THE GENERATION OF INTERNAL SOLITARY DISTURBANCES BY GRAVITY CURRENTS IN A TWO-LAYER FLUID

HONJI, Hiroyuki
Research Institute for Applied Mechanics, Kyushu University : Professor

Kamachi, Masafumi
Department of Hydraulic Civil Engineering, Kyushu University : Graduate Student

https://doi.org/10.5109/6777113

出版情報：Reports of Research Institute for Applied Mechanics. 29 (91), pp.13-25, 1981-07. 九州大学応用力学研究所
バージョン：
権利関係：

Reports of Research Institute for Applied Mechanics
Vol. XXIX, No. 91, 1981

THE GENERATION OF INTERNAL SOLITARY DISTURBANCES BY GRAVITY CURRENTS IN A TWO-LAYER FLUID

By Hiroyuki HONJI* and Masafumi KAMACHI**

The generation of internal disturbances (solitary bulges and waves) by a gravity current entering a two-layered water has been investigated by means of flow visualization in a 2 m water tank. It has been observed that a gravity current evolves into a solitary internal bulge, which eventually leads to the generation of a solitary internal wave. The solitary wave was found to form more effectively when a gravity current head is forced to collapse at a mesh screen placed transversely to the flow direction.

Key words: Gravity currents, Two-layered water, Internal solitary bulges, Internal solitary waves, Flow visualization

1. Introduction

Many papers have been concerned with gravity currents and internal waves in the ocean. These are reviewed in several recent monographs[1)~7)] and review papers[8)~11)]. Gravity currents and internal waves seem to have been investigated rather separately, although both are closely connected with each other. As reported in a preceding paper[12)], for example, some sediment gravity currents on a sloping floor give rise to a characteristic internal wave of sediment material. The gravity current entering a two-layer fluid was recently investigated by Holyer and Huppert[13)]. Internal solitary waves, which have been investigated by many authors[14)~20)], also seem to have a close connection with the gravity currents.

This paper reports the results of experiments on the generation of solitary internal bulges and waves by a single gravity current entering a two-layer system of fresh and salt waters.

* Professor, Research Institute for Applied Mechanics, Kyushu University, Fukuoka 812, Japan.
** Graduate Student, Department of Hydraulic Civil Engineering, Kyushu University. Fukuoka 812, Japan.

2. Experimental methods

The experiments were carried out using a water tank illustrated schematically in Fig. 1. The tank made of acrylic resin was 200 cm long, 15 cm wide, and 25 cm high. The tank was equipped with a lock at one end of it as shown in Fig. 1; the flow direction length of the lock was less than 15 cm. The depth of the lower layer of salt water was between 5 and 11 cm, and the total depth of water was about 20 cm. Gravity currents were formed in the following way. A two-layer system of fresh and salt waters was first prepared without a gate of the lock. Then an acrylic-resin plate as the gate was submerged slowly, and the fresh and salt waters in the lock were mixed up fully. The locked water with an intermediate density was released by pulling up the gate quickly. Immediately after the opening of the gate, a bulk of turbulent water of the intermediate density rushed in the interface of the ambient two-layer water. As time went on, a gravity current with a head region formed and began to travel along the interface. The salt concentration in water ranged from 0.8 to 3.6 %, and the water temperature from 7 to 14°C.

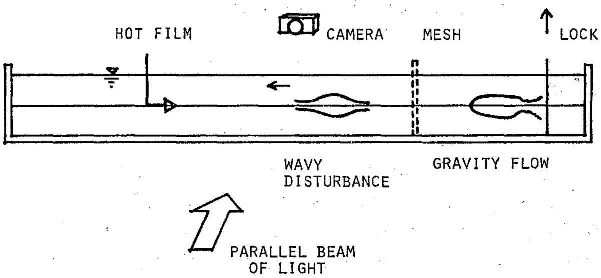


Fig. 1. Experimental apparatus.

An eight-fold mesh screen made of iron with a single square-mesh size of 0.2 × 0.2 cm, was used in some experiments to promote the transition from a gravity current head to a solitary wave. This screen was placed at a position about 60 cm distant from the lock gate. This distance was needed by the gravity current head to shape itself clearly.

Current and wave patterns were visualized by means of the methods of direct shadow and dye (methylene blue) injection. The visualized patterns were photographed with a camera which was at rest with respect to the tank. Velocity fluctuations were detected using a hot-film anemometer, and recorded by an oscillograph. A hot film probe of the anemometer was located at a position about 43 cm distant from one end of the tank, as in Fig. 1. The probe was made to point to the lock, and the velocity fluctuations were measured correctly only when some disturbances approached the probe from the direction of the lock.

3. Results

As described in §2, gravity currents were generated by releasing a salt water with an intermediate density at one end of the water tank. After releasing, a gravity current head traveled along the interface of a two-layered water. When the whole length of the tank was traveled, the head was reflected at a wall of the other side of the tank and began to retrace its steps. Thus the disturbance continued to travel by repeating the reflection at the tank walls until it died away. It was observed that the traveling disturbance changes gradually from a current head to a 'bulge',[5,16] which changes further into a solitary wave as time elapses; the bulge is here distinguished from the wave by the existence of an inside vortex pair. Such a process of changing from current to wave is displayed in Fig. 2, where t is the time passed after releasing the lock, and $\alpha=(\rho_2-\rho_1)/\rho_1$, ρ_1 and ρ_2 being the density of upper fresh water and that of lower salt water, respectively. The scale unit for all the presented pictures is cm.

Figure 3 shows the dependence of traveling speed V of a gravity current head on α of a layered water; V are normalized by the head speed V_0 at the smallest value of α. The head speed increases with the increase of α. A travel-time curve for a gravity current head is shown in Fig. 4, where X is the distance traveled by the head. A reflection point of the head is indicated by an arrow. The head speed de-

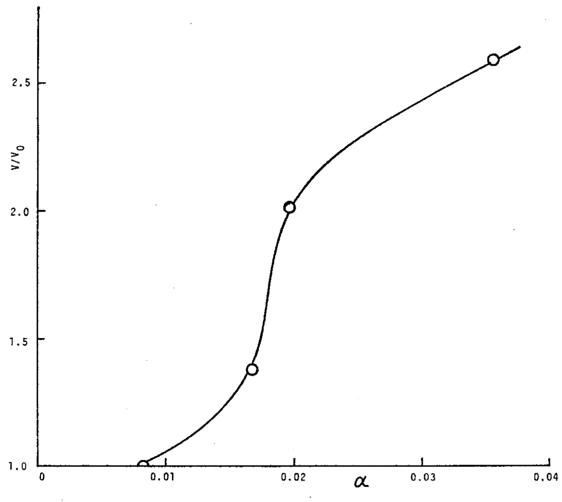


Fig. 3. Dependence of gravity current speed on water-density difference; volume of intruding water=1.5 *l*.

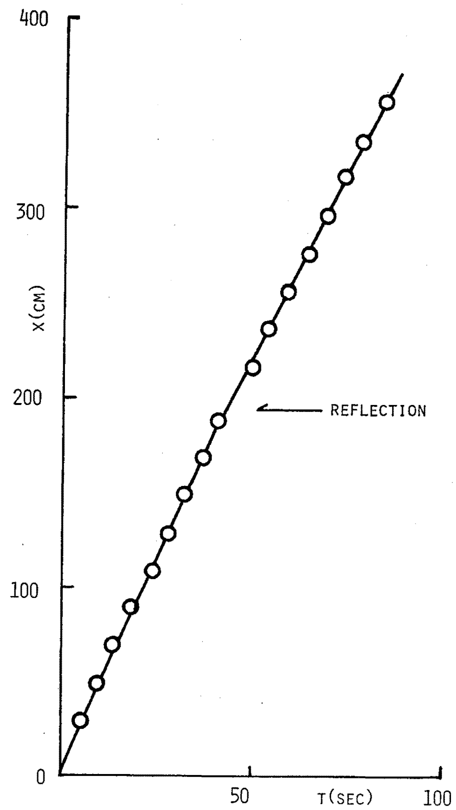


Fig. 4. Distance traveled by a gravity current head before and after its reflection at a tank wall. $\alpha=0.036$.

creases only slightly after the reflection.

A series of pictures, Fig. 5, shows the transfiguration of a rightward-moving current head when it collides with a similar leftward-moving head, which is not dyed however. Figure 5(a) shows the current head which is not much influenced by the other current approaching. The vertical thickness of the current increases abruptly when the two heads collide with each other, as seen from Figs. 5(b) and (c). The heads turn back after the head-on collision, but some mixing of both currents occurs as in Fig. 5(d).

The mixing of fresh and intruding currents takes place most actively at the rear of the head of a gravity current. This will be seen from a direct-shadow picture of Fig. 6, which is similar to the photographs obtained by J. E. Simpson (Holyer and Huppert[13]). Figure 7 shows a symmetrical bulge dyed with methylene blue ; the interfacial layer had been dyed by a preceding gravity current.

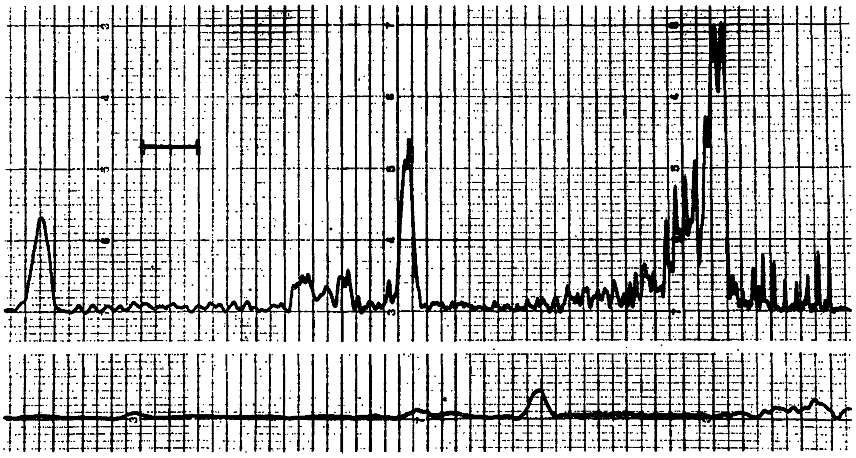


Fig. 10. Variation of out-put signals while a gravity current head continues to travel in the tank without the mesh screen; vertical scale is arbitrary. Time increases from right to left, and the lower trace continues from the upper. $\alpha=0.036$, Time scale=16 s.

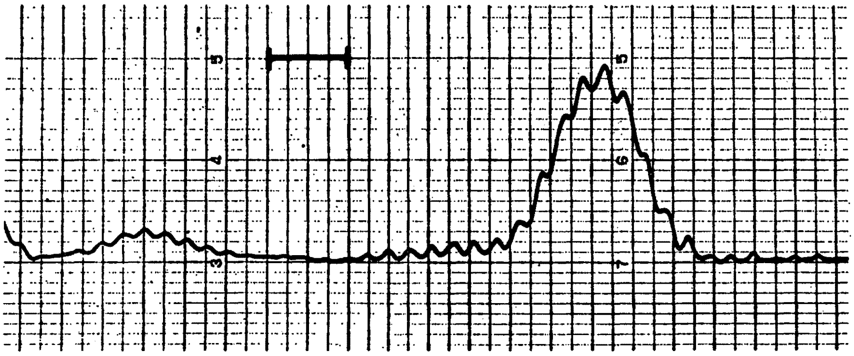


Fig. 11. Out-put signal from a bulge formed downstream of the mesh screen. $\alpha=0.036$, Time scale=4 s.

There is a possibility that the sudden interruption of mass transfer by a current head promotes the current to wave transition. In the present experiments, gravity heads were made to collapse at the mesh screen as described in §2. A solitary wave generated in this way is shown in Fig. 8, where an intrusion which has come through the screen and now died away is seen on the left side of the picture, and the wave traveling to the right is seen on the right.

In Figs. 9(a) to (h), a process of solitary wave generation around the screen is displayed in more detail. Figure 9(a) shows an undisturbed two-layer system with a transition layer, which was set up by a first gravity current. Figures 9(b) to (h) show the collision of a gravity current head with the screen, seen as a dark vertical thick line, and the generation of a solitary transitory bulge and a wave. In the last three pictures, the variation of a time line made visible with dye is shown. In Fig. 9(g), the time line is distorted considerably towards the traveling direction of the bulge, and indicates that the mass transfer is still dominant. Figure 9(h) shows the leftward-propagating disturbance after reflecting at a tank wall. The displacement of a new time line at the center of the picture is rather small, and the disturbance may be now regarded as a solitary 'wave'.

The process of solitary wave generation was observed by taking hot film oscillograms. A typical record taken when no mesh screen was emplyed is presented in Fig. 10. The largest spike in the upper trace shows the passage of a gravity current. As time goes on, the spikes decrease in height because of the reflection of the disturbance at the tank walls and its gradual dissipation. At later times, their waveforms are quite symmetrical indicating that the disturbance is a solitary wave rather than a current. It should be noted here that, as described in §2, the hot film probe was directed towards the lock, and so the velocity fluctuations were measured correctly only when the flow direction was from the lock to the probe; the measurements were made correctly around the spikes.

Figure 11 shows an oscillogram of hot film signals when the screen was employed. The largest spike in the oscillogram shows the passage of the first disturbance. The spike form is symmetrical though disturbed by small-scale ripples. This symmetrical form may also justify the fact that the transition from a gravity current head to a solitary wave is promoted by making the head collide with the screen.

A boundary gravity current under the interface of a two-layer water was visualized as shown in Fig. 12, where the current is traveling from left to right on a horizontal floor of the tank. As will be seen from the pictures, the interface is distorted as the front of the current travels, and this distortion continues to propagate as an internal wave even after the current itself has died away.

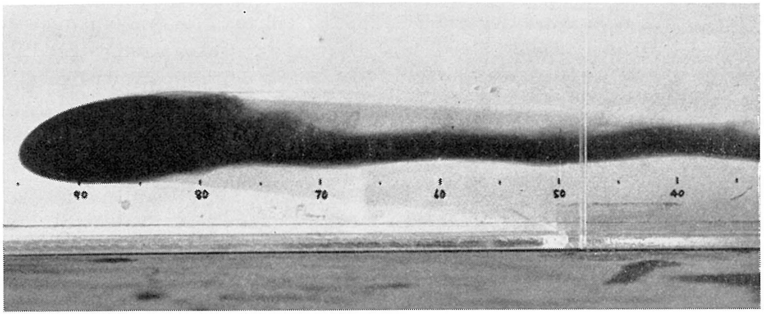
We would like to express our sincere thanks to Professors Y. Nakamura and T. Kambe for stimulating discussions. We are indebted to Dr A. Kaneko, N. Matsunaga, and Y. Shiraishi for useful suggestions and technical help. This work was supported by a Minisry of Education, Science, and Culture grant, which is gratefully acknowledged.

References

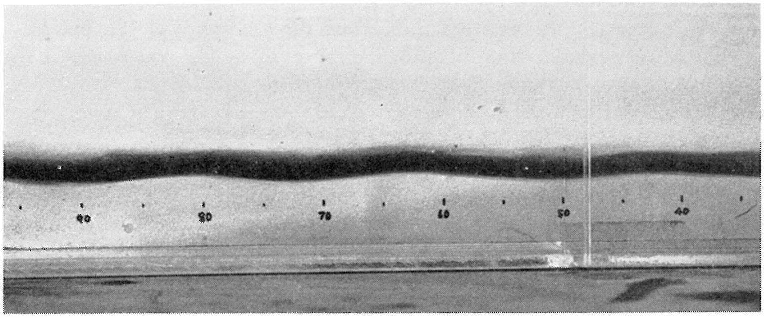
1) Krauss, W.: *Interne Wellen*, Gebruder Borntraeger, Berlin & Stuttgart, 1966.
2) Roberts, Jo: *Internal Gravity Waves in the Ocean*, Marcel Dekker, Inc., N. Y., 1975.

3) Tominaga, M.: *Kaiyo Hado*, Kyoritsu-Shuppan, Tokyo, 1976 (in Japanese).
4) Lighthill, J.: *Waves in Fluids*, Cambridge University Press, Cambridge, 1978.
5) Turner, J. S.: *Buoyancy Effects in Fluids*, Paperback edition, Cambridge University Press, Cambridge, 1979.
6) Phillips, O.M.: *The Dynamics of the Upper Ocean*, Paperback 2nd edition, Cambridge University Press, Cambridge, 1980.
7) Yih, C-S.: *Stratified Flows*, Academic Press, Inc., N. Y., 1980.
8) Thorpe, S. A.: Turbulence in stably stratified fluids: A review of laboratory experiments, Boundary-Layer Meteorology **5** (1973) 95–119.
9) Sherman, F. S., Imberger, J. and Corcos, G. M.: Turbulence and mixing in stably stratified waters, *Ann. Rev. Fluid Mech.* 1978, Vol. 10, pp. 267–288.
10) Garrett, C. and Munk, W.: Internal waves in the ocean, *Ann. Rev. Fluid Mech.* Vol. 11, 1979, pp. 339–369.
11) Miles, J. W.: Solitary waves, *Ann. Rev. Fluid Mech.* 1980, Vol. 12, pp. 11–43.
12) Honji, H.: Flow visualization of underwater avalanches, *International Symposium on Flow Visualization*, Bochum, Sept. 1980, Preprints, pp. 288–292.
13) Holyer, J. Y. and Huppert, H. E.: Gravity currents entering a two-layer fluid, J. Fluid Mech. **100** (1980) 739–767.
14) Peters, A. S. and Stoker, J. J.: Solitary waves in liquids having non-constant density, Comm. Pure and Appl. Math. **13** (1960) 115–164.
15) Benjamin, T. B.: Internal waves of permanent form in fluids of great depth, J. Fluid Mech. **29** (1967) 559–592.
16) Davis, R. E. and Acrivos, A.: Solitary internal waves in deep water, J. Fluid Mech. **29** (1967) 593–607.
17) Walker, L. R.: Interfacial solitary waves in a two-fluid medium, Phys. Fluids **16** (1973) 1796–1804.
18) Kao, T. W. and Pao, H. P.: Wake collapsse in the thermocline and internal solitary waves, J. Fluid Mech. **97** (1979) 115–127.
19) Pao, H. P. and Kao, T. W.: Internal solitary wave generation in the thermocline, *International Symposium on Flow Visualization*, Bochum, Sept. 1980, Preprints, pp. 272–276.
20) Maxworthy, T.: Non-linear dispersive waves in the laboratory and in nature, To appear in *Proceedings of Workshop on Non-linear Internal Waves*, S. I. O., La Jolla.

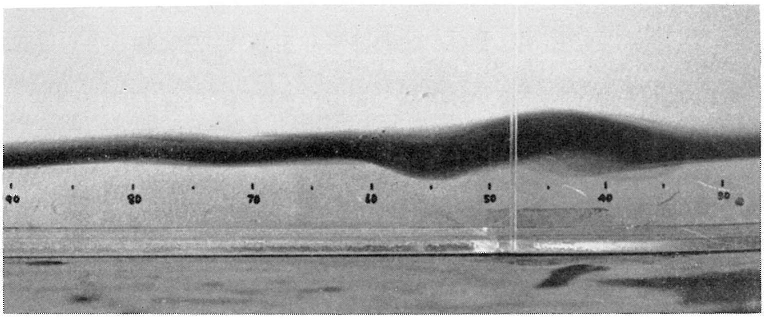
(Received April 25, 1981)



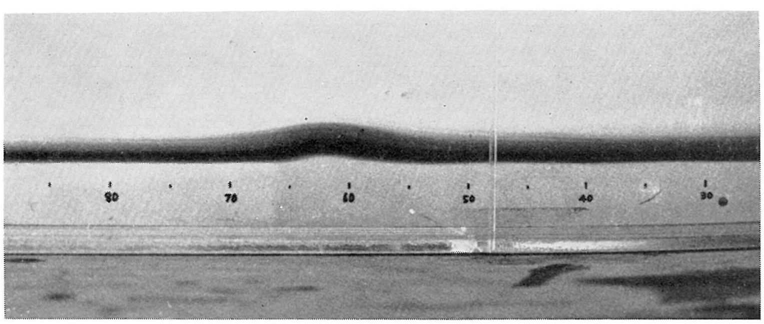
(a) $t=36$ s



(b) $t=47$ s

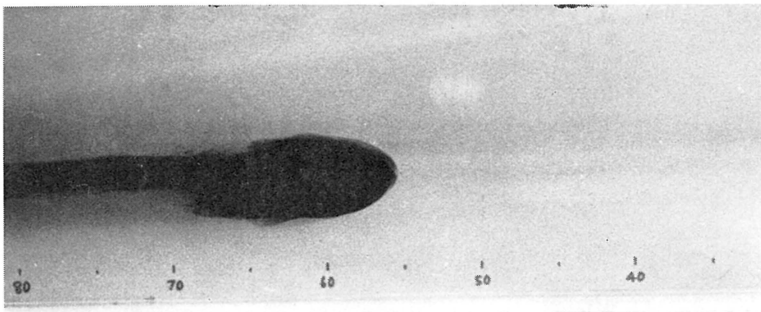


(c) $t=88$ s

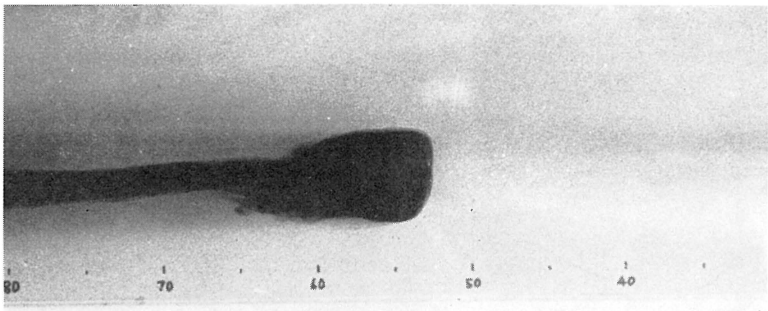


(d) $t=159$ s

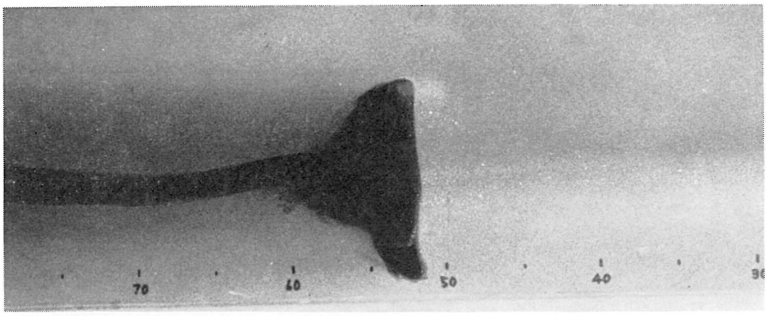
Fig. 2. Gravity current moving along the interface of a two-layer water. $\alpha=0.014$.



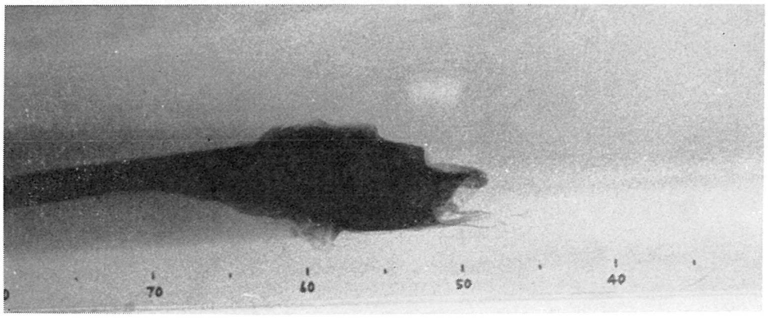
(a) $t = 33$ s



(b) $t = 34$ s



(c) $t = 37$ s



(d) $\alpha = 41$ s

Fig. 5. Head-on collision of gravity current heads at the center of the tank. $\alpha = 0.011$.

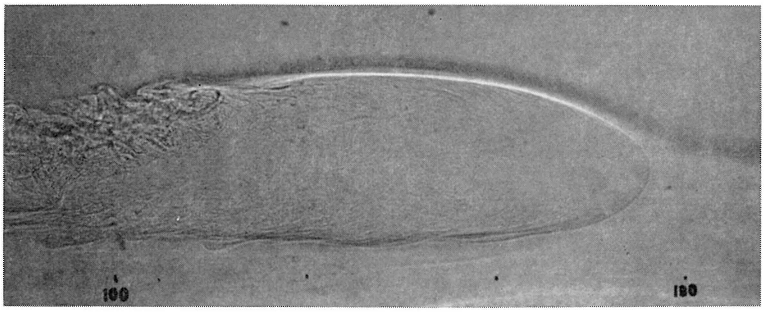


Fig. 6. A gravity current head visualized by the direct shadow. $\alpha=0.027$, $t=27$ s.

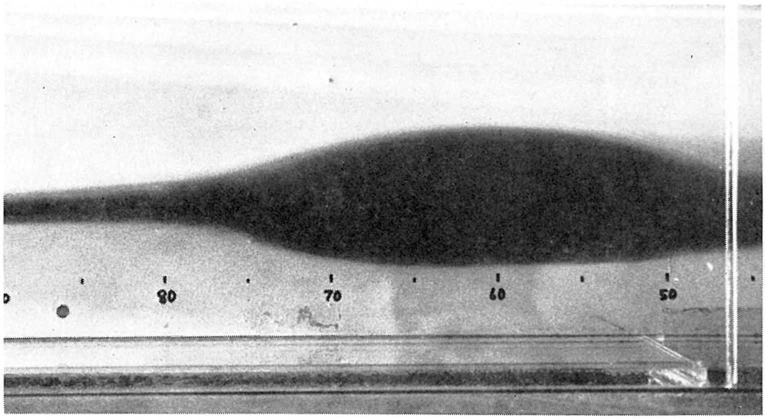


Fig. 7. A solitary bulge visualized with dye. $\alpha=0.012$, $t=34$ s.

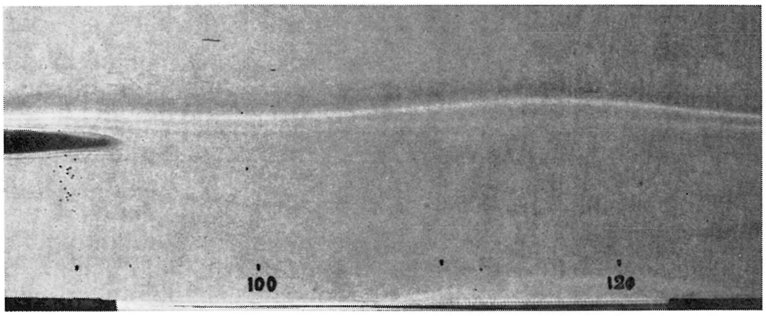
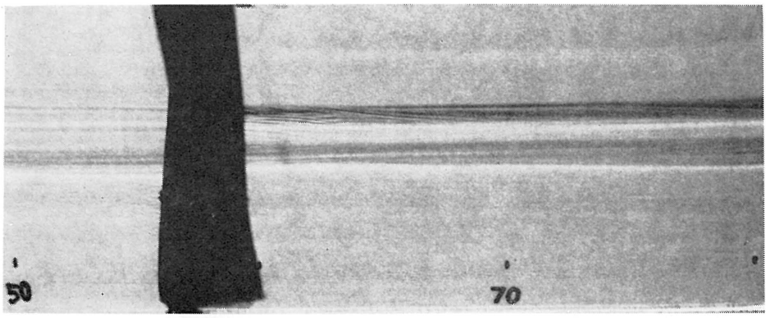
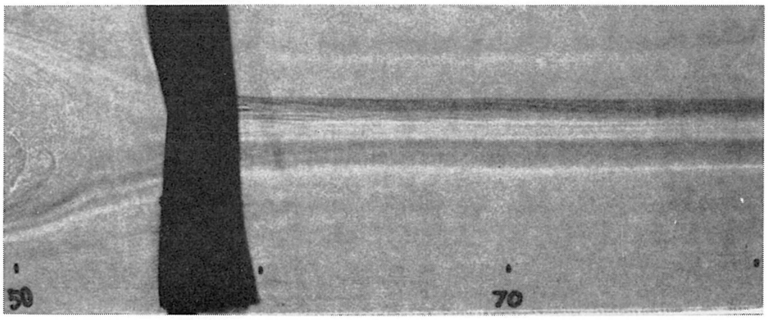


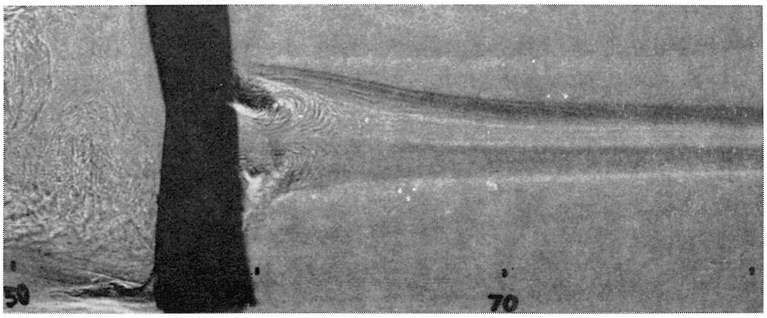
Fig. 8. Generation of a solitary bulge by an intrusion which has come through a mesh screen placed on the left. $\alpha=0.035$, $t=29$ s.



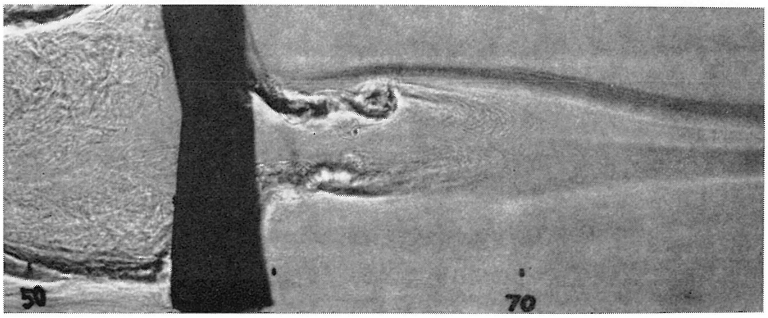
(a) $t=0$ s



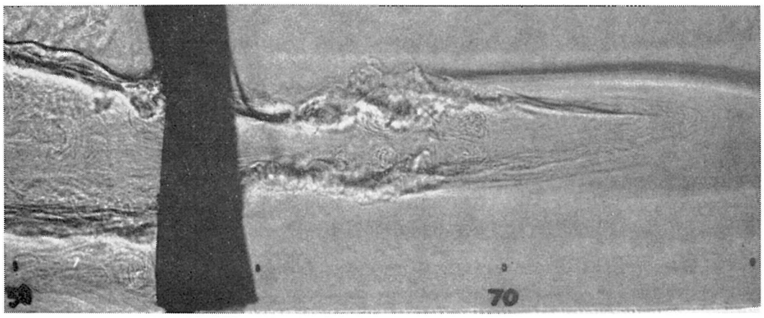
(b) $t=10$ s



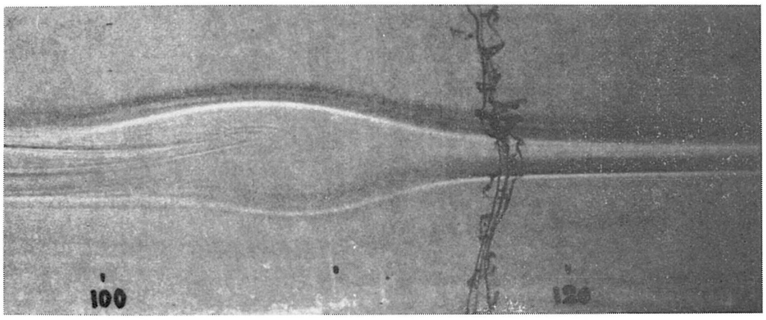
(c) $t=12$ s



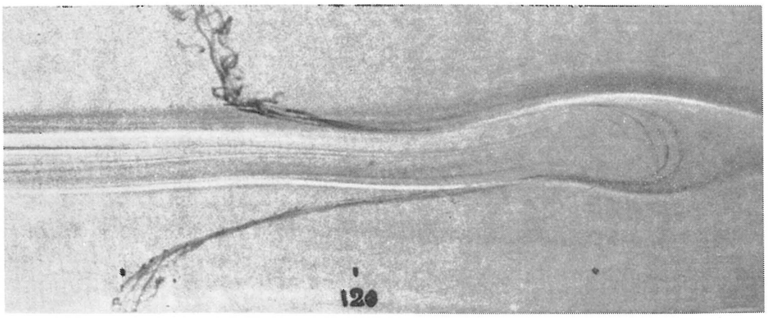
(d) $t=14$ s



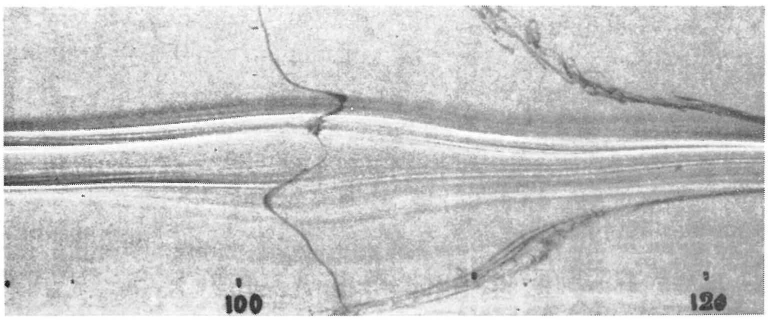
(e) $t=16$ s



(f) $t=23$ s

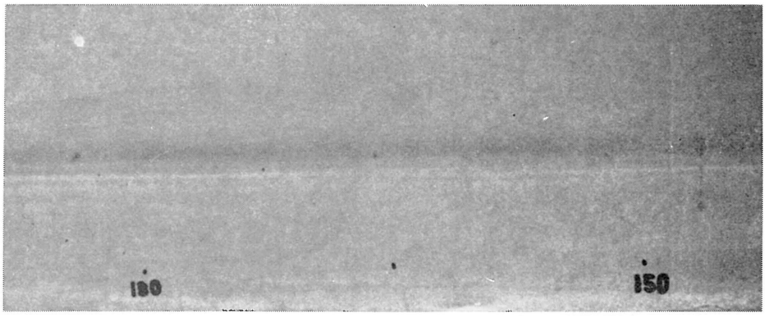


(g) $t=28$ s

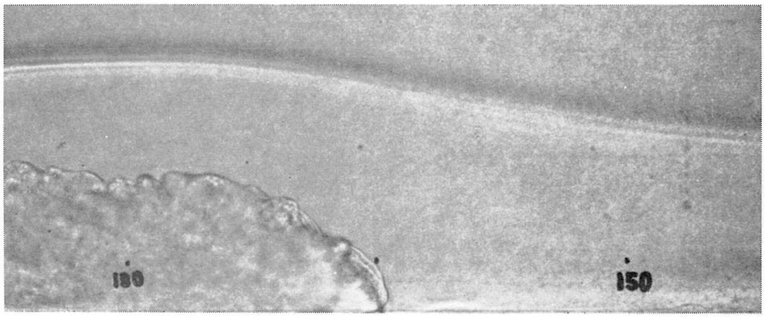


(h) $t=63$ s

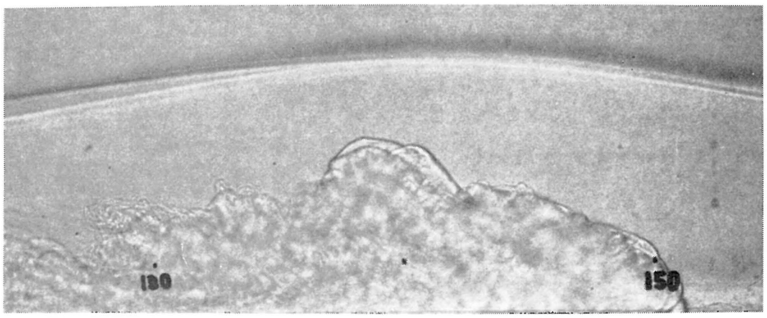
Fig. 9. Generation of a solitary bulge by a gravity current which has gone through the mesh screen. $\alpha=0.054$.



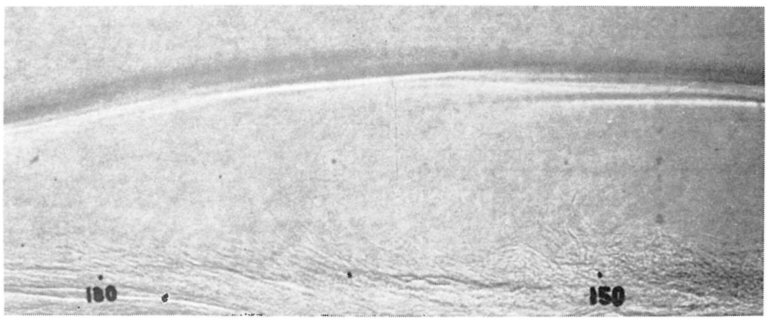
(a) $t=0$ s



(b) $t=10$ s



(c) $t=12$ s



(d) $t=25$ s

Fig. 12. Boundary gravity current and wavy deformation of the interface of fresh and salt waters. $\alpha=0.025$.