FORMATION MECHANISM OF BRICK-PATTERN RIPPLES

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FORMATION MECHANISM OF BRICK-PATTERN RIPPLES

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Three-dimensional brick-pattern streaming forms above a model of two-dimensional ripple marks under the oscillatory water motion. This type of streaming may possibly be responsible for forming the brick-pattern ripples of Bagnold (1946). A structure of flow above the brick-pattern ripples is suggested.

Key words: Brick-pattern ripple, Formation mechanism

1. Introduction

Bagnold[1] (1946) found that three-dimensional sand ripples form under the oscillatory water motion when the water amplitude is small, and called the resulting pattern of ripples 'brick pattern'. These ripples have transverse crests and longitudinal bridges spanning the ripple troughs as shown in Fig. 1. The transverse spacing of the bridges is very regular.

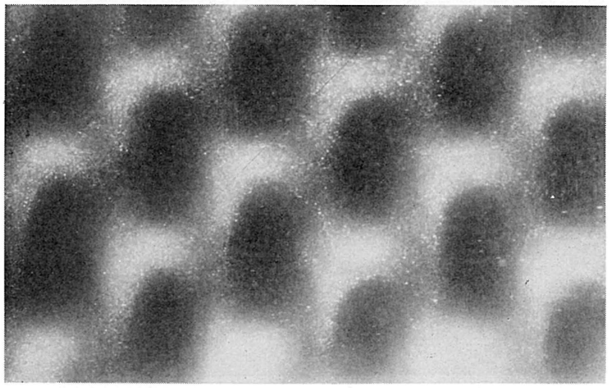

Fig. 1. Plan view of brick-pattern ripples in water oscillating right and left; crests are bright and troughs dark. Water amplitude and frequency are 1.5 cm and 1.7 Hz, respectively. Median diameter of glass beads as a bed material is 0.045 cm and their specific gravity 2.4. Pitch and height of ripple crests are 2.5 cm and 0.5 cm, respectively.

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Recently, one of the authors [2] found that a three-dimensional 'streaked' streaming is induced around a circular cylinder oscillating in water at rest; an example is shown in Fig. 2. This streaming may form in many types of oscillatory flow along curved walls due to the centrifugal instability of the flow.

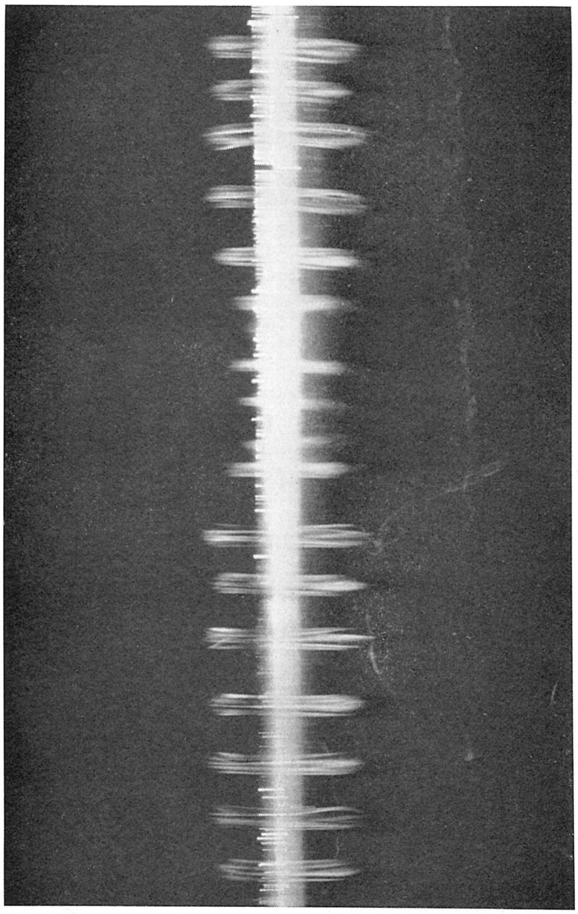


Fig. 2. Streaming visualized with dye along one side of a circular cylinder oscillating transversely in water at rest. Cylinder = 2.93 cm, d_0 = 1.94 cm, f = 0.21Hz.

In this paper, the results of observations of a brick-pattern streaming related to the streaked streaming and the brick-pattern ripples of glass beads are presented in 2 and 3, respectively. In relation to the brick-pattern streaming, the formation mechanism of brick-pattern ripples is discussed in 4.

2. Brick-pattern streaming

The experiment was carried out using a 45×30×25 cm glass-sided water tank, in which a model of two-dimensional ripples illustrated in Fig. 3 was oscillated transversely. The model consisted of an array of parallel half-circular cylinders fixed to the surface of a flat plate. The pitch L and waveheight H of the cylinders as ripple crests were 2.5 cm and 0.70 cm, respectively. The amplitude $d_0/2$ and frequency f of the oscillation were 0.7 cm and 0.36 Hz, respectively. In Fig. 3, three view planes are also indicated, which were illuminated with a projector through a slit. Water motion was visualized with suspended aluminum flakes.

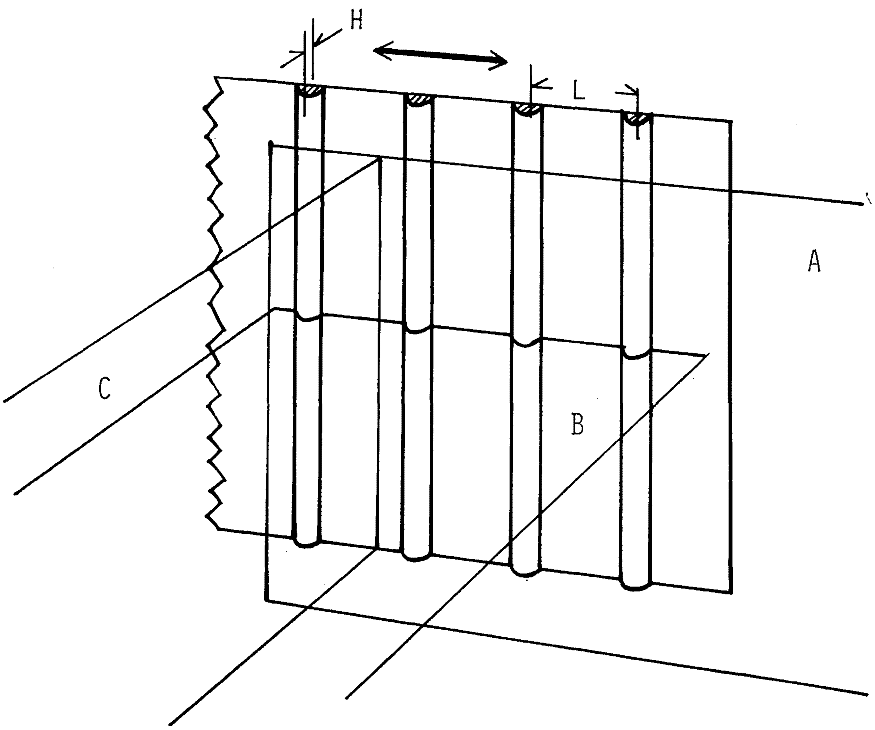


Fig. 3. Model of two-dimensional ripples oscillated in water at rest. Double arrow indicates the direction of oscillation. A, B, and C correspond to three different view planes for flow visualization.

When the model was oscillated in water at rest at relatively small amplitudes, longitudinal streaks of laminar streaming similar to that shown in Fig. 2 formed along each cylinder; 'streaming' means here the steady flow induced by primary oscillatory flow. A flow pattern of the streaming in plane-A is illustrated in Fig. 4 (top), where the position of streaks (shown by the horizontal line segments) on one cylinder is different from the positions of those on neighboring cylinders by half the transverse pitch of the streaks. No streaks adjoin in the direction of water oscillation, but they form on every two cylinders.

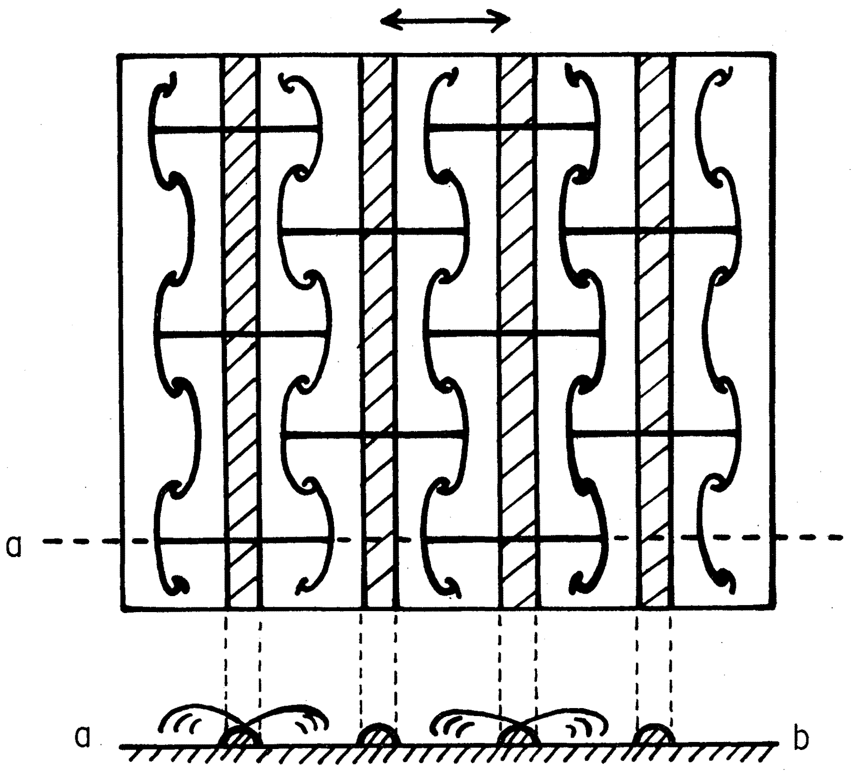


Fig. 4. Schematic diagram of laminar flow pattern in plane-A about L distant from the model (top), and that in plane-B (bottom), when d_0 is small. Horizontal line segments show streaks of flow like those of Fig. 2. Both ends of the streaks roll up and connect with one another transversely along the troughs between the transverse cylinders shaded. Roll-up vortices form on every two cylinders as shown in bottom.

A flow pattern in plane-A is also shown in Fig. 5, where a brick-pattern of dark vortex cells half-encircled by bright crescent arcs is seen. These arcs were visualized by suspended aluminum flakes reflecting the light projected from the right side of the picture. The crescent arcs are the streak ends which have rolled up in the troughs between the cylinders. If the light were projected from the left, the crescent arcs looking leftwards would be seen. This is due to the difference of the orientation of individual aluminum flakes in shear flow, as reported by Taneda [3].

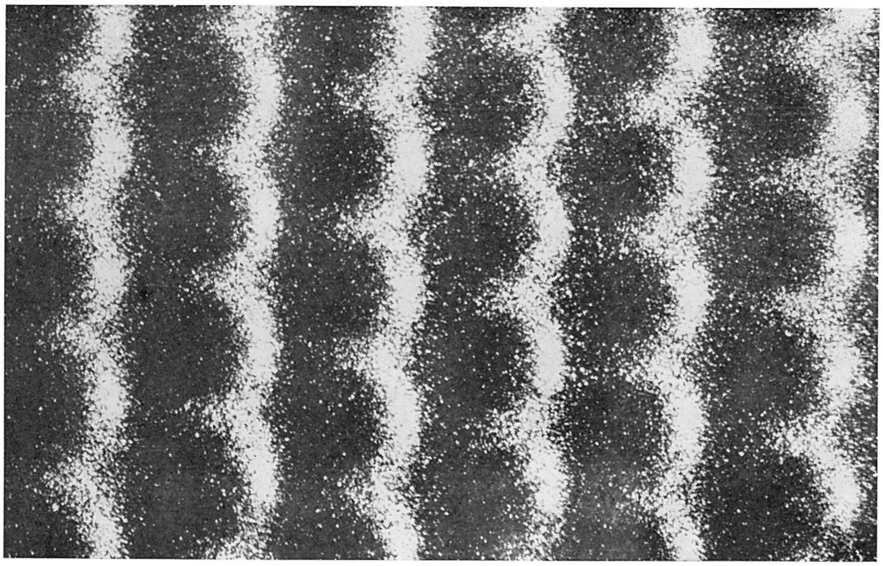


Fig. 5. Flow pattern in plane-A about L distant from the model, showing crescent arcs looking rightwards ; those looking leftwards in Fig. 4 also form, but are not visualized here. The letwards and rightwards looking crescent arcs form vortex cells arranging themselves in a brick-pattern as a whole. Cylinders are behind the dark regions of vortex cells.

Figure 6 shows a flow pattern in plane-B, where a vortex pair forms on every two cylinders as might be expected from Fig. 4 (bottom).

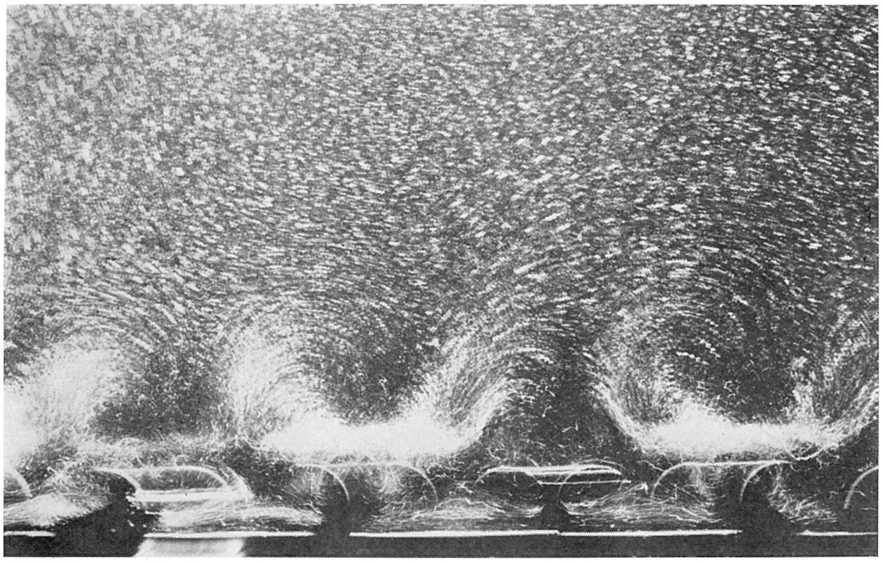


Fig. 6. Flow pattern in plane-B showing that a vortex pair corresponding to the right and left crescent arcs in Fig. 4 forms on every two cylinders.

Figure 7 shows a flow pattern in plane-C, where the vortex cells corresponding to those in Fig. 5 are seen.

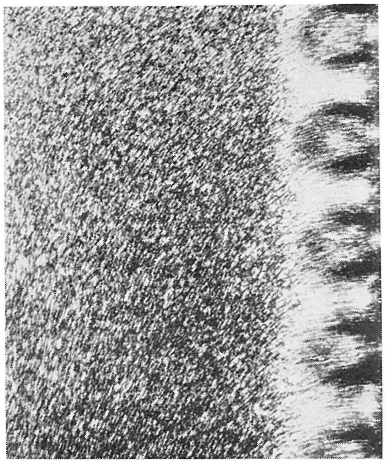


Fig. 7. Flow pattern in plane-C showing vortex cells on a trough between cylinders seen on the right.

3. Brick-pattern ripples above a two-dimensional ripple model

The experiment was carried out using a 15 × 15 × 60 cm closed-type water tunnel made of acrylic resin plates, in which water was oscillated by a motor-driven piston. A two-dimensional ripple model consisting of 11 parrallel half-circular cylinders with L = 2.5 cm and H = 0.50 cm fixed to a flat plate, which was placed on the bottom floor of the tunnel as shown in Fig. 8. The cylinder axes were transverse to the direction of water oscillation at a relatively large amplitude. The values of L and H of the ripple model were identical with those of real ripples of glass beads for d_0 = 3.0 cm and f = 1.8 Hz. Water in the tunnel was oscillated also at the same d_0 and f. Glass beads were scattered initially sparcely in the troughs of the model in order to see the initiation of three-dimensional ripple patterns. On the floors outside of the left and right outermost cylinders, a uniform layer of glass beads 0.5 cm thick was prepared.

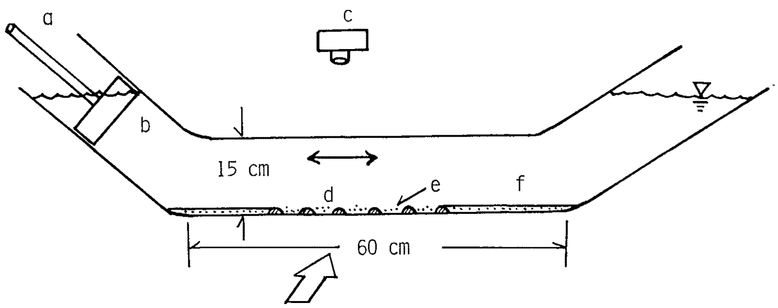
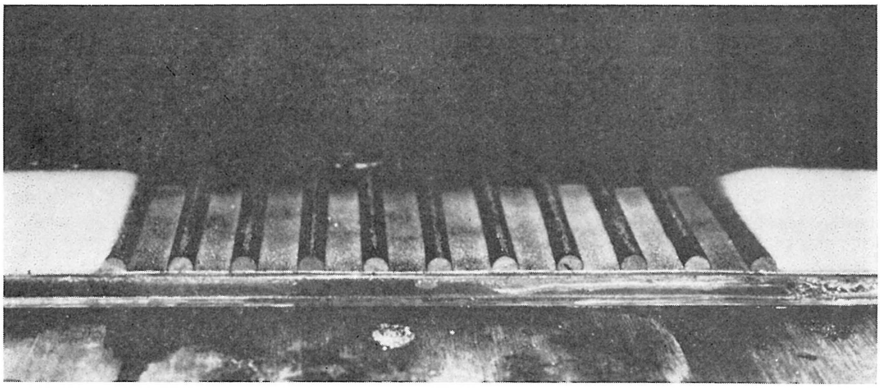


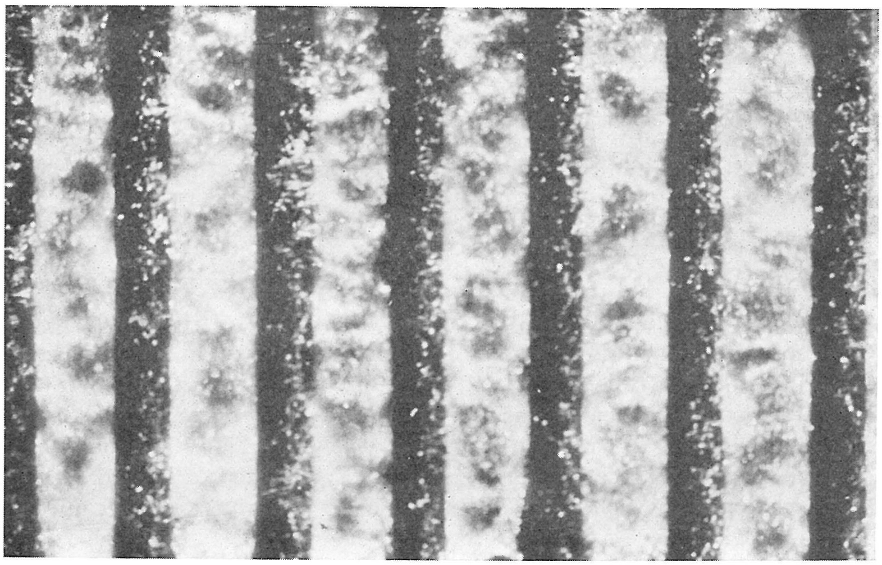
Fig. 8. Schematic diagram of U-shaped rectangular water tunnel. Double arrow indicates the direction of water oscillation, and open arrow that of light projection. a, connecting rod, b, piston, c, camera, d, cylinder as a model of a ripple crest, e, sparcely scattered initial glass beads, f, thick layer of glass beads.

In Fig. 9 a process of formation of brick-pattern ripples above the ripple model is shown. Figure 9 (a) shows the set-up in the test section of the tunnel before the onset of oscillatory water motion. While the glass beads were still sparce in the troughs after the onset of water oscillation, they showed an irregular pattern as shown in Fig. 9(b). Flow above the ripple model with the scattered glass beads consisted of two-dimensional separation vortices, which collapsed immediately and the flow became turbulent as a whole.

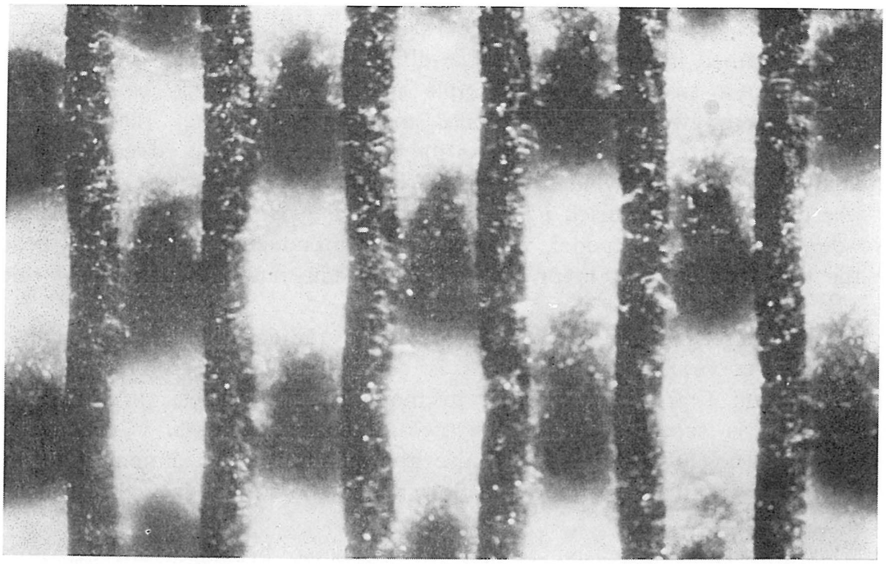
As the water oscillation continued, some glass beads outside of the model were transported into above the model and bridges of these glass beads began to span the troughs between the cylinders alternately, producing a brick-pattern as shown in Fig. 9 (c). The bridge formation started when the thickness of the glass-bead layer in the troughs exceeded about 0.5 H. As three-dimensional brick-pattern ripples developed with time, the flow above them became more and more turbulent. Figure 9 (d) shows the fully developed brick-pattern ripples. What is essential here is that the regular 'three-dimensional' brick-pattern is developed from the 'two-dimensional' ripple crests.



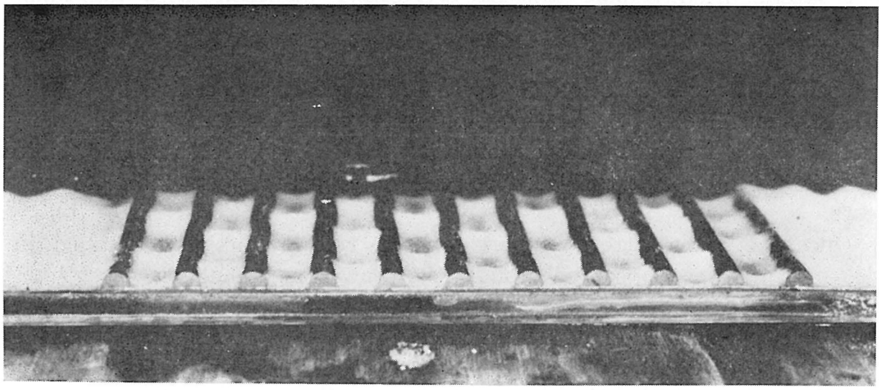
(a)



(b)



(c)



(d)

Fig. 9. Development of brick-pattern ripples of glass beads above two-dimensional ripple model.
(a) Bird's-eye-view of set-up in the test section before the onset of water oscillation as shown in Fig. 8.
(b) Plan view of irregular glass-bead pattern at 1.5 min after the onset of oscillation.
(c) Plan view of brick-pattern of bright bridges formed by glass beads,of which the quantity above the ripples was increased with time because of transportation from the both sides of the model.
(d) Bird's-eye-view of fully developed brick-pattern ripples at 10 min after the onset of oscillation.

4. Formation mechanism of brick-pattern ripples

As described in 3, laminar three-dimensional brick--pattern streaming forms above a two-dimensional ripple model, when d0 is small. This streaming is so weak that it cannot move glass beads. The alternate configuration of longitudinal streaks in this brick-pattern streaming indicates that the streaks avoid to adjoin each other.

As described in 4, brick-pattern ripples of glass beads form above a two-dimensional ripple model, when do is large enough to move glass beads on the bottom floor. A layer of the glass beads must be sufficiently thick for the brick-patterns to form.

Based on the results of observations so far described, the formation mechanism of brick-pattern ripples is considered in the following way. When do and f are large enough to move sand particles, primary oscillatory flow is separated from the two-dimensional crests. Separation vortices just behind the crests are also approximately two-dimensional, but they collapse immediately and the flow above the ripples is turbulent as a whole.

However, there is reason to belive that some brick-pattern streaming may be concealed in the turbulent flow above the two-dimensional ripples. This 'latent' pattern may not be necessarily identical with the laminar streaming pattern of Fig. 4, because do is now large and the streak segments may span multiple crests. Figure 10 shows a possible structure of such a brick-pattern streaming present in the turbulent flow, when each streak is considered to span two neighboring ripple crests. As reported by Kaneko[4], the formation region of brick-pattern ripples is rather limited, and this indicates that the latent streaks can hardly span more than two crests.

Once the brick-pattern ripples formed, roll-up vortices arranged in a brick-pattern were observed though the flow was turbulent. It should be stressed, however, that no laminar brick-pattern streaming of Fig. 10 is seen above the two-dimensional ripple model even at low values of f. Therefore, the spanning of two crests by the streaks leading to the realization of the streaming pattern like Fig. 10 would be made possible with the help of some regulative action of glass beads; the streaming and glass beads thus feed up each other to form regular patterns.

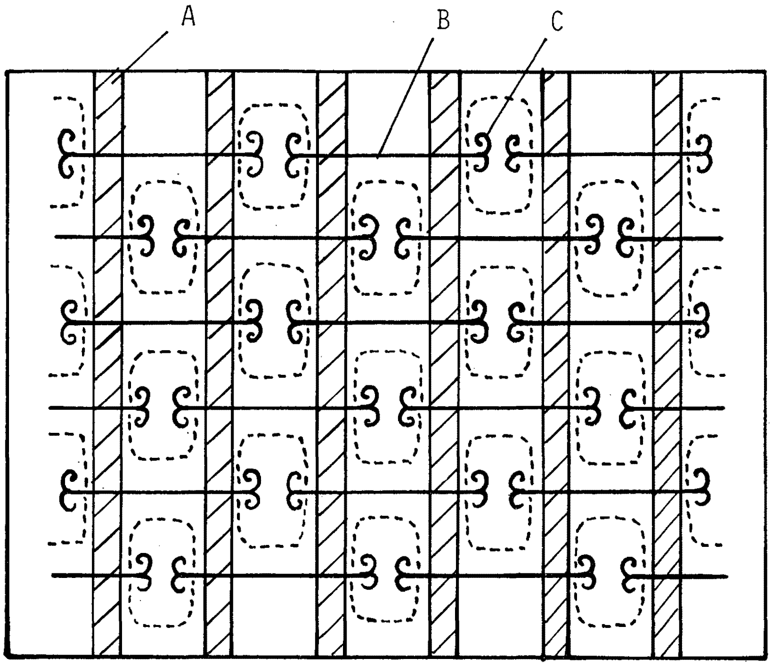


Fig. 10. Schematic diagram of a possible latent structure of brick-pattern streaming in turbulent flow above the brick-pattern ripples, when d_0 is large and longitudinal streaks span two cylinders, the direction of water oscillation being left and right. Shaded A is cylinder as a crest, B is streak under which a bridge spans the trough, and C shows rolled-up streak ends scouring the trough encircled by a dotted line.

It may be further speculated that sand is effectively sensitive only to some latent organized fluid motion of low frequencies in turbulent fluctuating flow. If sand responds to every fluctuating fluid motion of high frequencies directly, no regular structure of the sand will be expected to form in the turbulent flow. This is supported by the fact that brick-pattern ripples form only when an ample quantity of sand covers the bottom floor. This means also that sand regularizes apparently turbulent flow by singling out its intrinsic structure perhaps corresponding to the so-called organized motion[5)] in the flow.

In conclusion, the brick-pattern streaming may be regarded as an organized motion in the turbulent flow above ripples, and its embodiment is the brick-pattern ripples of sand.

Acknowledgments

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