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Abstract

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DETERMINATION OF THE PARAMETERS OF A WAVE FLOW FROM THE PARAMETERS OF THE PERIODIC BOTTOM STRUCTURES FORMED BY IT

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In the petrography of sedimentary rocks, methods for reconstructing the conditions of sedimentation from features of the fossil rock are of great importance. One such characteristic feature, making it possible to reconstruct the conditions of deposition of sandy sediments from water flows, is the so-called "ripple marks," or, more correctly, ripple periodic structures, which are often preserved on the surfaces of sandstone beds. Up to the present time, ripple structures have made it possible, more or less reliably, to establish only the type of flow (wave or channel), the initial orientation of the bed (its top or bottom), and in some particular cases to judge the depth of the flow. The reason for the scarcity of the information obtained from periodic ripple structures is due not only to insufficient knowledge of their properties, but also to the insufficiently clear and correct presentation, in a number of geological manuals, even of the specific features of marine and river ripples. Thus, for example, the obligatory symmetric structure of wave ripples is often indicated (in contrast to the asymmetric structure attributed only to channel structures)—a feature characteristic of rather "deep water," i.e., of small values of the ratio of wavelength to flow depth ($\lambda_{\mathrm{w}}/H \sim \pi$), but not of great depths. At present, owing to the results of experimental and theoretical study of periodic ripple structures of a wave flow, it has become possible to increase the reliability of reconstructing the sediment-accumulation environment from fossil ripple structures.

The present article sets forth a method for determining the parameters of a wave flow from the parameters of the ripple structures created by it. In addition to the purely applied significance noted above, it is also of interest from a purely theoretical standpoint.

Determination of the parameters of flows from the parameters of the periodic structures created by them is a complex problem and one that is practically difficult to solve. For a translational flow it is not solved at all because of its ambiguity. For a wave flow in the general case it is likewise practically not solvable, since periodic structures are not always created with sufficient

Fig. 1

Figure 1: Fig. 1

regularity, especially near the upper boundary of the region of their existence (at large values of velocities and periods), where ripples lose even their basic regularity—correct periodicity. But in those cases when a regular structure is created and preserved in the ripple system, it proves possible to establish a one-to-one correspondence between the parameters of a fully formed ripple system and the parameters of the wave flow that created them. For the direct problem (determination of the parameters of ripple structures from the parameters of a wave fl—

flow) in ([1]) we obtained the following expressions*:

$$\lambda_p = 0.732 \cdot 10^{-1} \left(\frac{d^3 \rho_t' g}{\rho_l \nu^2} \right)^{0.1} (v_B' + v_0) \tau_B = 3.65 \cdot 10^{-2} \left(\frac{d^3 \rho_t' g}{\rho_l \nu^2} \right)^{0.1} \frac{h_B + h_0}{H} c_\phi \tau; \quad (1')$$

$$h_p = 1.32 \cdot 10^{-2} \left(\frac{d^3 \rho_t' g}{\rho_l \nu^2} \right)^{0.1} (v_B' + v_0) \tau_B = 0.660 \cdot 10^{-2} \left(\frac{d^3 \rho_t' g}{\rho_l \nu^2} \right)^{0.1} \frac{h_B + h_0}{H} c_\phi \tau; \quad (1'')$$

$$S_p = S_B = v_B' / v_B'', \quad (1''')$$

where λ_p is the spacing, h_p the height, of the periodic structures; v_B' and v_B'' are the maximum values of the near-bottom velocity of the wave flow under the crest and trough; H, τ_B, h_B, and c_ϕ are the depth, period, wave height, and its phase velocity; d, ρ_t, ρ_l, ν, g are the diameter and density of particles ($\rho_t' = \rho_t - \rho_l$), the density and viscosity of the liquid, and the acceleration due to gravity; $S_B = v_B'/v_B''$ and $S_p = l^+/l^-$ (where l^+ and l^- are the projections of the gentle and steep slopes of a ripple) are characteristics of the symmetry of the wave flow and of the ripples.

Fig. 1

Expressions (1), however, are insufficient for determining the three independent quantities characterizing the wave flow, τ_B, v_B', H, or τ_B, h_B, H, since the first two of them, $(1')$ and $(1'')$, are linearly dependent, while $(1''')$ does not contain the dependence of S_B on the sought parameters of the wave flow (the dependence $v_B'' = f(\lambda_B, H)$ is unknown). Thus, instead of three conditions we have only one: $(1')$ or $(1'')$.

To obtain the missing equations it is therefore necessary to use additional relations between the characteristics of ripples and of the wave flow. One such

Fig. 2

Figure 2: Fig. 2

relation can be obtained from the more "fine structure" of the ripples—their transverse periodicity ([2]), and another from the dependence of the symmetry of the wave flow on the wavelength and depth or on c_ϕ.

In periodic structures of a wave (as also of a translatory) flow, besides the main periodicity, determined by the ripple spacing λ_p, there is one more— "transverse" —periodicity, by which the ripple height is modulated along their crests (Fig. 1). The principal feature of this periodicity is the coordination of the phases of the height modulations of neighboring crests (the height maxima of one crest are located opposite the minima of another), as a result of which a checkerboard structure is created in the system. This phase coordination is the result of the action of spatial—hydrodynamic—forces ([3]-[5]) between the elements of the periodicity of neighboring crests and individual particles.

If, as a characteristic of the doubly periodic structure, one introduces the angle α, formed by the direction of propagation of the flow and the direction connecting the nearest points of the crests that are in the same phase (for example, height maxima), then instead of two characteristics—the spacings of the main and transverse periodicities λ_p and λ_π—one may consider a single α, related to them by the relation $\tan\alpha = \lambda_\pi/2\lambda_p$.

For a translatory flow, as follows from the theory ([5]), α proves to be a constant quantity: $\alpha = \alpha_0 = 54°40'$, and depends neither on the magnitude of the forces (flow velocities) nor on the constants of the liquid and particles. In a wave flow,

* This form of the expressions for λ_p and h_p in terms of H and c_ϕ is valid for shallow water.

in which the accelerations are different from zero, α, generally speaking, is not equal to this value, since the hydrodynamic forces are a function not only of velocities, but also of accelerations. Therefore, only in those cases where the effect of accelerations is appreciably weaker than the effect of velocities does α in a wave flow prove to be very close to α_0 (2).

Experimental investigations carried out by us in a wave flow showed that the change in α is determined mainly by the change in the magnitude of the velocity, and not of the period* (see Fig. 2a), so that approximately α may be represented in the form:

Fig. 2

$$\alpha \approx 0.954\left[1+\left(\frac{v^0_{\cdot}}{v}\right)^5\right], \tag{2}$$

Fig. 3

Figure 3: Fig. 3

where $v^0_.$ is the hysteresis value of the shearing velocity (for particles of diameter 0.25 mm it is equal to ~ 10 cm/sec); the limiting value is

$$\alpha = \alpha_0 = 54^\circ 40' = 0.954$$

radian.

In addition to relation (2), the transverse periodicity makes it possible to obtain one more expression—practically, however, not quite equivalent to expression (2) —which relates the relative height of modulation of the crest $\Delta h_p/h_p$ to the flow velocity v' (Fig. 2b):

$$\frac{\Delta h_p}{h_p} \approx \frac{1.13 \cdot 10^{-3}}{d} \left(1 + 0.53\, \frac{v^0}{v_.}\right). \tag{2'}$$

Fig. 3

The quantity $\Delta h_p/h_p$ depends on the constants of the fluid and of the particles ($\Delta h_p/h_p$ decreases as the particle size increases), and, moreover, measuring it in nature is considerably more difficult than measuring α, since both in an actual flow and in fossil forms it is incomparably easier to measure elements in the horizontal plane than in the vertical one. All this greatly reduces the value of expression ($2'$).

For the possibility of using expression ($1''$), it is necessary, as was already indicated, to reveal the dependence of S (or v') on the wavelength and the depth, or on c_ϕ. If one uses the expressions for the transport of fluid in the bottom layer of a wave flow obtained by Stokes (6) or Higgins (7), which differ from one another only by a numerical coefficient, and takes into account their pulsating change over the wave period according to (8), then ($1''$) becomes

$$S_p = S = \frac{c_\phi}{c_\phi - \chi v'_p} \approx \left(1 + \chi\, \frac{v'}{c_\phi}\right), \tag{3}$$

in which χ is equal either to 1 (according to Stokes) or to 2.5 (according to Higgins).

As is seen from Fig. 3, the experimentally obtained dependence

$$S_p = S\,(c_\phi, v')$$

in the region of large S, where the accuracy of the measurements is $\sim$ 15–20%, is higher than the theoretical one by only 11%.

* Obtaining the correct complete dependence for α from theory is made difficult by the fact that we cannot precisely take into account all the forces acting in the boundary layer on particles situated on the crests of ripples.

In the region of small S_{v}, in which the measurements are more accurate ($\sim 10\%$), the discrepancy between the theoretical and experimental curves is still smaller. Thus, within the indicated accuracy of the measurements, the agreement of the expression $S^{\text{exp}}(c_\phi, v'_{\text{v}})$ with the theoretical one (for $\chi = 2.5$) proves satisfactory.

Expressions (2) and (3), together with (1′) and the dependence of c_ϕ and v'_{v} on the wave parameters,

$$c_\phi = \frac{\lambda_{\text{v}}}{\tau_{\text{v}}} = \sqrt{\frac{g}{k}\,\text{th}\,kH}, \tag{4}$$

$$v'_{\text{v}} = \frac{\pi h_{\text{v}}}{\tau_{\text{v}}}\frac{1}{\text{sh}\,kH}, \tag{5}$$

form a complete system of equations for determining the parameters of the wave flow from the parameters of periodic bottom structures, far from the upper boundary of the region of their existence (i.e., for regular and clearly expressed periodicities and ripple form).

Under optimal conditions the error in determining τ_{v}, v'_{v}, and H proves to be of the order of 20%; under less favorable conditions it increases to 50% and even more, but the very possibility of determining even the order of magnitude of the wave parameters—either by means of the system of equations (1′)-(5), or individually from particular characteristic features of the forms encountered—is in a number of cases undoubtedly a very positive result.

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Note: Figure translations are in progress. See original paper for figures.