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Anomalous Behavior of a Liquid-Particle System with Horizontal Vibration

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Abstract. Large scale collective motions of a liquid-particle system filled in a thin container were observed in the case where the container was given a horizontal vibration. Two kinds of particles with different diameters were used, and both densities of which were slightly larger than the liquid density. The particles showed large scale eddy motions with the size of the container, and the senses of rotation were almost determined by the position of the vibrator. When the vibrator was fixed at the right (left) side, the particles moved anti-clockwise (clockwise). Discussion is given on the mechanism of sustaining eddy motion and the choice of sense of rotation.

1. Introduction

Collective motion of liquid-particle systems within a vibrating container has been an interesting topic of research, since it is closely connected with the fluidization of the earth at earthquakes (YOSHIMI, 1991; OKA, 2001). In the most of past studies, however, small particles were packed three-dimensionally in a container, and behavior of whole particle system was observed but not individual particles. Moreover, particles with equal sizes were used.

In order to analyze the mechanism of fluidization precisely, motions of individual particles should be also observed in addition to collective motions. This is the motivation of the present study. Since motions of individual particles cannot be observed if they are packed three-dimensionally, the present authors chose a method to fill the particles in a thin container with clearance slightly larger than the particle diameter, so that they were arranged in one layer. The container was given a horizontal vibration by a vibrator. Although particle motions in this case were different from those in three-dimensional packing, this method would give us the first stage of understanding the fluidization of the quasi-two dimensional system.

The purpose of this paper is to report on an interesting behavior of a liquid-particle system which was found during an experiment of its fluidization. Precise analysis of this behavior is not yet done, but some discussions are made at the end of this paper. A

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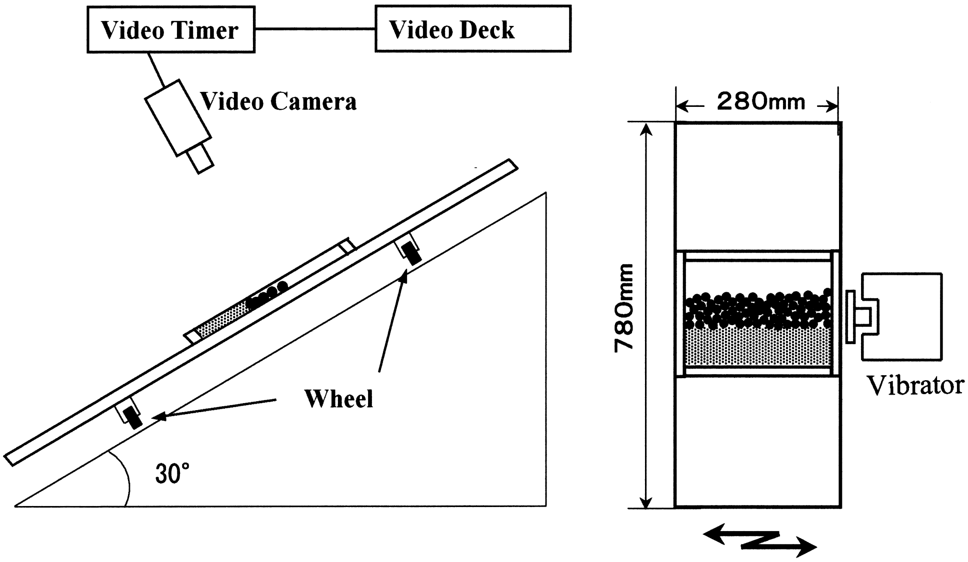

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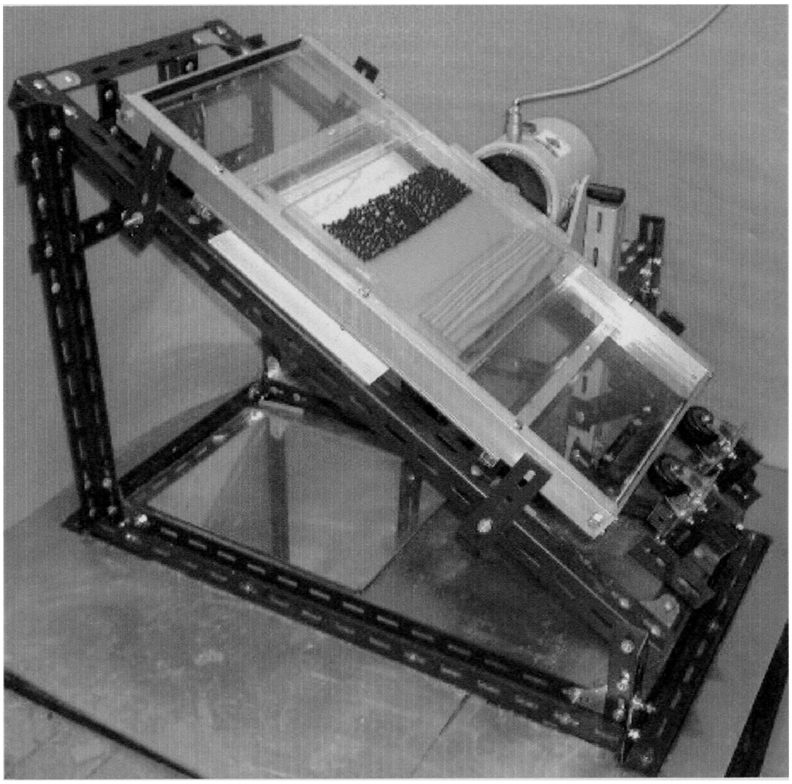

Fig. 1. Experimental setup. (a) Sketch of the setup, (b) Photograph of the main part of the apparatus.

preliminary report was made in the Symposium at the Research Institute for Mathematical Sciences, Kyoto University (KAWAKITA *et al.*, 2000).

2. Experimental Apparatus

Sketch of the whole experimental setup is shown in Fig. 1 with a photograph of its main part. A container of acrylic resin, with inner size 270 × 210 × 7 mm, was fixed on an aluminum frame, where the larger face of the container was inclined with angle 30 degree from the horizontal plane. The frame had four wheels and it was placed on iron rails, so that the frame could move smoothly in the horizontal direction. The frame was given a horizontal vibration by the use of a vibrator (EMIC, 512-A). The type of vibration was almost exactly sinusoidal. Initial phase of the motion of vibrator was so fixed that the rod started to move outwards when the vibrator was switched on (this initial phase will become a point of discussion in Sec. 4). Amplitude of vibration could not be controlled independently from the frequency; for example, the amplitude was automatically fixed at 0.4 mm for the frequency of 30 Hz.

Two kinds of plastic particles were used, one with diameter 6.0 mm and density 1.06 g/cm^3 (called larger particles), and the other with diameter 1.0 mm and density 1.03 g/cm^3 (called smaller particles).

The inclination of the container was given in order to reduce the effect of gravity on the particles, because the vibrator did not have enough power to cause strong fluidization. In order to avoid confusion, the narrow bottom of the container is called a lower boundary, and particle configurations and motions are described as if they were observed from the direction perpendicular to the larger face of the container.

As initial conditions the two kinds of particles were filled separately in the container with the water, so that they formed two horizontal layers. Both heights of the layers were 70 mm and the water was filled to the upper boundary, as is shown in Fig. 2.

The vibrator was switched on at a certain instant and behavior of the liquid-particle system was recorded by a video camera (VICTOR, GP-33) from the direction perpendicular to the container face.

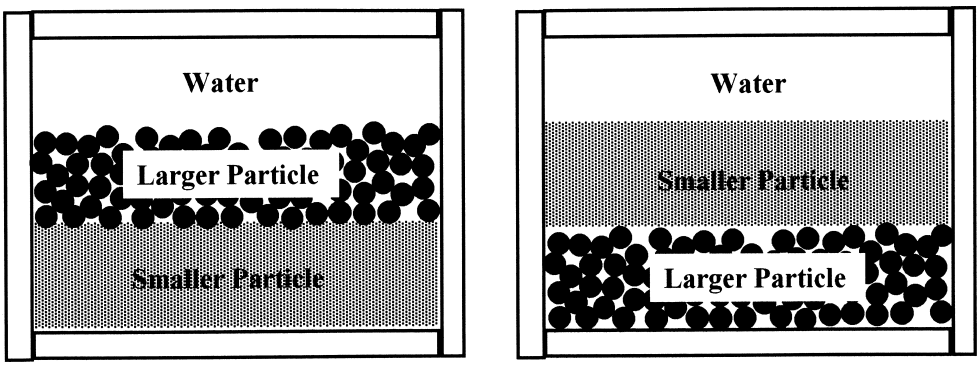

Fig. 2. Configurations of particle layers.

3. Results of Observation

3.1. Preliminary experiments

A preliminary experiment was made using only larger particles, where the particles showed no eddy motion. Particles remained in a closely packed state and showed no motion relative to the container wall. Another experiment using only smaller particles was also made, where the particles made a rather complicated collective motion. This case was not studied further, and is left for future work.

When two kinds of particles were used, larger particles were seen to make a large scale eddy motion as shown in Figs. 3 and 4, respectively, for two cases with opposite orders of the two layers. Here, the term "eddy" is used to indicate a collective motion of particles in a relatively large region with fixed sense of rotation. Note that smaller particles moved also, but they were not visualized. In the case where larger particles were placed below smaller ones, part of the larger particles near to the right boundary were seen to go up and penetrate into the above layer. They formed a small eddy motion, which later developed to a large scale eddy motion in anti-clockwise sense (the sense of rotation was confirmed from the video movie). The sense of rotation seemed to be governed by the position of the initial rise of larger particles. On the contrary, when larger particles were placed above the smaller ones, part of the larger particles near to the central part were seen to dive into the layer below to form an eddy motion also in anti-clockwise sense.

After these collective motions were established, the behavior of the liquid-particle system did not show further remarkable change. Two groups of larger particles on the right and left parts of the container remained at rest with nearly close packing condition.

Dependence of particle behavior on the frequency of vibrator was examined for both cases of the order of layers. It was found that the vibration with frequency 30 Hz was most effective in fluidizing the particle system. Therefore, the frequency was fixed at 30 Hz in the following experiments.

An experiment was also made by the use of smaller particles and a salt solution with the same density as the particles. In this case particles were floating in neutrally buoyant condition (without touching at the lower boundary), and they did not show eddy motion even if the container was given vibration for long time.

3.2. Effect of position of the vibrator

Among some results in the preliminary experiments the sense of rotation would be the most interesting one. Since there was a possibility that the sense of rotation depended on the position of the vibrator (the right or the left side of the container), eddy motions of particles were observed for four cases according to the position of the vibrator (the right or left) and the order of two layers, as shown schematically in Fig. 5. Five experimental runs were made for each case, and results of observation are shown in Fig. 6.

As is indicated in this figure, collective motions with two opposite eddies were observed in some fraction of runs. However, when one eddy motions appeared, they had mostly the fixed sense of rotation as mentioned above. Therefore, one can say that the reproducibility of the fixed sense of rotation was roughly confirmed. In order to make a stronger assertion more number of experimental runs are necessary, which will be made in future.

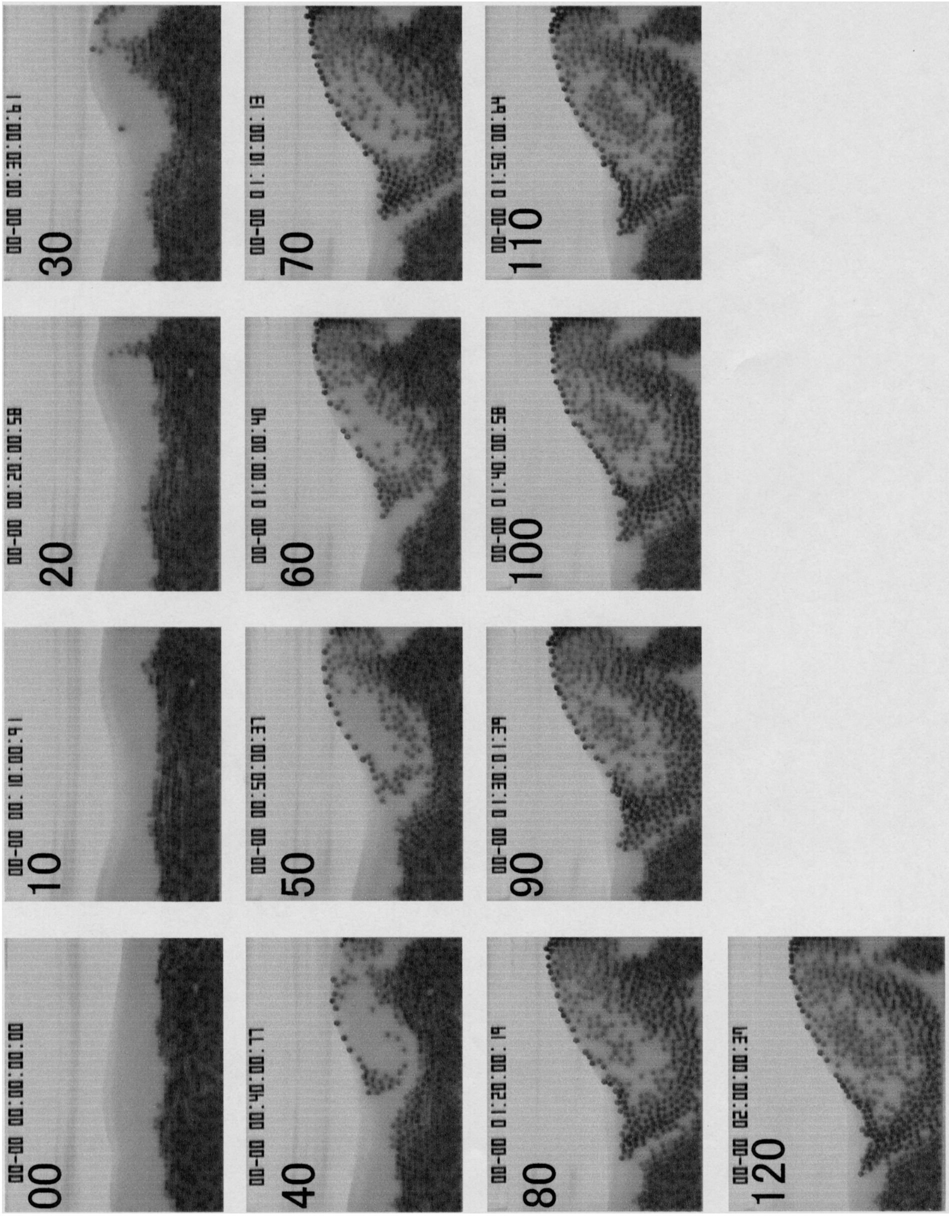

Fig. 3. Results of observation for the case where larger particles were initially placed below smaller ones. Numbers in frames indicate the time (min) after beginning of vibration.

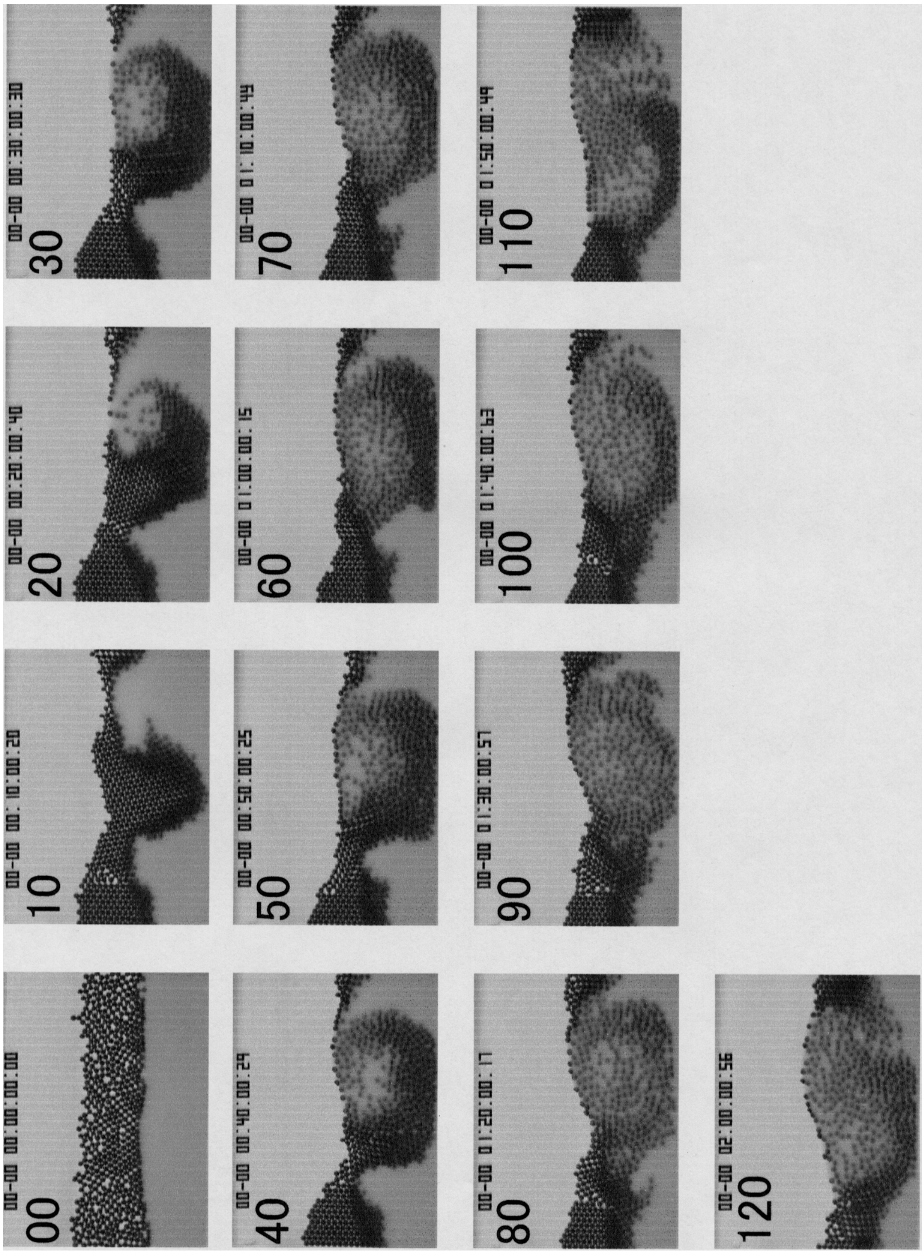

Fig. 4. Results of observation for the case where larger particles were initially placed above smaller ones.

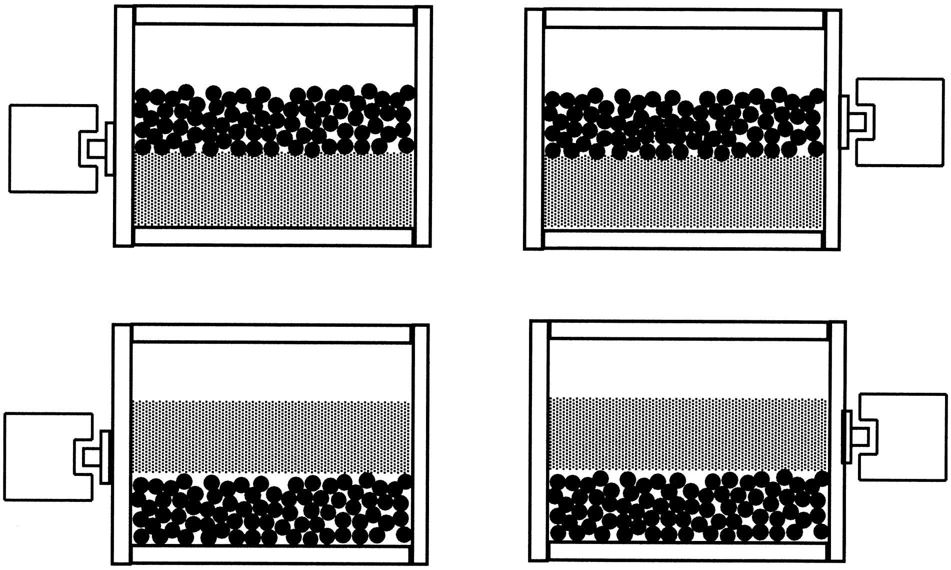

Fig. 5. Sketches to show four cases of experimental conditions.

4. Discussion

Physical interpretations of the present results are quite difficult in spite of the fact that the experimental apparatus and the procedure were simple. There are two questions to be answered.

One is the mechanism for sustaining the large scale eddy motion. The other is the mechanism for fixed sense of rotation. The first question is common with the large scale powder flow in the container with vertical vibration. In this case the friction at the side walls plays an important role (TAGUCHI, 1992; AOKI *et al.*, 1996; DURAN and REISINGER, 2000). In the same way in the present case with horizontal vibration the large scale eddy motions might have been caused by the friction at the lower boundary. This conjecture was confirmed by the preliminary experiments with neutrally buoyant particles, where eddy motion did not appear if the friction was absent.

The first question how the eddy motion was driven with the help of the friction at the lower boundary is still not solved. At the present stage some factors which are considered to be important are listed as follows. First, the particles were pressed horizontally in the right and left directions in turn within one period of vibration, owing to the inertia force. Secondly, this compression would have enhanced friction between particles and the lower boundary. Thirdly, once a steady eddy appeared, it would have produced an asymmetric compression among particles. A combined effect of these factors is a problem left for future study.

The second question on the mechanism to choose one sense of rotation from two possibilities is more difficult to answer. There may be a possibility that an elastic wave

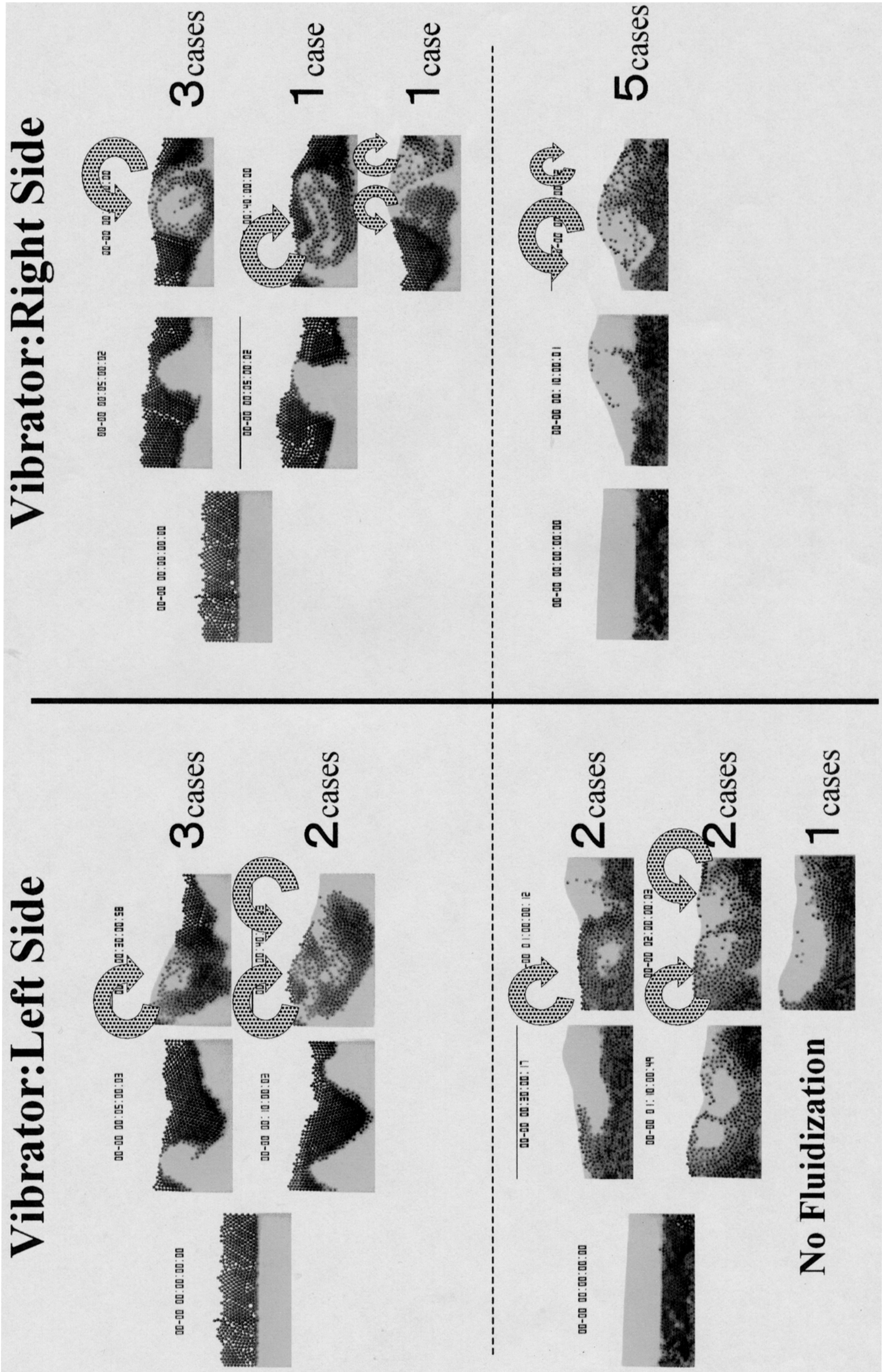

Fig. 6. Results of observations corresponding to the four conditions shown in Fig. 5.

caused by the vibrator was propagating horizontally within the aluminum frame. Then, it could have forced a uni-directional eddy motion of particles. However, the wavelength of the wave for the frequency of 30 Hz would have an order of 30 m, much larger than the container size. It is difficult to imagine that the container deformed according to this propagating wave.

Another factor might be the initial motion of the vibrating rod attached to the vibrator, which is mentioned in Sec. 2. There is a possibility that this initial motion governed the entire particle behavior after that. If this is the case, the second question is related to the fist one, since initial onset of a weak eddy motion may lead to steady motion with finite strength.

Some comments are necessary on the difference of the present experiment from another type of experiment with a mixture of particles of different sizes but without liquid. In the latter, larger particles tend to go upwards through interaction with smaller particles. This tendency was not observed in the present experiment. The reason is unknown, but a possibility of it is suggested here. In the present case the same tendency might have existed, but it would have taken much more time to confirm it, since both the gravity effect and the relative motions between two particle groups were much weakened owing to the liquid.

Next, the larger particles were arranged in one layer while smaller particles were packed nearly three-dimensionally. This was different from the situation in real fluidizations. The present study is considered to contribute to basic understanding of particle behavior confined in a vibrating container.

Finally, a necessity is pointed out to undertake more number of experiments with various conditions, such as different sizes of container, different kinds of liquid, different combinations of particle sizes and different strengths of vibration. They will lead to better understanding of phenomena and solutions of problems mentioned above.

Although these question are not yet solved, the present authors think that reporting the experimental results is meaningful in order to attract attention of scientists to this interesting phenomenon.

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