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PARTICLE WAVE FORMATION UNDER STANDING WATER WAVES

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The 'particle waves' of glass and polystyrene beads form under standing water waves in a wave tank. The ridges of particle waves tend to form below the nodes of the water waves. No particle waves form when polystyrene beads are made buoyant by introducing a salt water into the bottom layer of water in the tank.

Key words: Particle waves, Standing waves, Water waves

1. Introduction

The motion of solid particles in oscillatory fluid flow has been investigated extensively in connection with the problem of sounding air in a Kundt tube. As is well known, this tube contains air and some fine powder which lumps at the nodes of a vibrating column of air visualizing the length of a standing wave in the tube.

Rayleigh[1,2] made a theoretical investigation of this phenomenon, and later Andrade[3] carried out a detailed experimental study on the behavior of solid particles in the air in a sounding tube. Bagnold[4] investigated the motion of sand grains in oscillatory water motion and observed that they form the rolling grain ripples. Since then the motion of solid particles in oscillatory flow has been a notable subject of sedimentological and hydrological research of our natural environments. Kaneko and Honji[5,6] have studied the formation of 'particle waves', which are the rhythmic pattern of solid particles forming on the bottom floor of an oscillatory-water tank.

It is well known that an oscillatory water motion is set up when a surface wave of stationary type forms in a wave tank; the water particles below the wave nodes move horizontally and those below the loops vertically.

In the presence of such a standing water wave, solid particles scattered on

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the bottom floor of the tank form particle waves or ripple marks. In this paper are reported the results of an experimental study on the particle wave formation in a wave tank.

2. Experimental methods

The experiments were carried out using a wave tank 2 m long, 15 cm wide, and 25 cm deep, which is illustrated in Fig.1. Standing water waves were generated by a motor-driven flap-type wave generator. The frequency, amplitude, and wavelength of a standing wave motion were 1.6 Hz, 1.8 cm, and 30 cm, respectively. The depth of water in the tank was 18 cm, and the kinematic viscosity of water about 0.0135 cm^2/s. Exceptions to these values are the data for Fig.4, which were observed only once by using another wave tank 50 cm wide.

Mainly polystyrene beads of 1.5 mm in mean diameter were used as working particles, which were only slightly heavier than water. These beads were scattered on the bottom floor of the tank or made buoyant and suspended above it by introducing a salt solution into the lower layer of water in the tank. Glass beads of 1.05 mm in mean diameter were also used partly; all glass beads were settled on the bottom floor of the tank. Scattered beads were illuminated by a 1 KW flood lamp from above, and photographed with a 35 mm camera located above the tank.

3. Results

A process of particle wave formation in a homogeneous water in the wave tank is demonstrated in Fig.2; t is the time passed after the start of a wave motion of water. Figure 2(a) shows the polystyrene beads scattered sparsely on the rigid plane floor of the tank before disturbed by the wave motion. Two black squares marked on the upper side of each picture indicate the position of loops of the standing water wave.

Figure 2(b) shows a regular particle-wave pattern where the ridges run transversely to the right and left direction of water oscillation. A similar particle-

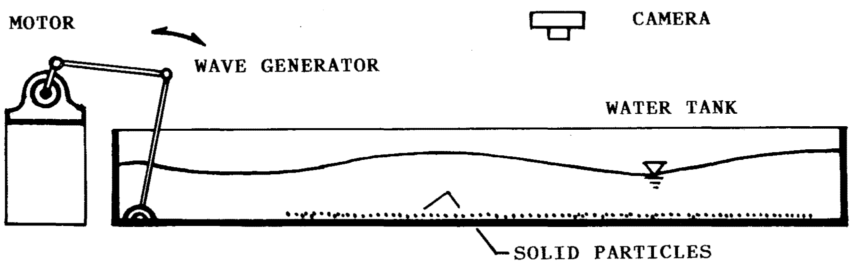
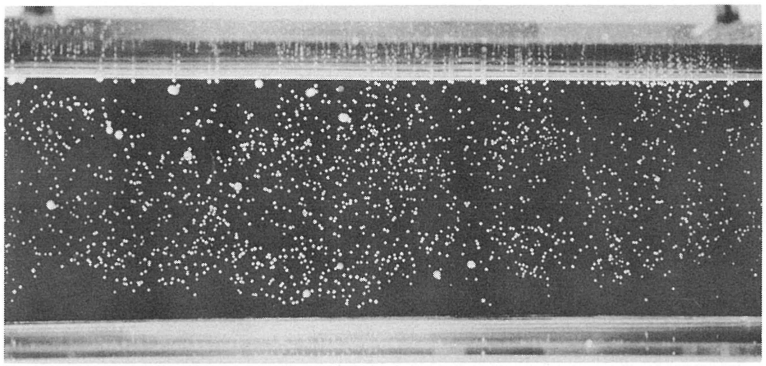
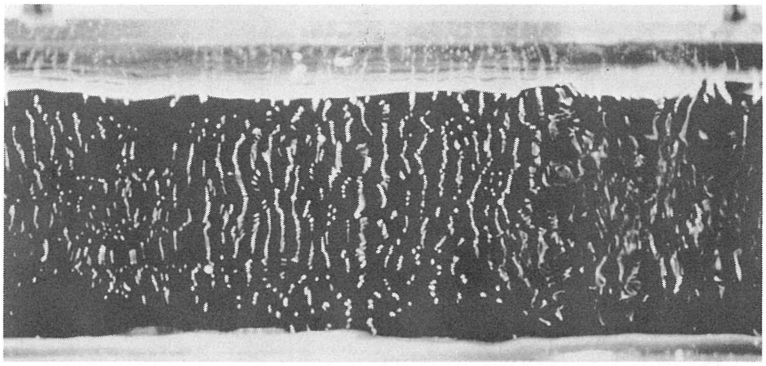


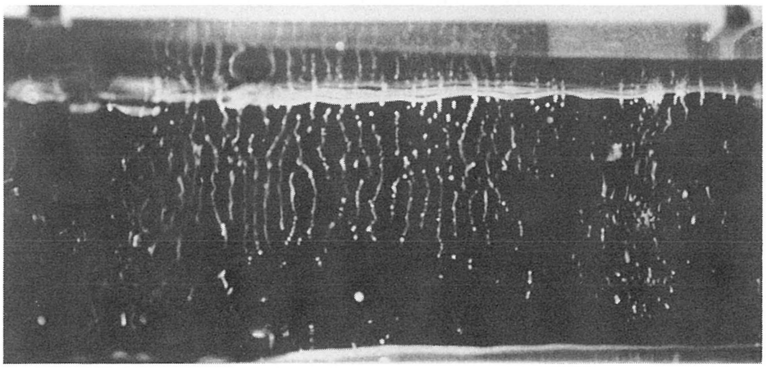
Fig.1. Experimental apparatus



(a) t = 0 s

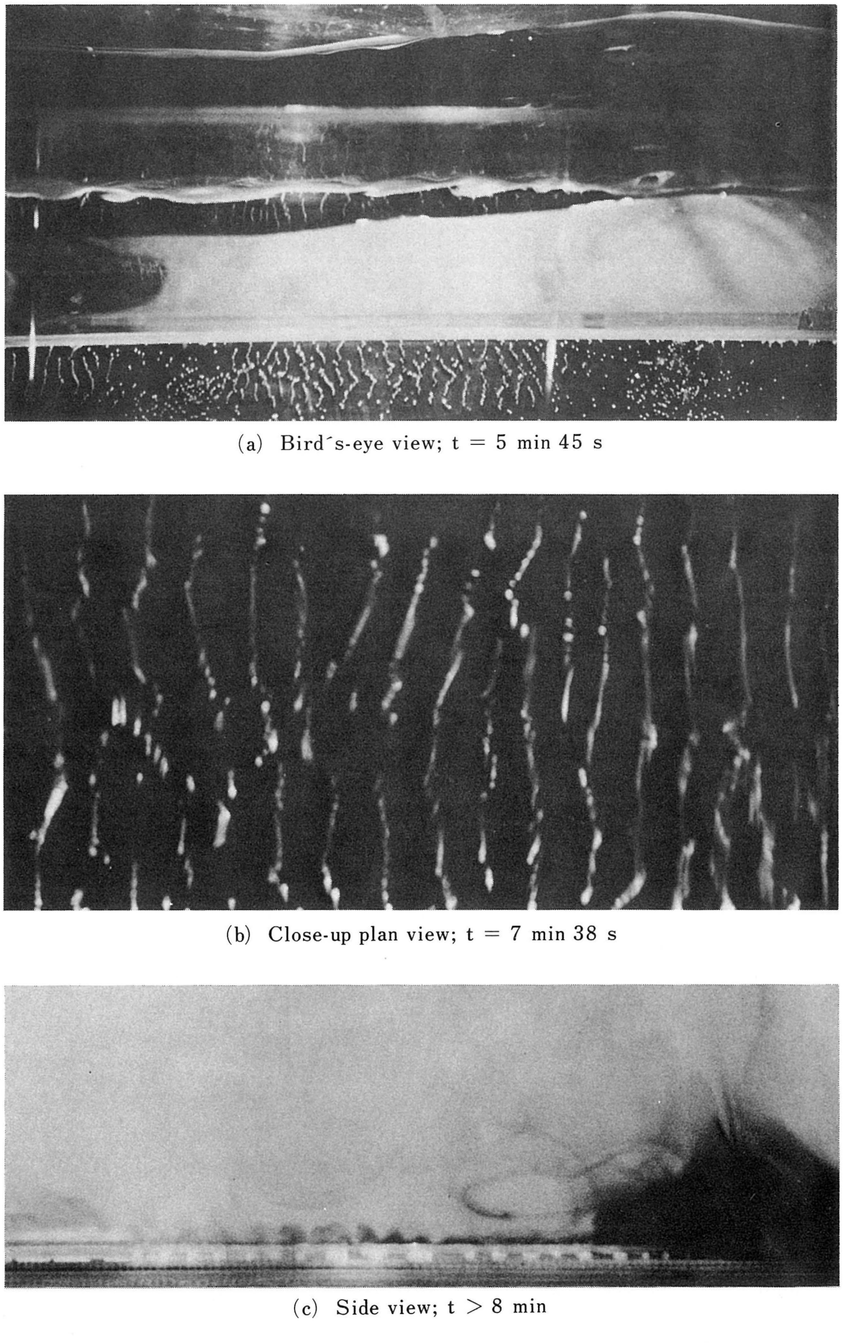


(b) t = 1 min 26 s



(c) t = 6 min 50 s

Fig. 2. Formation of a particle wave; plan views.



(a) Bird´s-eye view; t = 5 min 45 s

(b) Close-up plan view; t = 7 min 38 s

(c) Side view; t > 8 min

Fig.3. Three different views of the particle wave shown in Fig.2.

wave pattern at a fairly later time is shown in Fig. 2(c), where a group of particle-wave ridges is seen only around the node (the center of the picture) of the standing water wave. This picture indicates that particle waves tend to form below the wave nodes where the horizontal water motion is most vigorous. Below the wave loops, some particles continue to remain around their original positions without forming any regular particle patterns. The direction of water oscillation in all the pictures presented in this paper is right and left except Fig. 4.

Other three views of the particle wave shown in Fig. 2 are demonstrated in Fig. 3. Figure 3(a) shows a bird's-eye view of the particle and standing water waves. As mentioned above, the particle-wave ridges are seen only below the node of the water wave, indicated by an instantaneoue profile of the upper surface of the water. Figure 3 (b) shows the particle wave in a magnified scale; the mean wavelength is about 1 cm. A side view of the particle wave is shown in Fig. 3(c), where dye shows that a regular vortical streaming is induced around every particle wave ridge. This type of streaming may be responsible for determining directly the small scale wavelength of particle waves, although the large scale structure as a group of particle-wave ridges is determined directly by the wavelength of a standing water wave given externally. A detailed study of such an induced streaming is the subject of a preceding paper[8)].

Figure 4 shows a broad tank viewed slightly obliquely from above. A glycerin-water solution with the kinematic viscosity of 0.41 cm^2/s was used as a working fluid in this case. The frequency, amplitude, and wavelength of a standing wave motion were 1.4 Hz, 1.2 cm, and 52 cm, respectively. Two horizontal straight lines are the ridges of a particle wave of glass beads settled on the bottom floor of the tank. Above them are seen two vortical streamings visualized with tiny air bubbles; they are visualized only along the left side wall of the tank, similar

Fig. 4. Plan view of induced streaming and a particle wave formed on the bottom floor of a water tank 50 cm wide. $\nu = 0.41\ cm^2/s$.

streamings along the right side wall being incidentally disturbed. The formation of this type of streaming in standing water waves has been investigated in detail, and another paper[9] is devoted to this subject. Figure 4 indicates that a group of particle wave ridges becomes to span the whole width of a tank as a single straight ridge, when the tank is wide enough.

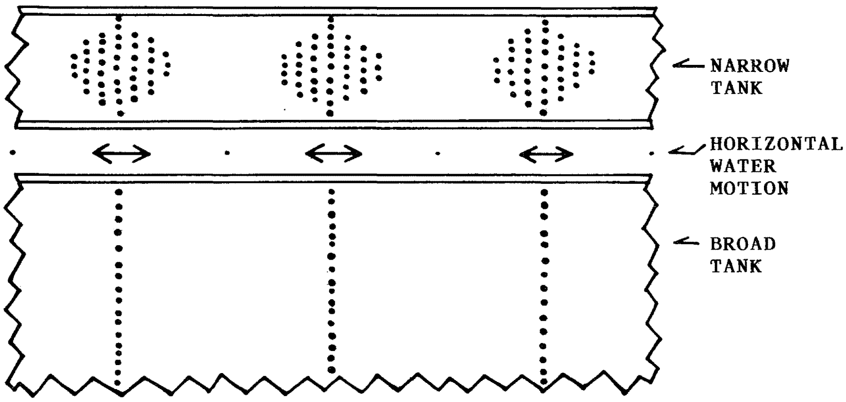


Fig.5. Schematic diagram of the relationship between standing water and particle waves.

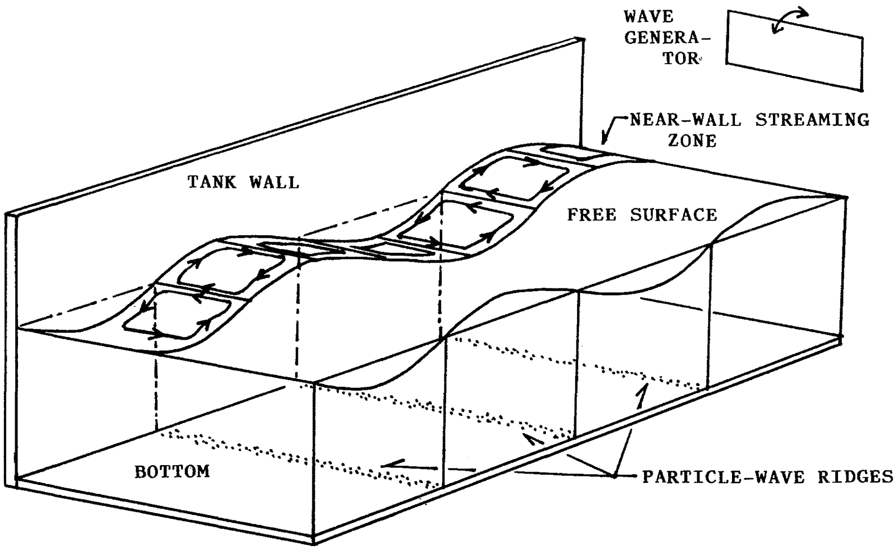


Fig.6. Bird's-eye view diagram of streamings, standing water wave and particle wave ridges in a broad tank.

This feature is illustrated schematically in a plan view of particle wave ridges in Fig.5, which may be almost self-explanatory. Not too many particles make a group of particle wave ridges as illustrated in the upper figure in Fig.5. Thus the ridges are most stable when they are just below the wave nodes. If the width of a wave tank is much narrower, its bottom floor may be occupied wholly by particle wave ridges. Therefore, `narrowness´ of a tank naturally depends on the number of particles scattered on the floor of that tank.

A schematic diagram of Fig.6 summarizes the whole system of a standing water wave, induced streaming in it, and particle waves on the bottom floor of a sufficiently broad wave tank. Particle wave ridges form below the nodes of the surface wave as described above. The near-wall streaming is induced due to the formation of oscillatory boundary layers on the walls of the tank. The direction of streaming is indicated by arrows in the figure. The streaming forms in the water as well as on the free surface of it, although the streaming attenuates downwards. The streaming has much in common with the so called acoustic streaming in Kundt tubes. Some computational results concerning the streaming are presented in a preceding paper[9].

We are here concerned with the case in which the lower layer of water is stratified with salt solution to make polystyrene beads slightly buoyant. Figure 7 shows a section of the bottom floor of the tank viewed obliquely from above, where $\triangle\rho/\rho_0$ is the fractional density difference between the upper thick layer of fresh water, whose density is ρ_0, and the lower thin layer of salt water. Polystyrene beads were suspended randomly about 1 cm above the floor surface by introducing the salt solution, and a standing wave was set up in the tank. They did not, however, form any regular patterns, while heavier glass beads rolling on the floor surface formed a regular particle-wave pattern. This indicates that the floor as a rigid boundary plays an essential role in forming particle

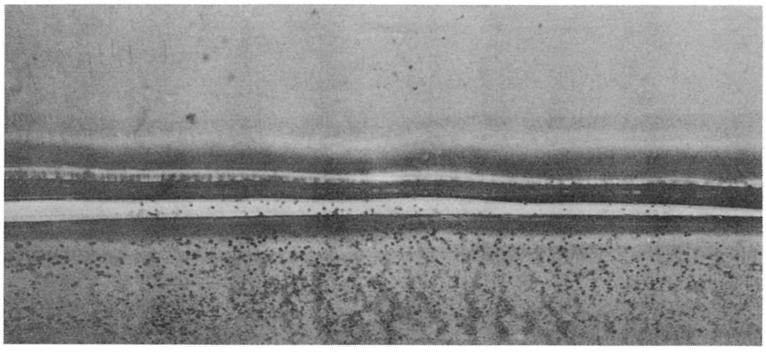
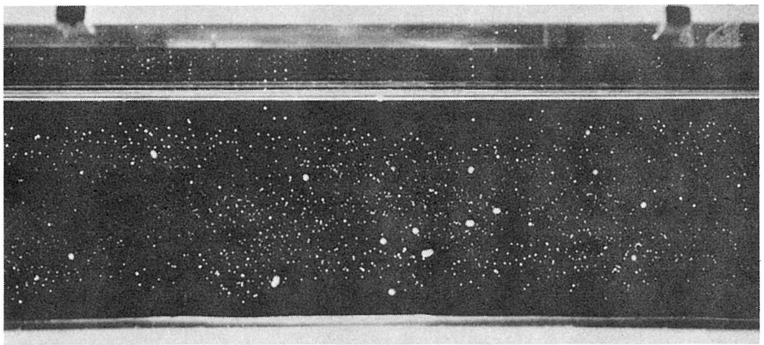


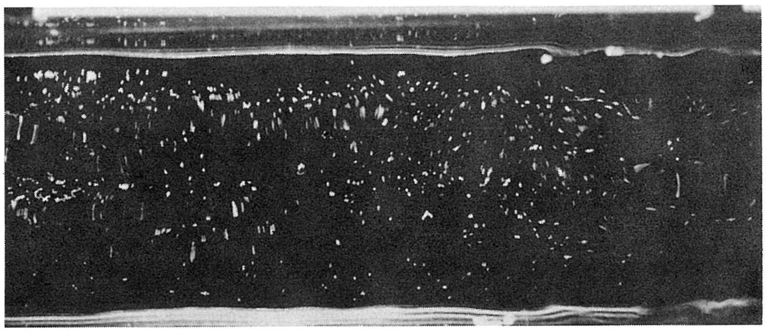
Fig.7. Randomly suspended polystyrene beads above the bottom floor and a particle wave of glass beads on the bottom floor. $t > 10$ min, $\triangle\rho/\rho_0 < 0.05$.

waves. Kaneko and Honji[7] suggested that some combination of attractive and repulsive fluid forces acting on two nearby particles must be considered. The result shown in Fig.7 may indicate that such a combination of the fluid forces can be achieved well by the presence of a rigid floor surface.

Figure 8 shows a similar feature that suspended polystyrene beads cannot form particle waves. The polystyrene beads were initially suspended in a layer of water slightly above the floor surface of the tank, as shown in Fig.8(a). The oscillatory motion of water continued for a fairly long time, but no regular pattern of the particles formed as shown in Fig.8(b).

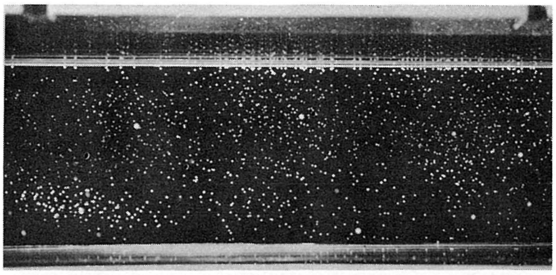


(a) t = 0 s

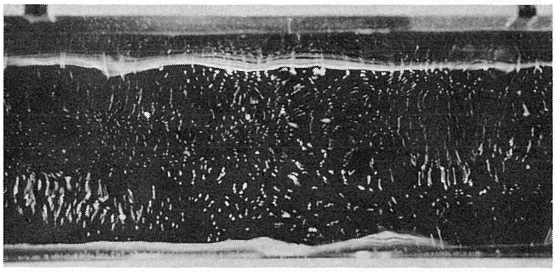


(b) t = 25 min

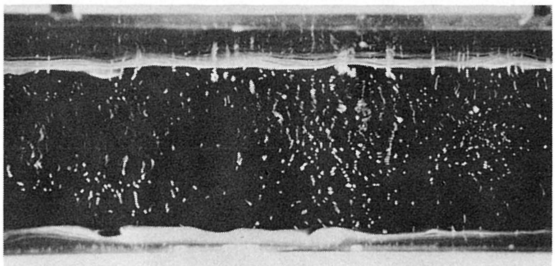
Fig.8. No particle-wave formation for polystyrene beads suspended about 0.5 cm above the floor surface. $\triangle\rho/\rho_0 = 0.026$.



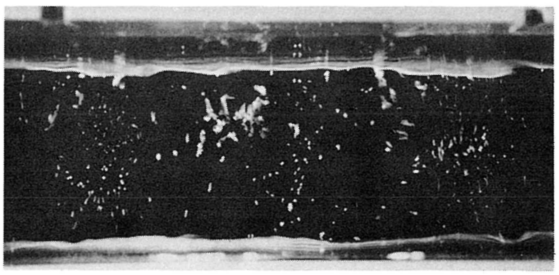
(a) t = 0 s



(b) t = 14 s

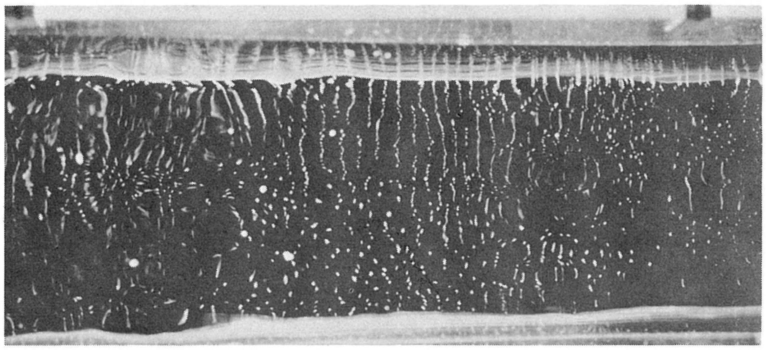


(c) t = 3.5 min

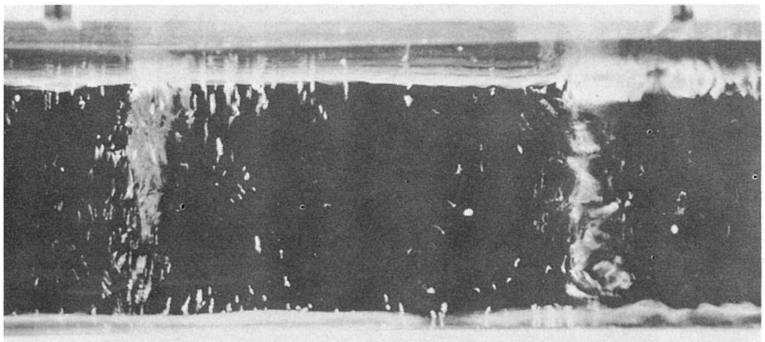


(d) t = 10 mmin

Fig.9. Particle wave formation at a critical value of density difference $\triangle\rho/\rho_o = 0.009$.



(a) t = 42 s



(b) t = 6 min

Fig.10. Particle wave formation with a slow unidirectional gravity flow of salt solution.

Figure 9 shows a process of particle wave formation at a critical value of $\triangle\rho/\rho_O$, above which no particle waves form. Polystyrene beads were almost rolling on the floor surface of the tank because of very slight salt concentration. As in Fig.2, the wave loops are indicated by two squares on the upper wall. Figure 9(a) shows an initial random distribution of the polystyrene beads on the bottom floor of the tank. Figures 9(b) and (c) show the particle patterns at intermediate stages of particle wave formation, and Fig.9(d) shows a pattern at an almost equilibrium stage of it. From Fig.9(d) it will be seen that some polystyrene particles are collected below the node of the standing wave, and other particles remain to be below the loops of it. However, even at this value of $\triangle\rho/\rho_O$, no clear ridges of the particle wave formed.

When a salt solution was introduced during the formation of a particle wave, a different type of the particle wave formed as shown in Fig.10. Figure 10(a) shows a particle wave before a unidirectional flow of the salt solution disturbs it, and Fig.10(b) shows a particle pattern formed after that flow has gone over the initial particle wave. By contrast, the ridges of this particle pattern formed below the loops of the standing water wave as shown in Fig.10(b); upper two squares indicate the position of the wave loops. Perhaps the particle pattern shown in Fig.10(b) was made up because the initial particle wave ridges below the wave nodes were wiped out by the unidirectional flow and piled up below the wave loops. These ridges shown in Fig.10(b) remained unchanged below the wave loops.

In conclusion, particle waves form under a standing water wave in a tank and their ridges generally tend to be collected below the node of the water wave. When solid particles are made buoyant by introducfng a salt solution into the lower layer of water, no regular particle waves form and the particle patterns remain irregular. This indicates that the presence of a rigid floor plays an essential role in the formation of particle waves.

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