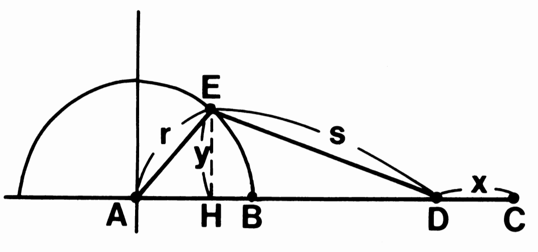

Figure 3 Examination on the landing of lake ice (horizontal thrust type).

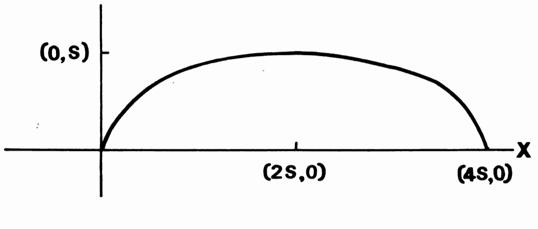

Figure 4 The critical height of sediment transport accompanied by the shoreward movement of lake ice (horizontal thrust type, $s=r$).

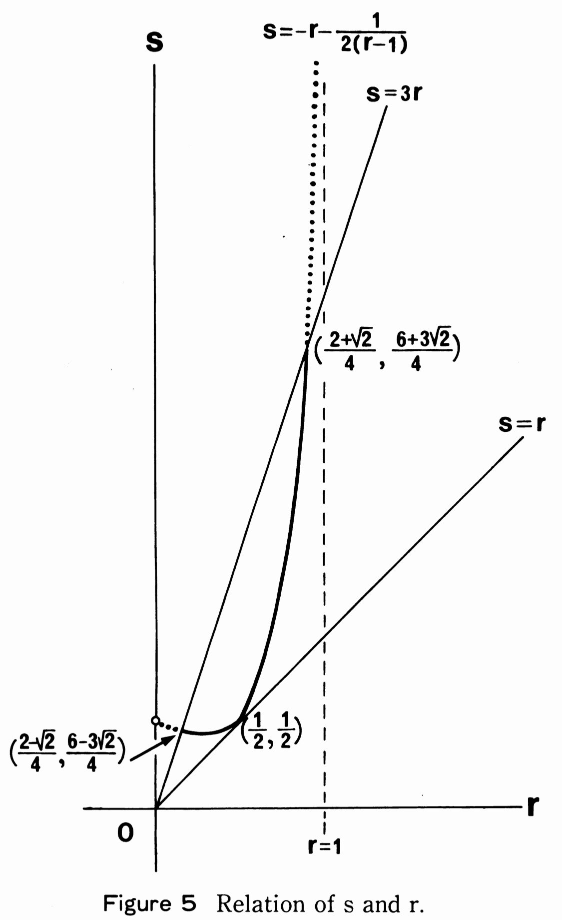

Figure 5 Relation of s and r.

where $\quad r \neq 1$ (11)

Equation (10) is presented in Figure 5. On this figure the relationship between s and r is denoted by the heavy solid and dotted lines on condition that the distance of landward movement of lake ice is unit distance 1. Although the value of s increases indefinitely when r approaches 1, almost all the combinations of r and s observed in the field surveys satisfy the following condition.

$$1 < \frac{s}{r} \leqq 3 \tag{12}$$

On figure 5 the heavy solid line satisfies the above condition. Hence, when x=1 and s/r satisfies the condition of inequality (12), y has the greatest value which satisfies the following inequality

$$\frac{2-\sqrt{2}}{4} \leqq y \leqq \frac{2+\sqrt{2}}{4} \tag{13}$$

(c) r>s>0. Examining equation (3) in much the same way as (b), we may draw the following conclusion. Namely, the greatest value of y is s when

$$x = s + r - \sqrt{r^2 - s^2} \tag{14}$$

Let us now substitute x=1 (unit distance) in equation (14). Then

$$1 = s + r - \sqrt{r^2 - s^2} \tag{15}$$

The graph of equation (15) corresponds to the one in which s and r are replaced by r and s respectively on Figure 5. Thus y has the greatest value which satisfies the following inequality

$$0 < y < 1 \tag{16}$$

Such cases (r>s>0), however, have rarely been observed in the field surveys.

Intrusion:

"Intrusion" occurs when frozen soil slabs or ice plates are penetrated into ice-made ramparts by the shoreward movement of lake ice. It is, therefore, a matter of course that they destroy the ice-made ramparts in some measure. Since the intruding frozen soil slabs or ice plates contain much sediment, they also supply the ice-made ramparts with fresh sediment. It was confirmed by the author in the field observations.

The critical height of sediment transport associated with "intrusion" is closely related to the distance of landward movement of lake ice and the angle of penetration of frozen soil slabs or ice plates to the lake ice surface. It is, therefore, considered that the preceding discussion on "overthrust" is roughly applicable to "intrusion".

DISCUSSION AND CONCLUSIONS

Through the examination on the sediment transport by the landing of lake ice, it became clear that both "overthrust" and "horizontal thrust" can efficiently transport sediment near the shoreline onshore or upward (Figures 2, 4, and 5).

Almost all the ice-made ramparts of the first row that are developed on the shores of Lake Kussharo are located 3 to 5m landward from the shoreline and their relative height is 0.5 to 2.0m (Sasaki, 1985). During the period from 28 January 1986 to 16 February 1986, the author conducted the field observation on the lake ice movements in Lake Kussharo. The survey results showed that the net movement of lake ice for the entire period when active ice movement repeatedly occurred was about 3m and its direction was shoreward (Sasaki, 1992).

From the investigation results described above, the author may conclude that the ice-made ramparts developed on the shores of Lake Kussharo are fully supplied with sediment by the thermal ice movements under modern climatic conditions.

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湖氷の湖岸への移動に伴う堆積物の運搬について

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湖氷が熱膨張と熱収縮を繰り返しながら湖岸に乗り上がる現象は，世界各地の内陸の湖沼で観察される。本研究では，Alestalo and Häikiö (1979) が行った湖氷の乗り上げ様式の分類にしたがって，それぞれの乗り上げ様式毎に汀線付近の堆積物が内陸方向にどの程度運搬されるのか（湖氷面からの高さと汀線からの水平距離）について検討した。

その結果，押しかぶせ型 (overthrust) と水平押し出し型 (horizontal thrust) は，共に比較的効率良く湖岸堆積物を内陸方向に運搬することができることが明らかになった。またこれまでに屈斜路湖で行った湖氷移動に関する野外調査の結果を，上述の検討内容にあてはめて考察してみたところ，屈斜路湖の湖岸に発達しているice-made ramparts は，現在の気候条件の下で発生する湖氷移動によって充分な堆積物の供給が行われているという結論を得た。

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