CHAPTER 183

TIDAL RESPONSE OF TWO-LAYER FLOW AT A RIVER MOUTH

by

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and

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ABSTRACT

This paper describes various features of tidal effects on the behavior of a salt wedge and on the mechanism of mixing between the salt water and the fresh water in the vicinity of a river mouth. The studies have been performed through experiments, field observations and throretical considerations. The condition upon which the fresh water begins to show an intermittent flow-pattern owing to an increase of the tidal action, and the criterion of a transition of the mixing type from negligible into intense, were obtained, with two dimensionless parameters λ and θ. The former parameter λ is given by $\lambda = A_o/U_oT_o$, in which T_o is the tidal period, A_o is the tidal amplitude of the sea level, and U_o is the temporal mean velocity of the fresh water at the river mouth. The latter parameter θ is the so-called Keulegan number. Besides, it came evident that a tidal motion of the salt wedge couldn't be understood without a consideration of the internal wave inside the mouth, which were induced by the tide, in addition to a direct effect of the tide.

1. Introduction

Since early times, in Japan, river mouths have been utilized in many ways, for example, as fishery ports, navigation harbors, suppliers of water for irrigation and industries, etc. The river mouth, in this meaning, is considered to be an important base for all industries. Recently, with a growth of utilization of the river mouths, a serious problem has attracted public attention. It is water pollution. Saline pollution owing to the salt wedge has widely been known from old times, as a main difficulty to agriculture, chemical industries and to citizens' lives. Nowadays, in addition, sewage poured from citizens'lives, and waste from industries have come a new matter of the utmost concern, since they give a damage to coastal fisheries, and its results rebound to human life again, as a danger against human health.

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To solve those problems, studies on the two-layer flow at a river mouth have an important role. Prediction of a length or a form of the salt wedge, control technique of its length[1], an estimate of the area of river water expanding over the sea, outflow patterns varying with a degree of river discharge[2),3),4),5] etc. are those of already revealed to a certain degree, which have greatly served to increase a correct comprehension on mechanics of the problems. Most of them, however, have been investigated under a tideless condition, and many studies concerning the tidal effect are, at present, left unsolved yet. Needless to say, there have been many studies related to a tidal estuary, but most of them are directed to established types of mixing, namely, intense mixing or moderate mixing, where tidal variations of flow, level and saline concentration, from time to time, are usually ignored, and instead, temporal mean values are important.

The present authors intend, hereby, to describe a fine mechanism of the two-layer flow which varies in response to the tide. They deal, first, with an equipment for experiments and a method of measurements, which were adopted in the study, in Section 2, next, with a relationship between outflow patterns of the fresh water and the tide in Section 3, third, with a periodical motion of the salt wedge due to the tide in Section 4, and finally, with a problem of tidal mixing between the fresh water and the salt water, and also with a contribution of the tide to a transition from the negligible mixing type into the intense mixing type in Section 5.

2. Experimental Equipment

In order to observe the whole behavior of the two-layer flow which extends widely from the upstream of a river to the open sea, an equipment was designed as shown in Fig. 1, so as to consist of a large water vessel and a long straight channel which connects to the vessel at right angles. The vessel and the channel correspond to the sea and a river, respectively. Since they are made of transparent acrylic acid resin, for the purpose of marking dye in water being observable from outside. A tide generator is specially devised so that the water level may follow any curve of hydrographs. Its block diagram is shown in Fig. 2. Salt water in the vessel is separated by a wide vinyl sheet on the bottom, from water which is pumped in and out from below to change the water level. Thus, the salt water is moved bodily up and down, and is kept undisturbed.

As a movie camera is insufficient to observe the whole behavior of the salt wedge, another optical method is additionally adopted. The diagram of the optical system is shown in Fig. 1. Light pulses emitted from a xenon lamp intermittently at constant intervals, are made parallel by a concave mirror, and reflected perpendicularly at many plane mirrors which are lined up along the channel. Many light beams thus divided penetrate the channel transversely, pass through narrow slits of 0.3 mm in width, which are attached on the other side of the channel, and arrive at a long sheet of photosensitive paper, which moves along the channel by 0.3 mm, synchronously with every arrival of pulses. Since light is reflected or refracted at the water surface and the interface, both levels are exposed on the sheet, from time to time. Thus, a tidal change of the surface and the interface can be obtained at 10 cm intervals along the channel. The behavior of the two-layer flow outside the mouth are caught with a 8 mm movie camera, by the aid of fluorescein sodium liquid as a tracer.

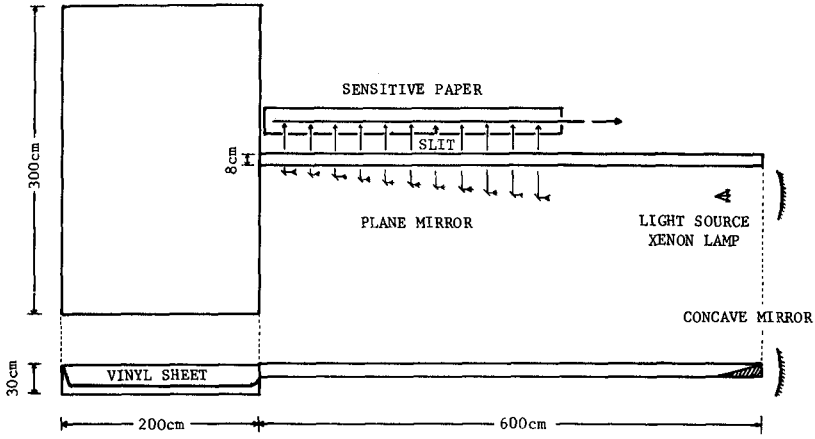


Figure 1.

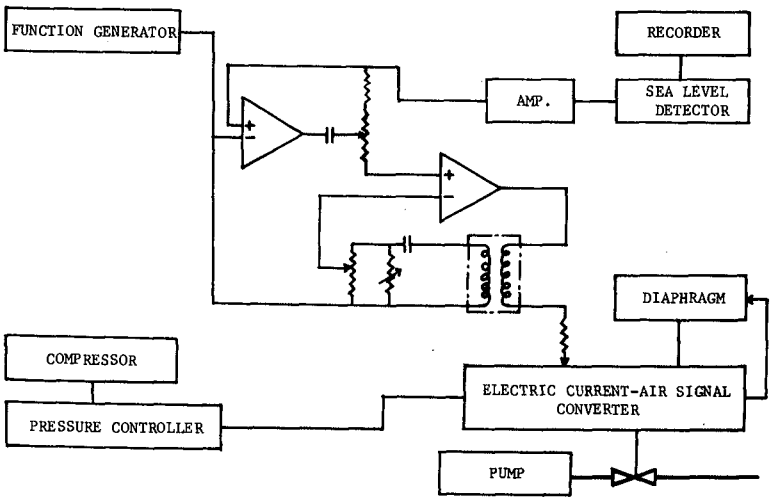


Figure 2

3. Tidal Change of Flow Pattern

An appearance of outflow pattern varies depending on only the amount of a river discharge, if it is assumed tideless. When the discharge grows, the outflow pattern approaches an extreme type called the E pattern, which resembles a turbulent jet of homogeneous fluid. On the other hand, if the discharge falls off, it reaches the other extreme type called the A pattern, whose stream lines extend slowly in all directions over the sea without turbulence. According to experiments, three transitional types lie between those extreme two, and they are called the B, C and D patterns. All patterns are shown in Fig. 3 (1), and they can be classified with two parameters, which are the Keulegan number θ and the Reynolds number R respectively, where $\theta = (\nu\varepsilon g)^{1/3}/U_o$ and $R = U_o b/\nu$. The symbol b is a cross-sectional mean velocity of the fresh water at the mouth, ν is a kinematic viscosity, and $\varepsilon = (\rho_2 - \rho_1)/\rho_2$, where ρ_1 and ρ_2 are densities of the fresh water and the salt water respectively. The classification is shown in Fig. 3 (2).

When the tide exists, every pattern varies from time to time. At a flood tide, it has a trend to approach the A pattern, and at the ebb tide, it changes toward the E pattern. A degree of the tidal range dominates a change of the pattern. According to experiments, if an amplitude of the tide level is small, or a tidal period is long enough, the change is small, and the fresh water always flows out from the mouth over the whole tidal period. However, when the amplitude grows up excessively, or the tidal period decreases below a certain value, the fresh water sometimes stops or flows upstream at the flood. If it develops extremely, the fresh water, which has flown out at the ebb, cannot return into the river even at the flood, and it produces a special pattern, an "intermittent flow", every tidal cycle. In such a case, mixing of the fresh water and the salt water develops, and an adoption of the two-layer theory becomes impossible.

Two examples are shown in Figs. 4 and 5, which are those transferred from movie films. The former one is photographed on condition that the discharge is 6.70 cm^3/s, the tide amplitude is 1.70 cm, the tide period is 1380 sec and $\varepsilon = 0.018$. If tideless, the upper values are those of the B, or C pattern, whose condition is $\theta R^{0.137} = 0.673$. However, the tide lets the fresh water change its flow pattern from time to time. Under the above condition, the upstream flow doesn't occur even at the flood. According to tidal hours, the flow pattern varies in such a manner that it shows the pattern C at the high and low waters, B at the flood, and E at the ebb. Fig. 5 is another example under condition that the discharge is 2.89 cm^3/s, the amplitude is 2.29 cm, the tidal period is 360 sec and $\varepsilon = 0.020$. If tideless, the flow pattern belongs to B somewhat close to A with a relationship, $\theta R^{0.137} = 0.849$. Compared with the former case, in this case, the discharge and the period are so small that the tidal effect is strong. At every hour of the tide, the pattern shows A or B at the high and low waters, D at the ebb and an upstream flowing pattern at the flood, when the surface at the mouth is occupied by the salt water, namely, this type is an intermittent flow.

Other experimental results are all situated between those two cases, where sometimes the fresh water stops at the ebb, or sometimes the fresh water flows upstream in a type different from the intermittent flow.

Next, a criterion, upon which above various types occur, will be

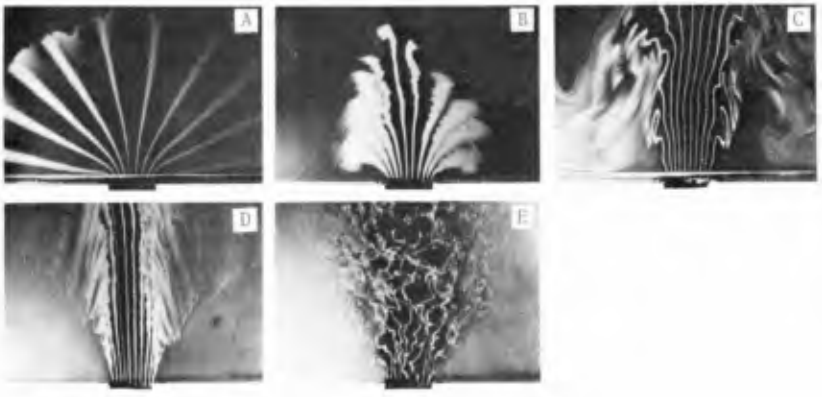


Figure 3(1).

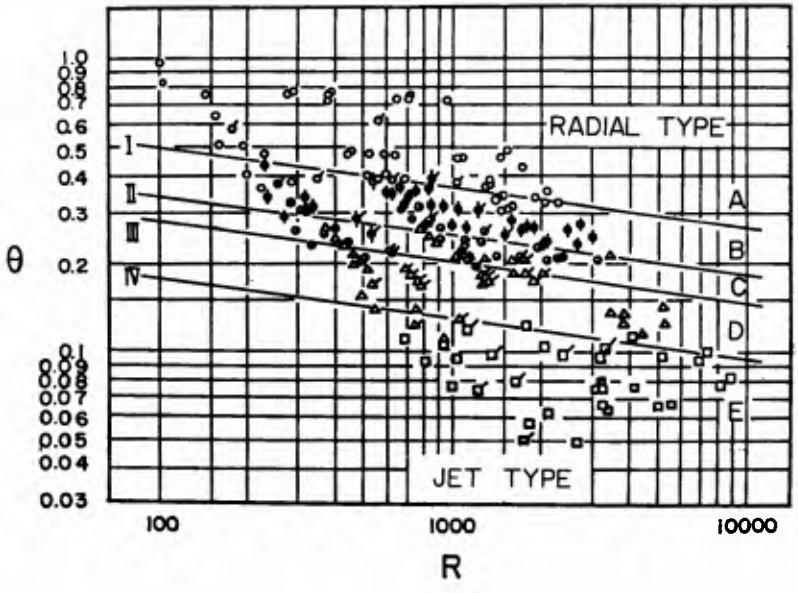


Figure 3(2).

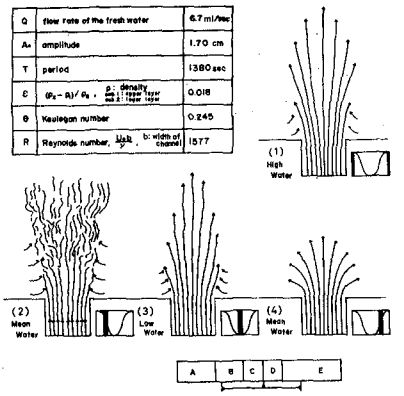


Figure 4.

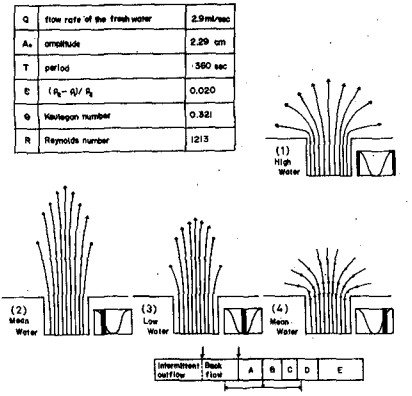


Figure 5.

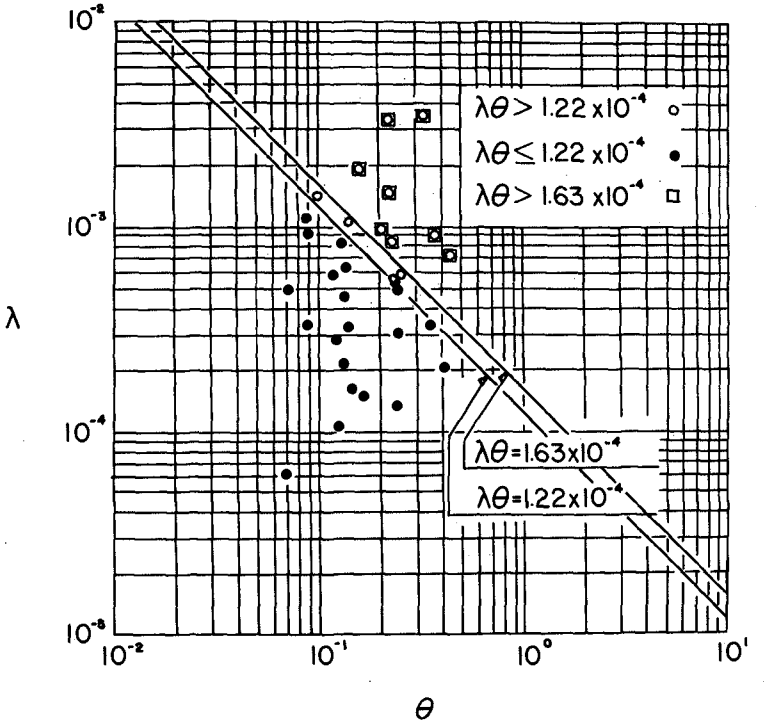


Figure 6.

discussed. Since a condition on which the fresh water flows upstream seems to arise, when the tidal current exceeds a temporal mean velocity of the fresh water, the ratio of both velocities will be a dimensionless parameter which dominates this problem. An intensity of the tidal current can be regarded as a function of A_o/T_o, where A_o is the amplitude of the tidal level and T_o is the period. Therefore, the ratio λ, which is represented by $\lambda = A_o/U_oT_o$, should be a parameter required. In addition, the velocity U_o of the fresh water is so deeply related to the two-layer flow system itself, that this problem seems to have a relation also to the Keulegan number θ.

Thus, by using those two parameters λ and θ, various patterns are classified as follows.

$\lambda\theta < 1.22 \times 10^{-4}$: The fresh water always flows out, over the whole tidal period.
$\lambda\theta = 1.22 \times 10^{-4}$: The fresh water stops at the flood.
$1.22 \times 10^{-4} < \lambda\theta < 1.63 \times 10^{-4}$: The fresh water flows backward into the river, at the flood, but it is no intermittent flow.
$\lambda\theta = 1.63 \times 10^{-4}$: The salt water covers the surface temporarily in the vicinity of the mouth, at the flood.
$\lambda\theta > 1.63 \times 10^{-4}$: The intermittent flow occurs.

Those conditions are shown in Fig. 6. The value of U_o is evaluated from the equation $U_o = (\varepsilon gQ/b)^{1/3}$, which is derived from two equations, $Q = bh_1U_o$ and $U_o^2/\varepsilon gh = 1$, where Q and h_1 are temporal mean values of the discharge and a depth of the fresh water at the mouth, respectively. There arises a question whether the conditions thus obtained from experiments are valid for natural rivers or not. This will be discussed again in Section 5, with some theoretical consideration.

4. Tidal Change of Two-Layer Flow and Its Propagation

Problems of a stationary two-layer flow inside the river mouth are more or less related to those of the salt wedge. A prediction of a form of the salt wedge plays an important part for solving problems of this kind, and it is possible from the theory after Schijf-Schönfeld, by using a coefficient of interfacial resistance. Physical properties of the interfacial resistance have not fully been revealed yet, but studies on those are growing through experiments and field observations, along a definite line to relate the resistance with a certain parameter ψ, which is composed of the Reynolds number R and the interfacial Froude number F_i, as $\psi = RF_i^2$.

Studies on the dynamical behavior of the two-layer flow which is under the tidal effect have been also developed in some degree mainly through field observations. For example, a front of the salt wedge is formed steep at the high water and is flattened at the low water; The surface level moves with not always the same phase with that of the interface; the salt wedge advances at the flood and retreats at the ebb, while the fresh water continuously flows down over the whole period, etc. Those are nowadays well-known facts, though fairly empirical.

The authors conducted a series of experiments with high accuracy on those problems, and also made field observations to test experimental

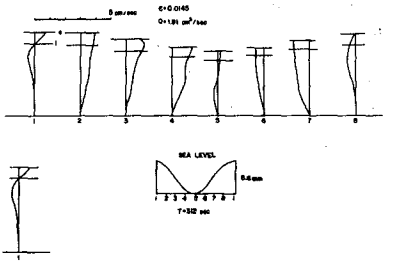


Figure 7(1).

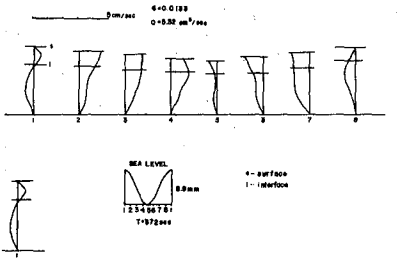
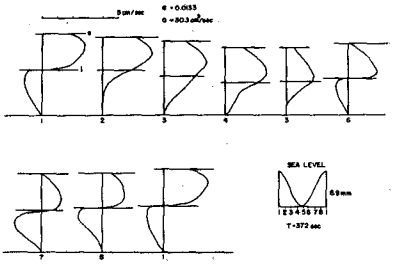


Figure 7(2).



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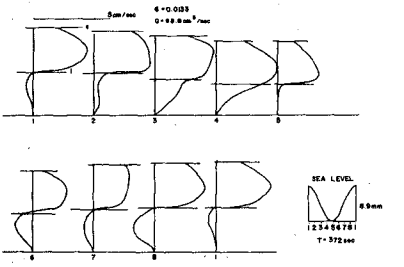

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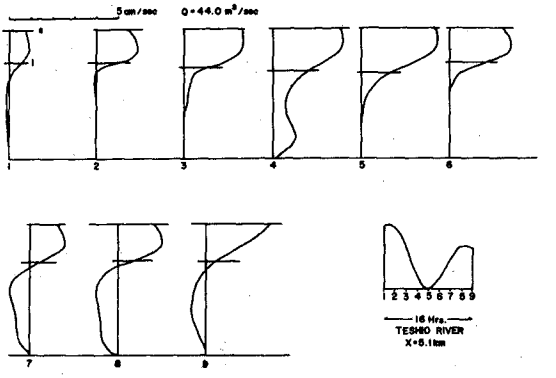


Figure 7(5).

results.

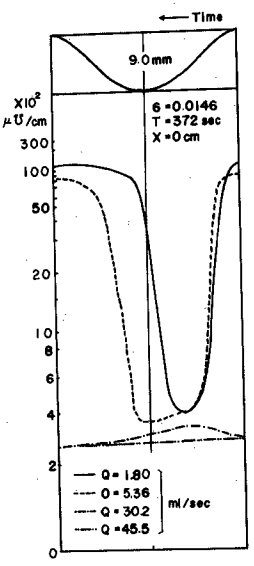
(a) Results of Model Experiments and Analyses

First, a change of the vertical distribution of velocity due to the tide is examined. Figs. 7 (1), (2), (3) and (4) show some examples. Observational points are 2.75 m upstream from the mouth, in cases of (1) and (2), and 1.3 m in (3) and (4). The discharge of the fresh water increases, in order, from (1) to (4). Fig. 8 shows a tidal change of salt concentration in the surface water (in electrical conductivity, $\mu\mho$/cm) at the mouth, at various values of discharge. Fig. 9 shows the same at different places inside the mouth. Throughout experiments, the tidal change of the level is given to move sinusoidally. If the discharge is small, for example, $Q = 1.91$ cm^3/s in Fig. 8, the salt water occupies the surface for some distance from the mouth at the flood, and it suggests an intermittent flow. This case belongs to a condition of the intermittent flow, $\lambda\theta > 1.63 \times 10^{-4}$, and the shape of the fresh water is sketched as shown in Fig. 10. When the discharge increases, the intermittent or upstream types disappear and the fresh water flows down every tidal hour, but on the other hand, the salt water beneath the fresh water, moves upstream and downstream according to the tidal hours. Such a case has frequently been experienced in field observations as shown in Fig. 7(5). However, the change of the interfacial level is more remarkable in field than in experiment.

As described above, the level, interface, velocity and salinity, change periodically with the tide at every point along the channel, and it suggests that those variations may propagate along the channel. Observations at two points, one of which is 50 cm upstream from the mouth and the other 350 cm, provide some properties of those propagations. Two examples are shown in Figs. 11 and 12. Experiments were performed with dye as a tracer and a movie camera. Fig. 11 is an example of no discharge, when the tidal periods are 33.3 sec and 100 sec. Both curves are different in phase with each other, where an exactly opposite trend can be found. This is because of that the case of 33.3 sec is resonant with the proper period of the channel which is 31.9 sec. According to a detailed observation at the upstream point, a change of velocity and level is observed always to have a phase difference $\pi/2$, the former being ahead of the latter. This fact is understood from a consideration that there occurs a cooscillating tide in the channel caused by the tide outside. Fig. 12 shows an example with the discharge 12.0 cm^3/s. The approximate behavior is almost the same with that of no discharge, since the amount of the discharge is relatively small. In those two examples, the effect of the external wave which is caused by the tide is dominant on the motion of water inside the channel, where the interface between the fresh water and the salt water moves at the same phase with the water surface.

The tidal current induced in the channel is next examined theoretically, in order to compare the observed results with it. If the channel has a constant depth and its length is small compared to the wave length of the external wave, equations of motion and continuity are given at the first approximation for an inviscid two-layer flow, as follows.

$$h_1 \frac{\partial u_1}{\partial x} + \frac{\partial}{\partial t}(\eta_1 - \eta_2) = 0 \qquad (1)$$



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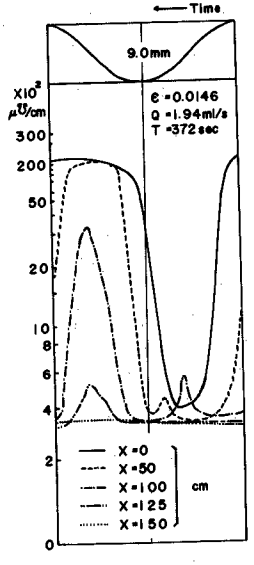

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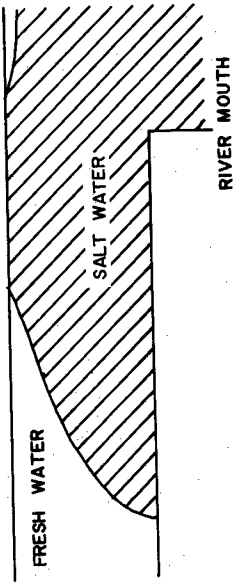

Figure 10.

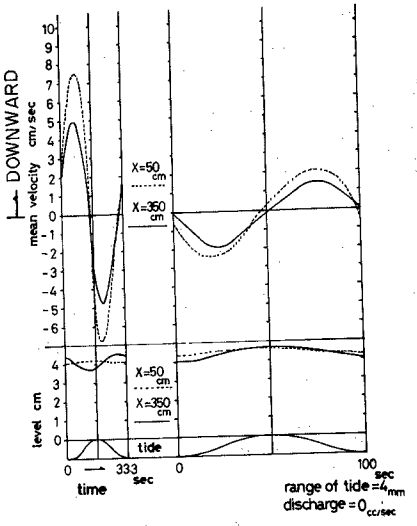

Figure 11.

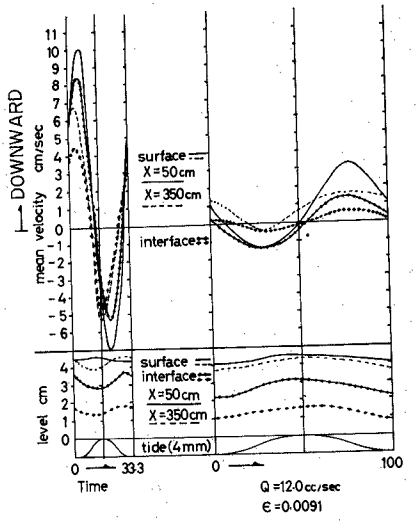

Figure 12.

$$h_2\frac{\partial u_2}{\partial x} + \frac{\partial \eta_2}{\partial t} = 0 \qquad (2)$$

$$\frac{\partial u_1}{\partial t} = -g\frac{\partial \eta_1}{\partial x} \qquad (3)$$

$$\frac{\partial u_2}{\partial t} = -g\frac{\rho_1}{\rho_2}\frac{\partial \eta_1}{\partial x} - \varepsilon g\frac{\partial \eta_2}{\partial x} \qquad (4)$$

where t is time, x is a coordinate along the channel from the mouth, η_1 and η_2 are vertical deviations of the surface and the interface from their temporal mean values, h and u are depth and velocity at each layer, and subscripts 1 and 2 represent the upper and the lower layers. By combining four equations, the next form of u is derived.

$$\frac{\partial^4 u_1}{\partial t^4} - g\,(h_1 + h_2)\frac{\partial^4 u_1}{\partial t^2 \partial x^2} + \varepsilon g^2 h_1 h_2 \frac{\partial^4 u_1}{\partial x^4} = 0 \qquad (5)$$

By introducing new symbols C_s as a velocity of the external wave, and C_i as the internal wave, such as $C_s^2 = g\,(h_1 + h_2)$, and $C_i^2 = \varepsilon g h_1 h_2/(h_1+h_2)$, a general solution, $u_1 = f(mx + \sigma t) + F(mx - \sigma t)$ is obtained from Eq. (5) under the condition $\varepsilon \ll 1$, where $\sigma/m = C_{s,i}$ which represents both C_s and C_i together. Similarly u_2, η_1 and η_2 are given in the same form with u_1.

$$\eta_1 = \eta_{10}\cos\,(mx - \sigma t) \qquad (6\text{-}1)$$

$$\eta_2 = \left(1 - \frac{gh_1}{C_{s,i}^2}\right)\eta_{10}\cos\,(mx - \sigma t) \qquad (6\text{-}2)$$

$$u_1 = \frac{g}{C_{s,i}}\eta_{10}\cos\,(mx - \sigma t) \qquad (6\text{-}3)$$

$$u_2 = \frac{C_{s,i}}{h_2}\left(1 - \frac{gh_1}{C_{s,i}^2}\right)\eta_{10}\cos\,(mx - \sigma t) \qquad (6\text{-}4)$$

Since the upper end of the channel exists, it can be assumed that the velocity $u = 0$ at $x = \ell$ which is the distance from the mouth. Furthermore, putting the tide level $\eta_1 = \eta_{10}\cos\,(\sigma t + \varepsilon)$ outside the mouth, solutions are given as follows.

$$\eta_1 = \eta_{10}\frac{\cos\{m(x - \ell)\}}{\cos m\ell}\cos\,(\sigma t + \varepsilon) \qquad (7\text{-}1)$$

$$\eta_2 = \left(1 - \frac{gh_1}{C_{s,i}^2}\right)\eta_{10}\frac{\cos\{m(x - \ell)\}}{\cos m}\cos\,(\sigma t + \varepsilon) \qquad (7\text{-}2)$$

$$u_1 = \frac{g}{C_{s,i}}\eta_{10}\frac{\sin\{m(x - \ell)\}}{\cos m\ell}\sin\,(\sigma t + \varepsilon) \qquad (7\text{-}3)$$

$$u_2 = \frac{C_{s,i}}{h_2}\left(1 - \frac{gh_1}{C_{s,i}^2}\right)\eta_{10}\frac{\sin\{m(x - \ell)\}}{\cos m\ell}\sin\,(\sigma t + \varepsilon) \qquad (7\text{-}4)$$

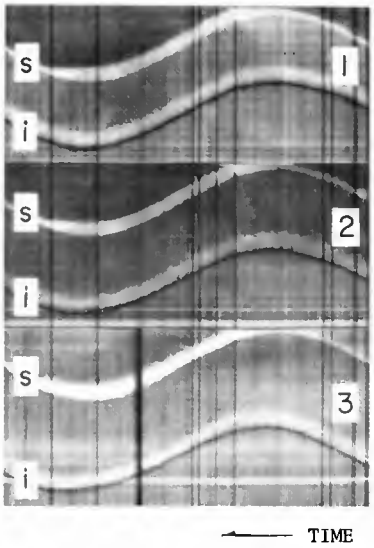

Figure 13.

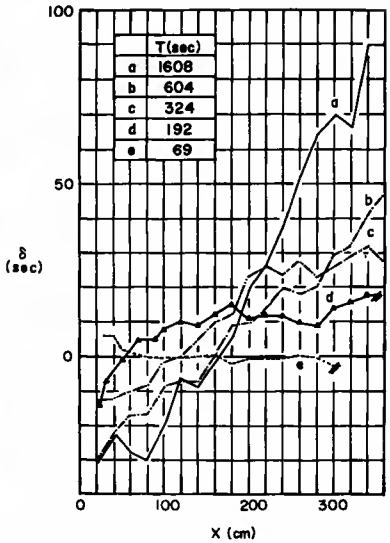

Figure 14.

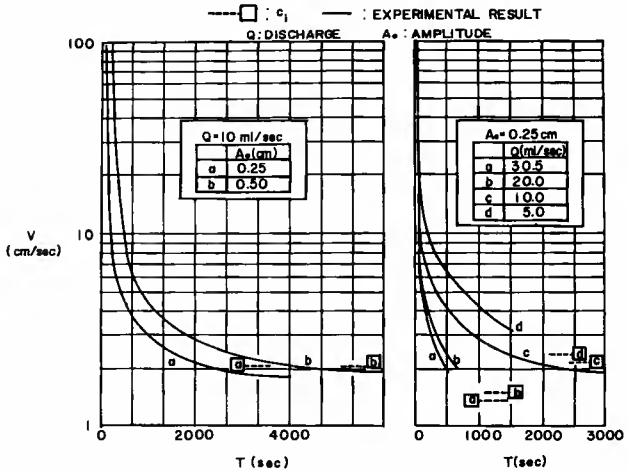

Figure 15(1).

Figure 15(2).

Substituting experimental values which are shown in Fig. 12, as $\eta_{10} = 0.2$ cm, $T = 100$ sec and $\ell = 450$ cm, into Eq. (7-3), the value, $u_{10} \doteqdot u_{20} = 1.36$ cm/s is found. This value is consistent well with the cross-sectional mean velocity, 1.2 cm/s, which is calculated from the lateral velocity distribution. Besides, the phase difference of the velocity and the level which has already been described as $\pi/2$, is also explained by those equations.

As pointed out like those, changes of the level and the velocity owing to the tide with the period 100 sec, coincide with those estimated from Eq. (7-3), where the propagation is based on the external wave. This fact, however, is not always true, because the interface grows remarkable with a distance from the mouth, and also with an increase of the tidal period. Such an example is shown in Fig. 13. These pictures are obtained through the technique by using the light-beam system which has already been described in Section 2. Since a propagation of the surface level is very fast, owing to its dependence on the external wave, the time difference cannot be detected at any station, but on the other hand, the interface is recognized to delay with a distance from the mouth. This means that the interface is affected more strongly by the internal wave. The experiments were made under condition that $Q = 9.67$ cm^3/s, $\varepsilon = 0.0067$, $\eta_{10} = 1.0$ cm, $T = 1623$ cm and a time interval of every exposure is 8.92 sec.

In order to investigate how the phase difference of the surface and the interface is related to the tidal period, experiments were repeated in a direction toward a decision of the time delay δ of the interface behind the surface, at various points along the channel. The results are shown in Fig. 14, in which $Q = 10$ cm^3/s and $\eta_{10} = 0.27$ cm. From this figure, it can be understood that an increase of δ is approximately linear against x. Its gradient δ_1 has a trend to grow steep with an increase of the tidal period. This means that a change of the interface propagates upstream with a certain velocity which depends on the tidal period. The velocity V is estimated undoubtedly as the reciprocal of δ_1. The dependencyof V on the tidal period is seen also in Figs. 15 (1) and (2), in which the discharge or the tide amplitude is taken as a parameter, where the amplitude is very small compared with the whole depth.

From those results, it is found that V is exceedingly large at the period of 100 sec and the phase difference between the surface and the interface is negligible, but it decreases with a growth of the tidal period, and finally it converges to a certain small value. Those final values become to be independent of the tide amplitude, but they depend on only the discharge. Convergent values are very close to those calculated from the following equation which gives the velocity of an internal wave.

$$C_i = -\frac{U_2h_1 + U_1h_2}{h_1 + h_2} + \sqrt{g\frac{h_1h_2}{h_1 + h_2} - \frac{(U_1 - U_2)^2h_1h_2}{(h_1 + h_2)^2}} \qquad (8)$$

This coincidence proves that a change of the interface brought by the tide has a property of the internal gravity wave.

In conclusion, a short period of the tide produces only the external wave at both the surface and the interface, but a sufficiently long period of the tide causes the external wave at the surface and the internal wave

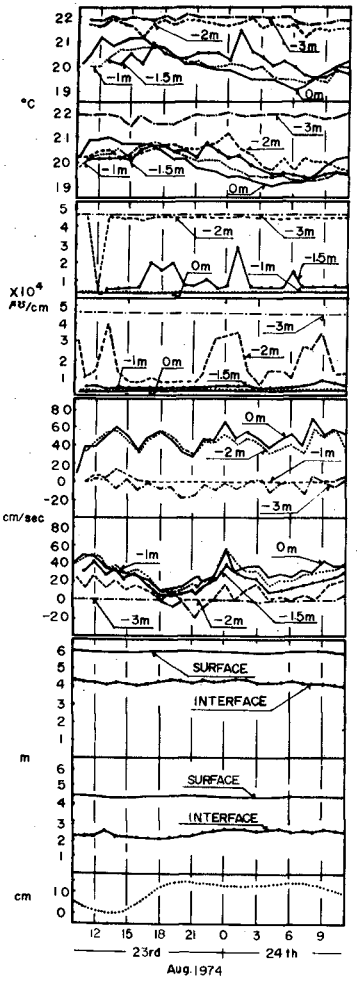

Figure 16.

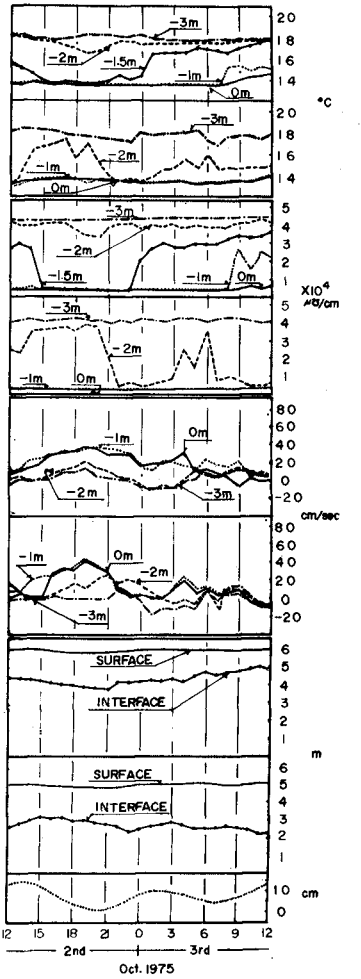

Figure 17.

at the interface. There is no theory sufficient to explain all those phenomena in detail yet, but it is not only interesting but also important for a study on the salt wedge. Under the condition of a long period, it must be noticed that a velocity of the flow in the salt layer also propagates with the velocity of the internal wave, although a velocity of the fresh water shows that of the external wave. Then, the surface level rises and falls almost simultaneously everywhere along the channel, nevertheless, the interface delays in time behind the surface, with an increase of the distance, because a propagation of the velocity of the salt water is very slow. In an extreme case, when the surface rises, the interface at a certain point may sometimes fall. It is possible that the origin of the internal wave is situated at some place inside the river mouth, from paying attention to Fig. 14. Needless to say, the occurrence of the internal wave is due to the tide, but the mechanism in what manner the tide passes through the mouth is still unknown and it belongs to the future study. If the tidal period is short enough, the effect of the internal wave disappears inside the mouth, and the interface rises and falls simultaneously at any point, as shown in Fig. 14.

(b) Field Observation of the Two-Layer Flow and Analyses

Figs. 16 and 17 show examples of field observation, at two stations along the Teshio River in Hokkaido. One is 0.5 km upstream from the mouth, and the other is 5.1 km. Observations at both stations were made at every one hour over the whole period of 25 hours. Since the Japan Sea to which the Teshio River opens, has a small tidal range of about 30 cm at its maximum, the length of the salt wedge is little affected by the tide. The relationship between the length and the river discharge is shown in Fig. 18. In the case of Fig. 16, as the discharge is about 90 m^3/s, the length of the salt wedge is estimated about 15 km. In Fig. 17, the length is expected 22 km, since the discharge is 44 m^3/s. According to the hydrograph obtained at the station of 18.3 km from the mouth, the change of the water level coincides with the tide, except flood days. This means that the external wave caused by the tide can travel for a great distance along the river without decay.

The surface level, interface velocity, water temperature and electrical conductivity were observed. It is noticeable that the change of the velocity contains irregular components whose periods are smaller than the tide, at the lower station. It seems to have been caused by the stormy weather which produces a seiche with a long period. After eliminating those components, the careful comparison of tidal components of the level, interface and velocity with each other, will lead to understanding that they are waves rather progressive towards upstream, than standing waves which have been discussed in the preceding section. This is evident from the fact that there is no reflection from the upstream of the river and the tide is caught without decay even at a very far station upstream from the river mouth.

In such a case, Proudman's solutions seems to be adoptable. The velocity is calculated from Eq. (6) as u_{10} = 10.7 cm/s. This is very close to the cross-sectionally averaged value 13 cm/s, while the value at the center of the flow is 20 cm/s, as shown in Fig. 13. As described like those, since all the changes are thought progressive, there can be a phase difference at two stations upper and lower. However, the external wave is estimated as 7 m/s in velocity and its travel time is only 11 minutes over the distance of 4.6 km between both stations.

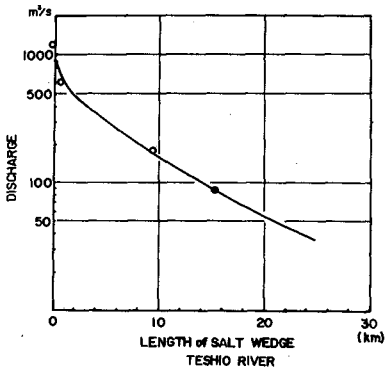

Figure 18.

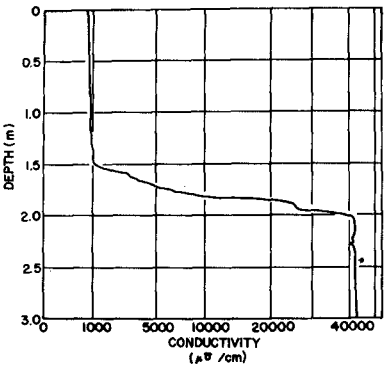

Figure 20.

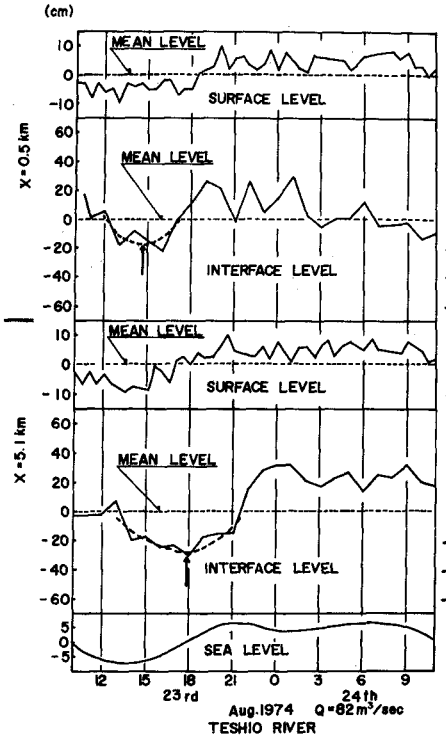

Figure 19(1).

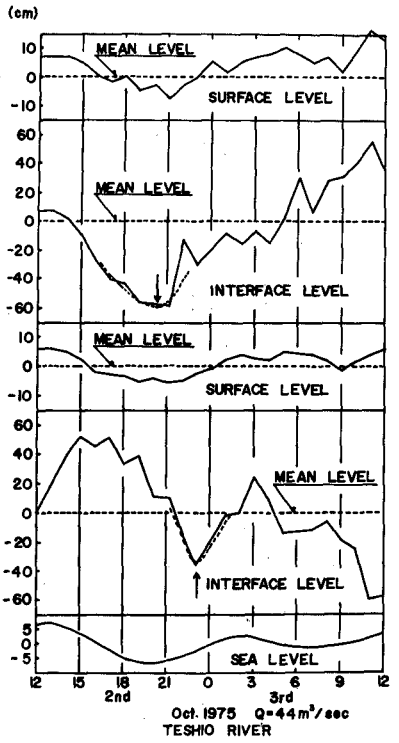

Figure 19(2).

Therefore, the time difference of the surface level is not detected between the two stations. For the purpose of finding of the detailed relationship between the surface and interface levels, enlarged figures are shown in Figs. 19 (1) and (2), in which the interface is defined as a level of 30,000 μ℧/cm in electrical conductivity. A representative type of the vertical distribution of electrical conductivity which corresponds to density, is shown in Fig. 20. The time difference of the surface level and the interface is negligible at the lower station, but not at the upper station as easily expected. There are 3-4 hours in Fig. 19 (1) and 2.5-3 hours in Fig. 19 (2). They are approximately the same with values of the internal wave which passes through two stations, where the former is calculated 3.1 hours and the latter 2.7 hours by using Eq. (8).

From all those experienced in field observation, the tidal effect at the Teshio River can be regarded as the same with that experienced in the experiment of a long tidal period which has already been described. It must be stressed again that the velocity change in the salt layer propagates with a velocity of the internal wave also in field observations. However, the velocity of the fresh water doesn't seem, for the present, to have a property of propagation of the internal wave.

There are many other important problems unsolved. For example, the case in which the tidal range becomes comparable with the water depth; a problem of the degree of a change of the interface level, which is much larger in field than in experiment, etc. are belonging to future studies.

5. Tidal Mixing of Two Layers

In a case of a negligible tide, mixing of the two-layer flow is thought to occur by interfacial instability and turbulence, caused by an increase of the relative velocity of the two layers. In such a case, the salt wedge has another phenomenon. The increase of the relative velocity brings a retreat of the salt wedge and finally pushes it out from the river mouth into the sea. From those two facts, it is understandable that if the salt wedge exists inside the river, mixing of two layers is always weak or negligible. Therefore, the existence of various types of mixing has been, hitherto, considered to depend on the tidal effect. The intense mixing type of a density current inside a river mouth or an estuary is, for instance, possible only in a case of the great range of tide.

In order to test this point of view, the authors repeated experiments with various degrees of the tidal range. However, contrary to expectation, there occurred no intense mixing, nor moderate mixing but always a type of distinctly separated two-layer flow, at any large value of the tidal range. As has already been described, the channel used in the experiments has a smooth bed and smooth sides, since it is made of acrylic resin. According to another experiment in which roughness is given to the bed, flow patterns change completely and mixing occurs even with a relatively small tidal range.

Examples are shown in Figs. 21 (a), (b), (c) and (d), whose conditions are, $T = 200$ sec, $Q = 10$ cm^3/s, $\varepsilon = 0.0067$ and the total depth is 4 cm. The roughness is given with rectangular wooden pieces having a square cross-section of 6 mm × 6 mm and every spacing is 10 cm in distance. Figs. from (a) to (d) are photographed at the flood, where the amplitudes of the tidal range are $\eta_{10} = 4.9$ mm, 8.4 mm, 17.3 mm and 20.7 mm,

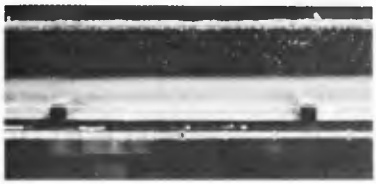

Figure 21(a).

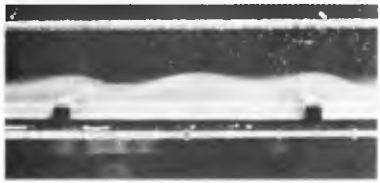

Figure 21(b).

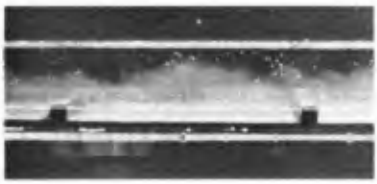

Figure 21(c).

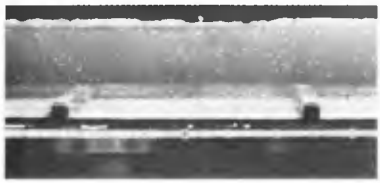

Figure 21(d).

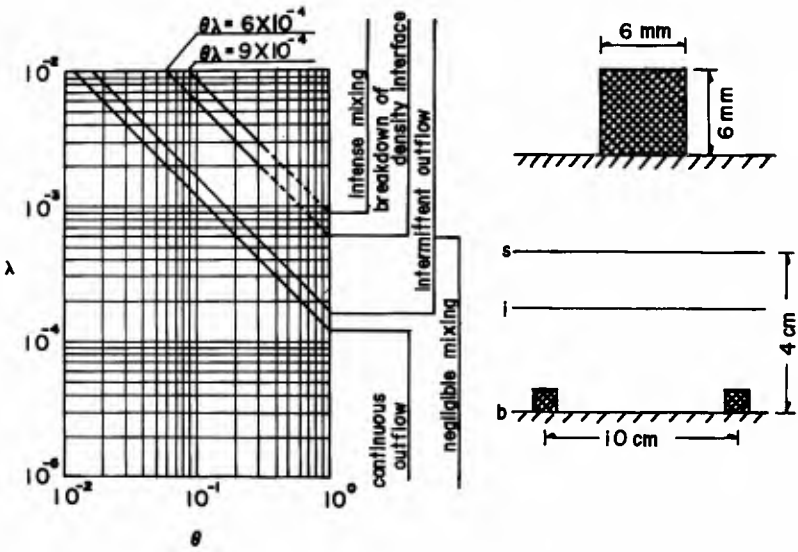

Figure 22.

respectively. The interface is distinct and straight horizontally in Fig. (a). Lee waves occur in Fig. (b), and the interface begins to break down in Fig. (c), in which many vortices produced behind wooden pieces move with the current, gradually growing and disturbing the interface, and finally break the interface in such a manner that vortices drags down the interface into themselves, and cause mixing of the two layers. A type of fully developed mixing is found in Fig. (d), which is that of the so-called intense mixing. In the case of Fig. (d), however, the interface has a trend to restore its original two-layer type at the ebb time. Therefore, in order to keep the intense type over the whole period, a larger amplitude is necessary.

As thus described, mixing is deeply dependent on the roughness of the channel and a strength of the tidal current. The degree of mixing is classified with two parameters λ and θ, which have already been used in the classifications of outflow pattern, as shown in Fig. 22. Although experiments are not so plentiful enough to derive the conclusion yet, within the limited range of values of θ, breaking of the interface occurs, when $\lambda\theta \geq 6 \times 10^{-4}$, and a transition to the intense mixing type is found, when $\lambda\theta \geq 9 \times 10^{-4}$. But the observational results in field are not so coincident with those values, that another new parameter should be introduced, instead of λ. According to field measurements, since the tidal current depends rather on a velocity of the external wave, than on the tidal period, another parameter such as $\lambda_u = KgA_o/C_gU_o$ was tried to take into account, but at present it is not successful. Unification of the results, both in field and experiment, by discovering a reasonable parameter, is an important problem for further study.

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