# TRANSPORT OF LIQUID BY TRAVELING SOLITARY WAVES

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A mechanism for the transport of liquid by solitary waves periodically traveling in the same direction is described. The assumption that, in accordance with this mechanism, the tidal waves transport ocean water westward, which is chiefly responsible for the large-scale currents, is substantiated.

It is well known that a traveling (progressive) solitary wave, propagating on the surface of a fluid, transports a mass of fluid equal to the mass of the fluid contained in the crest of the wave with the velocity of propagation of the wave [1]. This statement follows from the law of conservation of mass of a fluid.

A transporting action of the solitary waves periodically traveling in the same direction along a limited-size basin produces a deficit in the liquid (a decreased level) at the initial (starting) edge of the basin and in excess (an increased level) at the end (final) edge. As a consequence, a reverse compensating flow of the liquid is formed headed from the final edge of the basin towards the starting edge [1].

If we imagine that an induced solitary wave at the right boundary A of the channel (Fig. 1) is formed under the action of a certain wave-forming force, and then this formed wave, fixed in shape, travels to the left boundary B of the channel, where the wave-forming force vanishes and the wave breaks up, then if the processes in the channel are comparatively slow (a quasistatic case), they can be described in the following way.

When the wave forms at the starting edge A of the channel, the mass is "loaded into the wave" through the gain of fluid at the point where the crest forms, and the wave, therefore, becomes a carrier of a certain quantity of mass equal to the mass of fluid contained in the volume coccupied by the crest. While propagating in the channel, the formed wave, fixed in shape and volume, transport, with its propagation velocity, some mass in the direction from A to B; this mass is constant in value (shown by hatching in Fig. 1), yet it is variable in the composition of particles of the liquid (a rapid-consecutive or discrete-wave motion [1]). We note that the aforementioned variability in the content of mass of a traveling wave does not affect the value of the volume of the wave and its mass. After the wave has reached the left end of the channel and the wave-forming force has vanished, the wave is destroyed ("the mass is unloaded from the wave") and the mass of liquid contained in the wave is found at the left (final) end B of the channel, forming here an elevated level (and a horizontal pressure gradient), which produces a backward, compensating motion of the liquid in the channel in the direction from B to A. The motion proceeds until the horizontal pressure gradient vanishes.

In this way, processes of the formation of a solitary wave at the first (starting) end of the channel, its motion towards the second (final) end, and its destruction at the final end cause compensating flows of the liquid in the channel from the final end B to the starting end A (Fig. 1, arrows) both at the times of formation and destruction of the waves. While the shaped, fixed-in-volume, solitary wave travels, no compensating flows arise in the unperturbed part of the channel (beyond the wave).

The described regularities in the transport of liquid by waves, as well as regularities in the formation of compensating flows from the opposite direction, were tested experimentally [1]. Experiments have confirmed that the solitary waves, moving in the same direction along the channel, produce a deficiency in the liquid in the initial region of the channel (low-level of the surge) and its excess (high-level of the surge) in the final region of the channel.

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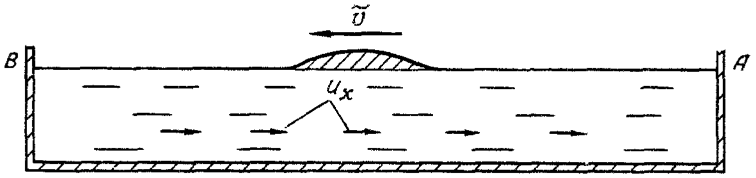

Fig. 1. Wave transport in a liquid by waves in a channel and reverse flows; $\tilde{v}$, velocity of propagation of the wave; $u_x$, velocity of the reverse flow.

The analysis of mass transfer by solitary humped waves moving at the surface of a basin is of interest for oceanography (Fig. 2). We will show that these waves, traveling periodically in the same direction along a certain x axis, set up in the basin two opposite rotations (closed circular flows), located at both sides of the x axis.

We consider a basin of rectangular cross section filled with a liquid. We will neglect viscosity and other real physicomechanical properties of liquids (except for incompressibility) since we consider slow (quasistatic) motions of the liquid, neglecting dynamic forces and energy consumption. A generator of a traveling wave can be represented, for example, in the form of a body placed above the basin and moving parallel to the x axis (not shown in Fig. 2), and attracting the liquid. A physical analog of the described hypothetical experiment can be imagined as a massive body, traveling above the basin (for example, the moon, traveling above the ocean), when the forces of the gravitational attraction between the body and the liquid form a moving tidal humped ridge at the surface. Under laboratory conditions, the described hypothetical experiment can be realized as follows: The surface of a liquid filling a vessel is covered by a thin inpenetrable magnetic film. A permanent magnet is moved above the film, forming a traveling domed wave on the flexible film, and therefore, on the surface of the liquid [1]. Apparently, the mass transport of such a "closed" wave is equal to the mass transport of an open solitary wave of the same profile. The above-mentioned experiment can also be realized with the help of a magnetic liquid.

Let us consider the three aforementioned stages of existence of a humped wave in the basin: 1) formation of the wave at the initial edge A of the basin under the action of a wave-forming force; 2) motion of the wave at the surface of the basin along the x axis from A to B; 3) destruction of the wave at the final edge B of the basin due to the vanishing of the wave-generating force. Our discussion will use the example of a model in which the generation of a wave occurs due to a slow horizontal motion with the given velocity $\tilde{v}$ of a certain attracting body-generator above the basin from right to left along the x axis with the motion of this body beginning beyond the right-boundary A of the basin and ending beyond the left boundary B. This ensures the formation of a humped solitary wave at the right edge of the basin, motion of the wave from the right edge of the basin to the left edge, and destruction of the wave at the left edge of the basin.

1. Wave Formation. Initially, while the body-generator is above the right edge of the basin, a dome-shaped hump K begins to form at the surface of the liquid in the extreme right region L of the basin (Fig. 3a). This formation produces a compensating flow of the liquid in the region K from the other parts of the basin since the total volume of the liquid in the basin is constant. During subsequent motion of the body-generator above the basin, the dome-shaped hump at the surface of the liquid in the region L gradually increases in volume; at the same time, while the dome grows, the liquid continues moving towards the hump, as shown in Fig. 3a by arrows c).

2. Wave Motion. During subsequent motion of the body-generator from right to left above the basin, the formation of the dome-shaped wave is completed, and a formed wave fixed in shape and volume, continues its motion to the left edge of the basin (Fig. 3b), transporting in this direction the mass of the rigid-dome K in a rapid-consecutive manner, i.e., by means of small horizontal impulsive displacements (shown by arrows $v_x$ in Fig. 3b) of particles of a liquid in the wave. Since the shape and the volume of the traveling wave are constant, compensating flows of the liquid do not arise in the remaining (beyond-the-wave) part of the basin. It should be noted that in the case of solitary waves having a considerable length, pulses of the horizontal rapid-consecutive transfer are greatly smoothed, and the nonuniformity of the velocity $v_x$ is negligible.

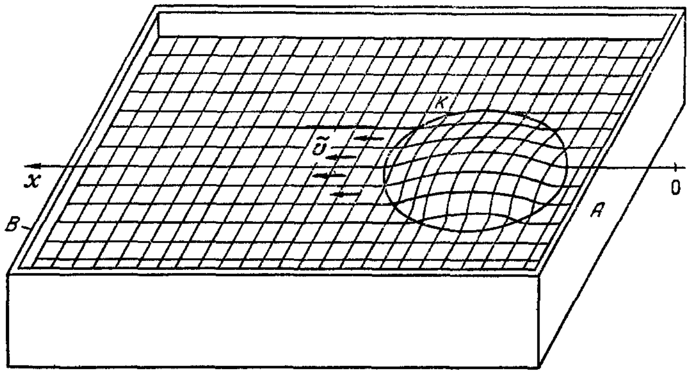

Fig. 2. A humped progressive solitary wave at the surface of a basin.

3. Wave Destruction. When the body-generator approaches the left edge of the basin and starts to pass beyond the limits of the basin (Fig. 3c), the wave K gradually starts to vanish and the mass of the liquid brought by the wave is found in the extreme left region H of the basin as an excess of the liquid, causing an increase in the level and a reverse, compensating gradient flow of the liquid from the region H in the direction shown by arrows c in Fig. 3c.

On the basis of the aforementioned, it can be concluded that the periodic repetition of the described motion of the solitary humped waves at the surface of a limited-size basin, i.e., a cyclic alternation of the stages of the formation (Fig. 3a), motion (Fig. 3b), and destruction (Fig. 3c) of the solitary humped waves, leads to the formation of a continuous (with a certain degree of nonuniformity) processes of a circular motion of a liquid according to the diagram, shown in Fig. 3d. This motion is characterized by the presence of two circular countercurrent eddies, schematic images of which are mirror reflections of each other with respect to the x axis, coinciding with the direction of propagation of the center of a humped wave. In Fig. 3d, the arrows $v_x$ show the direction of motion of a primary discrete-wave surface transfer of the liquid by a traveling wave; arrows c show the direction of the compensating motions in the upper (clockwise) and in the lower (counterclockwise) eddies; arrows $u_x$ show a reverse (opposite to the direction of the x axis) central compensating motion of the liquid from the region H of the liquid excess to the region L of the liquid deficiency. The latter motion of the liquid can be specified as a subsurface motion since there is a direct (along the x axis) primary motion $v_x$ in the surface layer of the liquid.

A pattern that we have constructed (Fig. 3d) depicts the motion of the liquid under the action of traveling solitary surface waves and is very similar to the pattern of motion of the fluid in the "typical ocean" [2-5]. The latter is characterized by the presence of a powerful westerly transport of fluid along the equator in the tropical zone of the ocean and by two eddies, running in the opposite directions on both sides of the equator, the northern anticyclonic (clockwise) eddy in the northern hemisphere and the southern cyclonic eddy (counterclockwise) in the Southern Hemisphere, with the southern eddy being a mirror reflection of the northern one. Besides, there is an equatorial subsurface current headed eastward. The so-called boundary large-scale currents, running form the equator towards the poles at the west coasts of the ocean and from the poles towards the equator at the east coasts are the components of the currents of such structure. We note that at present there is no universally recognized explanation for the mechanism of the formation of the aforementioned "typical structure" of the large-scale ocean currents.

With consideration for the regularities in the above-mentioned mechanism for wave transport of the liquid, similarity between the structure of the large-scale currents in the tropical ocean and the obtained scheme of motion of the liquid (Fig. 3d) in a limited-size basin can be explained by the presence of the progressive tidal humped waves, traveling periodically in the same direction at the surface of the oceans, the maxima of which are, as is known, in the torrid zone of the oceans. In the assumed model for the transport of ocean waters based on the considered mechanism for the wave transport of a liquid, the moon and the sun are wave-forming body-generators, traveling along the torrid zone of the oceans. The tidal progressive waves on the surface of the ocean, arising due to the tide-forming forces exerted by the moon, and tidal waves, considerably smaller in amplitude, due to the tide-

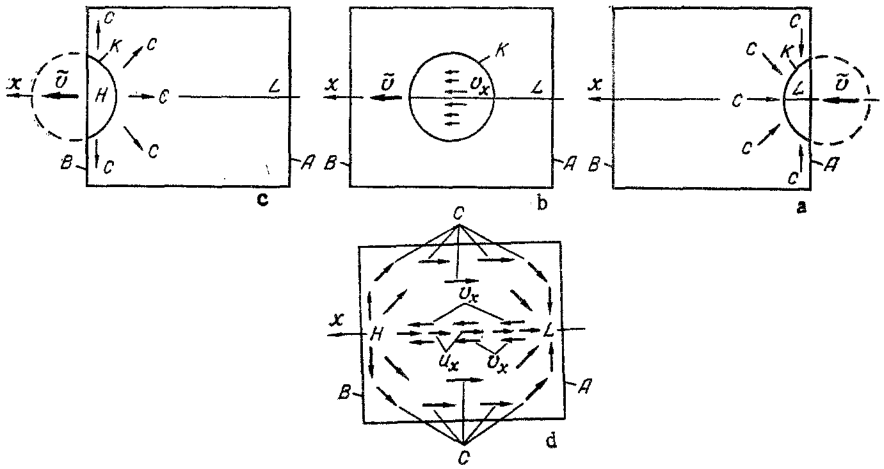

Fig. 3. Mechanism of the formation of two countercurrent eddies in a basin under the action of humped solitary waves traveling in the same direction: (a) wave formation; (b) motion of the formed wave; (c) wave destruction; (d) general pattern of the flows for repetitive periodic motion of the solitary waves along the x axis; $\tilde{v}$, wave velocity; $v_x$, horizontal component of the velocity of a discrete-wave motion of liquid; c, velocity of the liquid in the eddies; $u_x$, velocity of the reverse flow just below the surface.

forming forces exerted by the sun, traveling in subtropical latitudes westward, realize the mass transfer of ocean waters in the western direction, creating an excess of liquid in western region of the oceans and its deficit in eastern regions [4, 6]. Differences in the elevations of the tidal waves, arising due to the forces exerted by the moon and by the sun, inequalities in the periods of these waves, a considerable time of existence of the compensating currents, correcting the differences in elevation in the ocean, other (nonwave) factors of the motion of the ocean water considerably complicate the process of the mass transfer and fluid currents in the real ocean as compared with the scheme shown in Fig. 3d; however, they are similar in their main features. In our opinion, this is a strong argument in favor of the assumption on the existence of the mechanism of the transport of the ocean water, described above.

A quantitative estimate of the value of the wave transport of the water in the Atlantic Ocean and a comparison of the obtained value with the measured values for the west—east transfer of water in this ocean, known from the ocenographical literature, gives good agreement between the calculated and measured values.

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