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EXPERIMENTAL STUDY OF WAVE PROCESSES IN AN AQUEOUS SUSPENSION OF BENTONITE CLAY

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The practical value of studying wave propagation in water suspensions of bentonite stems from the broad use of these disperse systems in oil-well drilling.

As was shown in [1, 2], wave processes in bentonite have several characteristic features, including anomalous oscillation peaks in the incident wave which are considerably greater than the pressure of the initiating pulse, a successive increase in pressure in these peaks in a series of tests conducted with the same boundary conditions for initiation, etc. The studies [1, 2] described the results of investigations only in a dilute suspension of bentonite with a mass concentration c = 6% for the disperse phase in water. This concentration is near the critical concentration at which structure formation can take place in the mixture (see [3] and its bibliography, for example). Here, the impulsive pressures were recorded over a relatively short time interval – about 1 msec.

The goal of the present study is to further experimentally investigate waves in a system with a developed three-dimensional structure (c = 10%). The chosen time of observation of the waves is longer – on the order of 10 msec. This allows us to record the passage not only of the incident waves, but also of reflected waves, unloading waves, etc. along the entire tube.

1. Experimental Unit. The compression waves were initiated in a vertical shock tube [2]. The measurements were organized as follows. Three groups of pressure gauges were located along the low-pressure chamber (LPC) A, B, C at distances of 2, 5, 7 m from the diaphragm. The distance between two gages in a group $\Delta x = 0.25$ m. The triggering gauges controlled the measurement circuit – the front of the incident wave successively initiated electrical signals which alternately activated oscillographs and frequency meters operating in the slave rgeime. This was achieved by synchronizing the oscillograph readings with respect to time – the intervals measured by the frequency meters τ_1 and τ_2 corresponded to the time of passage of the wave from group to group or the time of delay of activation of the oscillographs relative to one another.

2. Trial Experiments. Water was chosen as the standard model liquid. Its low viscosity and the linear dependence of its volume on pressure up to 100 MPa made it possible to examine the results obtained from shock loading of the water column in an acoustic approximation.

A typical test is shown in Fig. 1. The intensity of the incident wave p_1 is close to the pressure of the driving gas in the high-pressure chamber (HPC) – $p_e = 2.4$ MPa. The initial pressure in the LPC $p_0 \approx 0.1$ MPa. The result is shown in the form of a kinematic curve in the coordinates x (height of the liquid column) – t (time) and illustrates the process of transmission of the compression wave (solid line) and rarefaction wave (dashed

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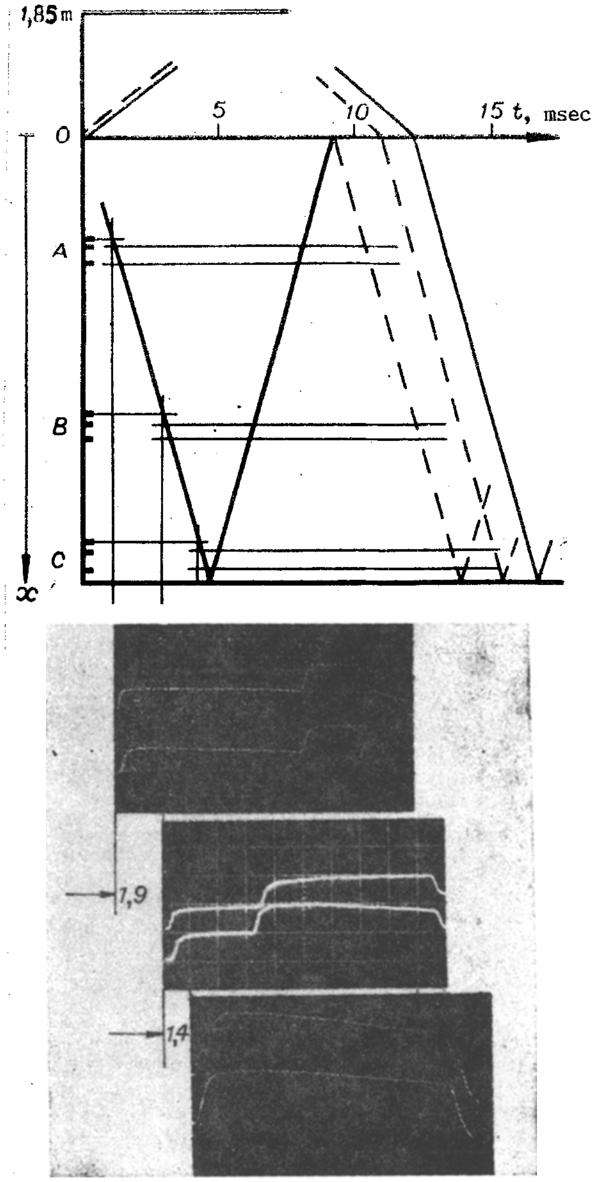

Fig. 1

line). Also shown are the pressure oscillograms from A, B, and C corresponding to the given wave pattern. The top ray on the oscillogram corresponds to the signal from the top gauge in the group, while the bottom ray corresponds to the signal form the bottom gauge. The thin horizontal lines on the x–t diagrams show the location of the gauges on the tube. The length of the lines corresponds to the duration of the oscillograph scan of the given group. The pressure oscillograms are shifted along the t axis by the intervals τ_1 and τ_2 recorded by the frequency meters (thin vertical lines). The signals on each photographic record are equidistant, so that it is fairly easy to follow the movement of the disturbances along the tube. The direction of propagation of the compression and rarefaction waves is determined by comparing the time shift of identical perturbations on the oscillogram and the spatial distribution of the corresponding gauges along the tube.

Analysis of the trial experiments shows that the results are in agreement with the acoustic approximation of shock-wave theory. In particular, the velocity of the incident D_1 and reflected D_2 waves is close to the speed of sound in pure water. The reflection from the rigid wall and the free surface is acoustic. Finally, the measurements reproduce well and are independent of the number of shock loadings of the water column.

Initiation of a wave in the tube creates a rather complex pattern of flows, this pattern being related to the formation of centrifugal Riemann waves in the HPC and their reflection

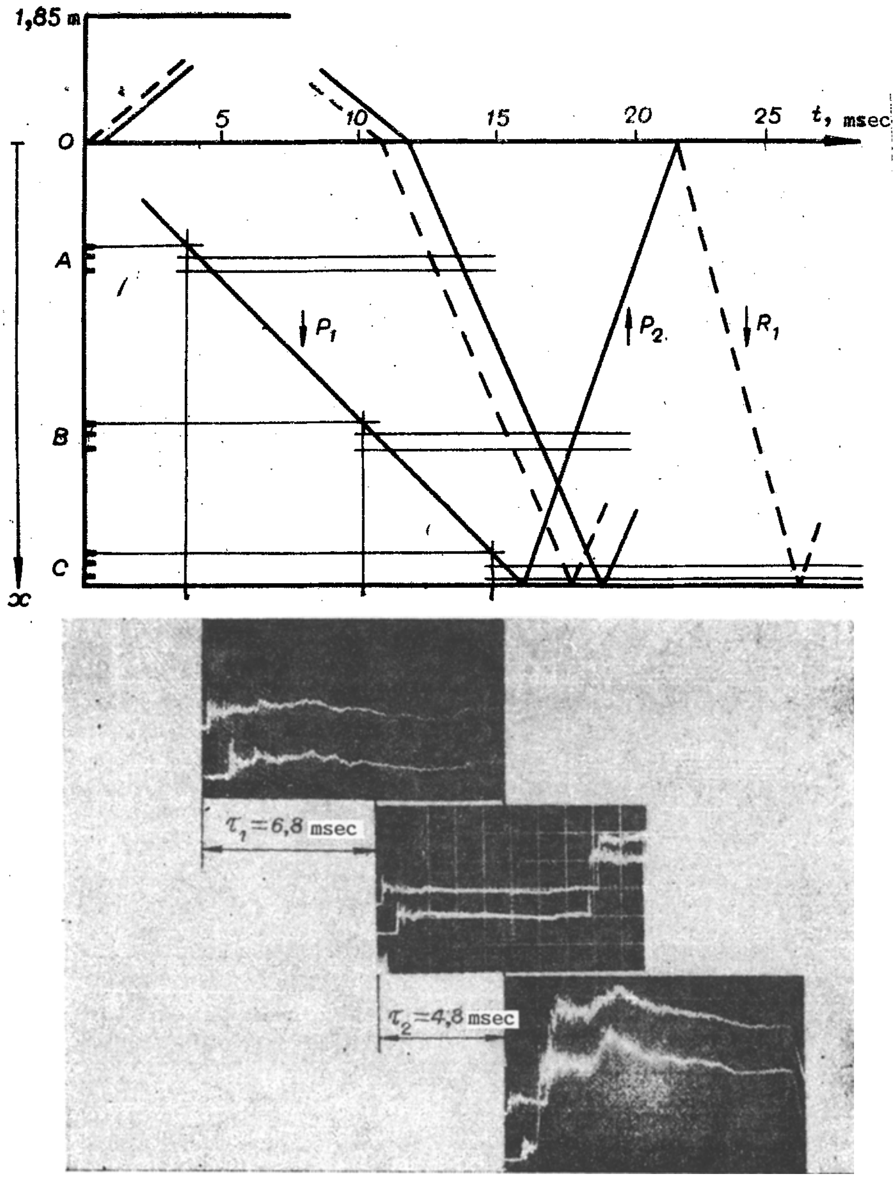

Fig. 2a

and with refraction of the forward compression wave at the gas–liquid interface. The effect of perturbations which develop in the HPC on the field of measured pressures was determined experimentally by using chambers of different lengths L_{HPC}. With the elapse of a period of time $t^* = 2L_{HPC}/c_g$ after initiation (where c_g is the speed of sound in the gas), the liquid was systematically disturbed by rarefaction waves reflected from the top end of the HPC and then by the high-pressure zone following these waves. In connection with this fact, the chamber lengths were chosen so that disturbances from the HPC would reach the channel with the liquid after 11 and 12 msec, respectively, without having an appreciable effect on the pressure profile of the wave in the water. Calibration of the pressure gauges by means of diaphragms of different thicknesses showed that their sensitivity was independent of the wave amplitude. The relative error of the measurement of velocity of the incident wave was no greater than 3%.

3. Waves in Bentonite Suspension. In studying the propagation of waves in a suspension of bentonite clay, we conducted each test as a series of shock loadings of a column of the disperse system. Each shock was initiated by a "piston" with the same working-gas pressure $p_e = 2.1$ MPa.

We will examine the result of one such test consisting of four shock loadings of a column of a 10% water suspension of bentonite (about 2.8 kg of clay per 25 kg of water).

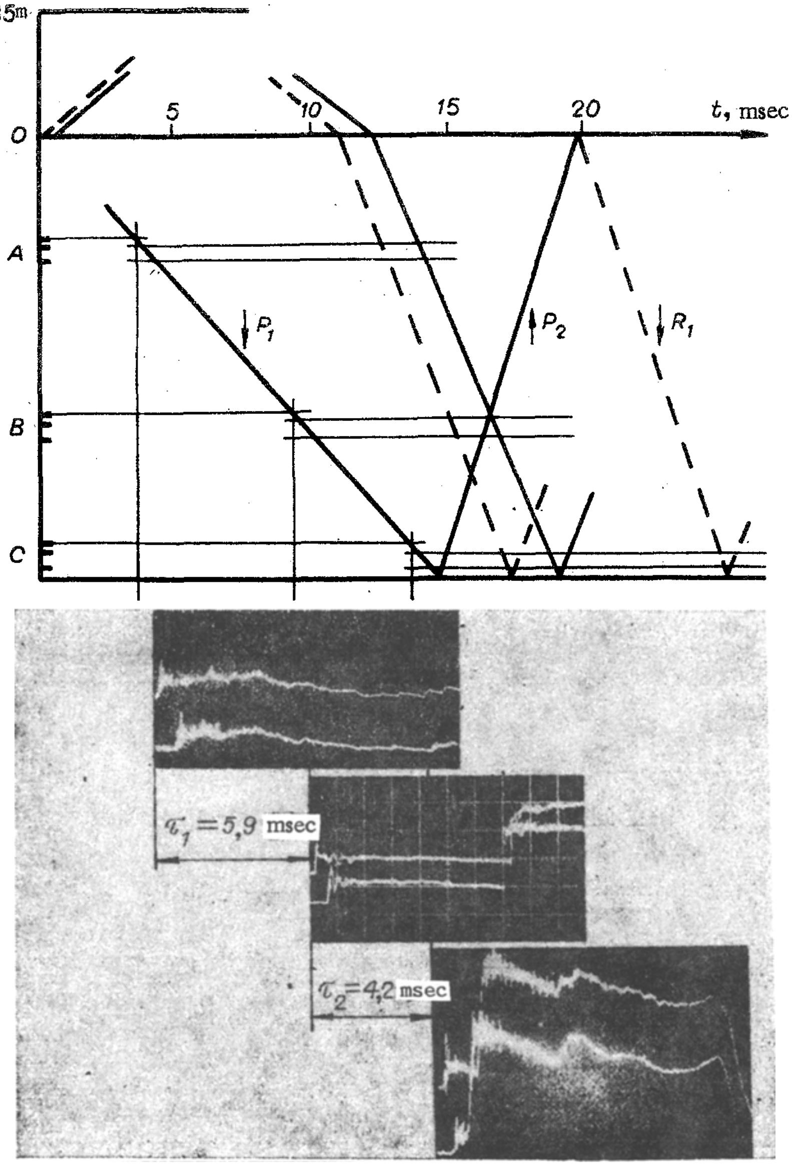

Fig. 2b

The mixture was first subjected to repeated shocks to remove random gas from the tube. The shocks in the test were produced in the same medium at an increasing rate, i.e., we shortened the time over which the suspension was held at rest after the previous shock loading.

Figure 2a shows oscillograms and the x–t diagram of the first shock, when the suspension was left to rest for a period $\Delta t_3 \geq 10$ min. The mean velocity of the incident wave along the HPC was $D_1 \approx 450$ m/sec, while the mean velocity of the reflected wave was $D_2 \approx 1300$ m/sec. In the next test (Fig. 2b), the incident wave propagated at a velocity $D_1 \approx 500$ m/sec and the reflected wave travelled at a velocity $D_2 \approx 1450$ m/sec. The conditions of this test differed from those in the previous test in the fact that the time of rest of the suspension was reduced to $\Delta t_3 = 7$ min. The third shock loading was done after $\Delta t_3 = 5$ min had elapsed from the previous loading (Fig. 2c). Here, $D_1 \approx 600$ m/sec and $D_2 \approx 1450$ m/sec. The fourth shock (Fig. 2d), with $D_1 \approx 700$ m/sec and $D_2 \approx 1450$ m/sec, corresponded to the minimum possible period of rest of the suspension on the unit $\Delta t_3 = 4$ min.

We note the following features of the tests. Systematic perturbations behind the shock front, moving from the HPC to the system in the form of rarefaction compression waves, propagated at velocities of 1100-1200 m/sec. This is greater than D_1. The velocity of the compression wave reflected from the rigid wall, as the rarefaction wave R_1, was close to the

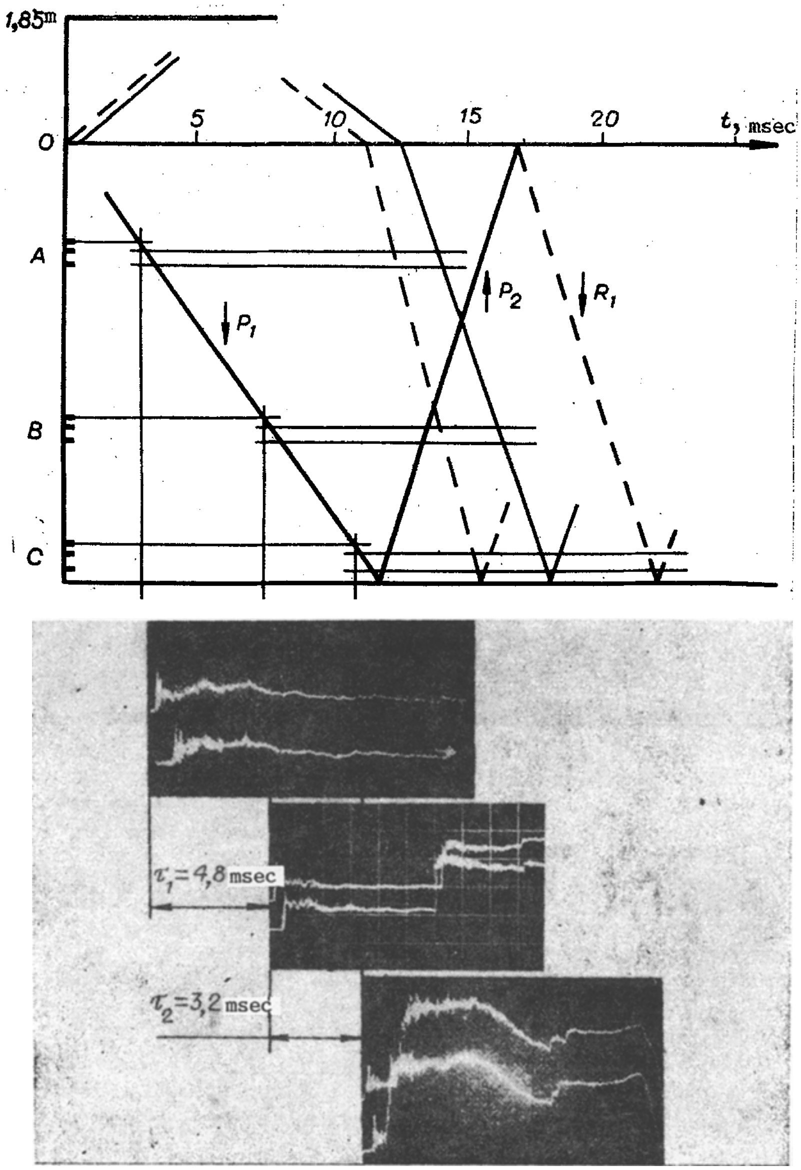

Fig. 2c

speed of sound in pure water (about 1450 m/sec). Nonacoustic reflection from the rigid end p_2/p_1 = 3-4 was seen in the 10% water suspension of bentonite. Here, p_1 and p_2 are the pressure in the incident and reflected waves (p_2/p_1 = 2 in water). There was almost no change in the amplitude of the incident wave with distance, which is related to the constancy of the boundary conditions at the gas–suspension interface during the time of recording of the wave (the driving gas of the HPC acts as a continuous "piston").

A characteristic sign of the structure of the front of both the incident and reflected waves in bentonite is oscillation of pressure with the frequency 20-30 kHz. The amplitude of these oscillations is many times greater than the amplitude of the "ringing" which inevitably develops in the walls of the tube after rupture of the diaphragm. In connection with the fact that the pulsation frequencies which are recorded are close to the natural resonance frequencies of the gauges (about 40 kHz), we conducted additional tests. By direct comparison of the readings of the standard LKh-type gauge and a gauge with a higher natural frequency (about 300 kHz) [4], we established from these tests that the oscillatory process in question is sufficiently slow compared to the processes involving the establishment of equilibrium in the working part of the pressure gauges we used.

4. Discussion of Results. The experiments included measurement of the pressure behind the fronts and the velocities of the fronts of the incident and reflected waves. The same value of p_1 was used for all tests. The initial density of the mixture differed slightly

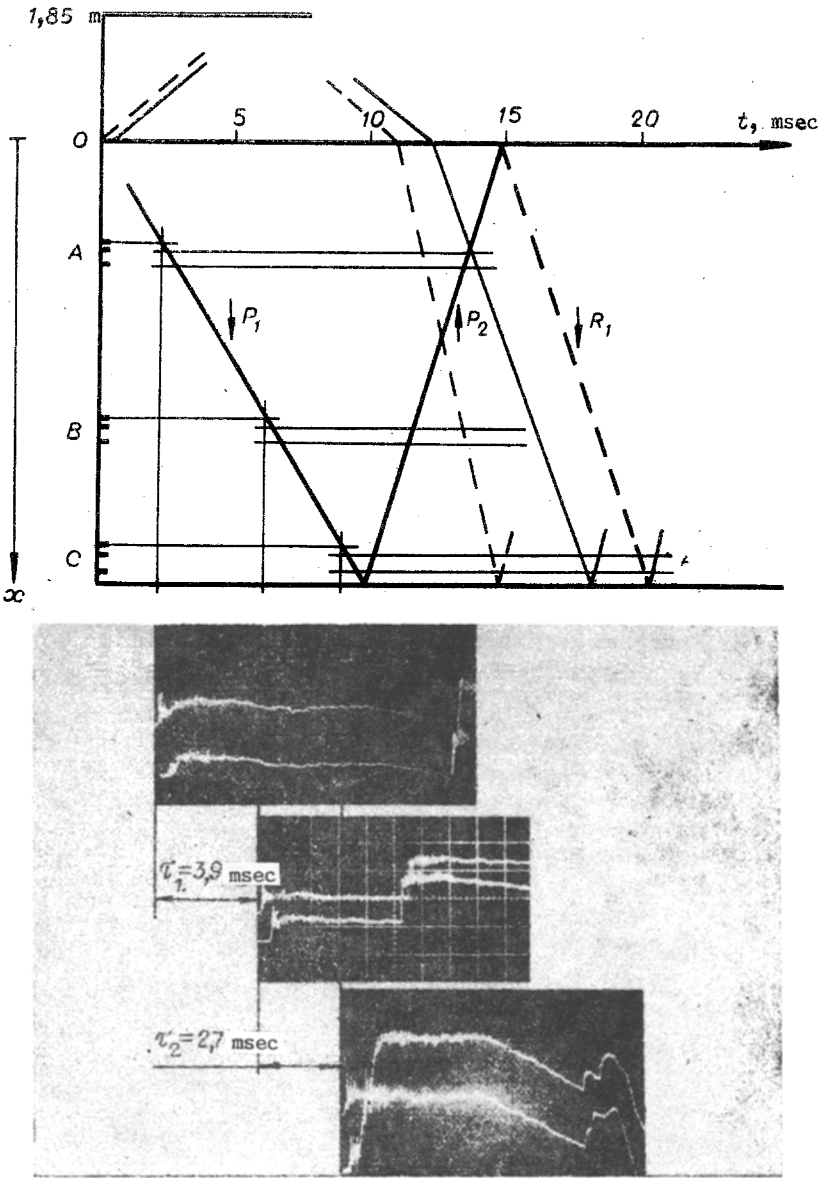

Fig. 2d

from the density of water $\rho_0 = 1.07 \cdot 10^3$ kg/m^3, $p_0 \approx 0.1$ MPa. Using mechanical relations linking the parameters on the front of the incident wave, we write the expression for the change in internal energy

$$\Delta\varepsilon = (1/2)\left(p_1^2 - p_0^2\right)/\left(D_1^2\rho_0^2\right), \tag{4.1}$$

from which it follows that $\Delta\varepsilon$ changed from loading to loading in the tests and evidently depends on the dureation of the pauses Δt_3.

The dependence of D_1 on the cylicity of the shock loading may be related to strength effects in the suspension, which has a developed thixotropic-coagulation structure [3]. The strength of the latter at rest is characterized by the potential energy of interaction $Q_0 < 0$, which is determined by the Van der Waals forces between the solid particles of colloidal size. This bond energy should be taken into account for relatively weak waves by introducing the corresponding terms into Eq. (4.1). The configuration of the system before the front up to the moment of initiation of the wave depends on the degree of thixotropic recovery fo the structure, i.e., $Q_0 = f(\Delta t_3)$. Complete failure of the structure ($Q_1 = 0$) and roughly identical states of the medium are probable after the front, as is evidenced by the constancy of the velocities D_2 and R_1.

When the structure is for some reason poorly developed (has not recovered ($\Delta t_3 \to 0$) or has an insufficient concentration of the disperse phase, as in [2]), the velocity of the front will be close to the sonic velocity in the dispersion medium c_ℓ = 1450 m/sec. Otherwise, when the value of Q_0 is maximal, D_1 will be lower than c_ℓ due to loss of energy in the wave front during disintegration of the structure. In those tests with the given suspension when Δt_3 was about a half hour, $D_1 \approx 400$ m/sec. This value is evidently close to the limiting minimum value [5].

Nonacoustic reflection of the shock wave is connected with a jump in the velocity front and the impulse of the reflected wave, propagating in a medium with a failed structure. With complete stoppage of the flow at the rigid end of the tube, we can obtain the following from the mechanical relations for incident and reflected waves

$$p_2/p_1 = 1 + D_2\rho_2(1 - p_0/p_1)/(D_1\rho_0),$$

where $D_2 \approx c_\ell$ = 1450 m/sec and ρ_2 is the density behind the front of the reflected wave. In accordance with this formula, for waves propagating in a 10% suspension, the ratio p_2/p_1 = 3-4. In a 6% suspension of bentonite, where $D_1 \approx D_2$, reflection is close to acoustic [2].

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