

# The influence of the membrane on the passage of a shock wave pulse in sand

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The effect of shielding a sand fill with aluminum foil (membrane) on the evolution of shock wave pulses was experimentally investigated. The experiments were conducted using a shock tube equipped with a section of the fill medium. The effect of shielding on the propagation dynamics of the main and probe pulses in a compacted sand fill medium was studied. It was found that shielding has virtually no effect on the shape of the propagating main pulse, while it significantly alters the shape of the transmitted probe pulses.

**Keywords:** shock tube, shock wave pulse, sand fill medium, shielding foil, probing pulse.

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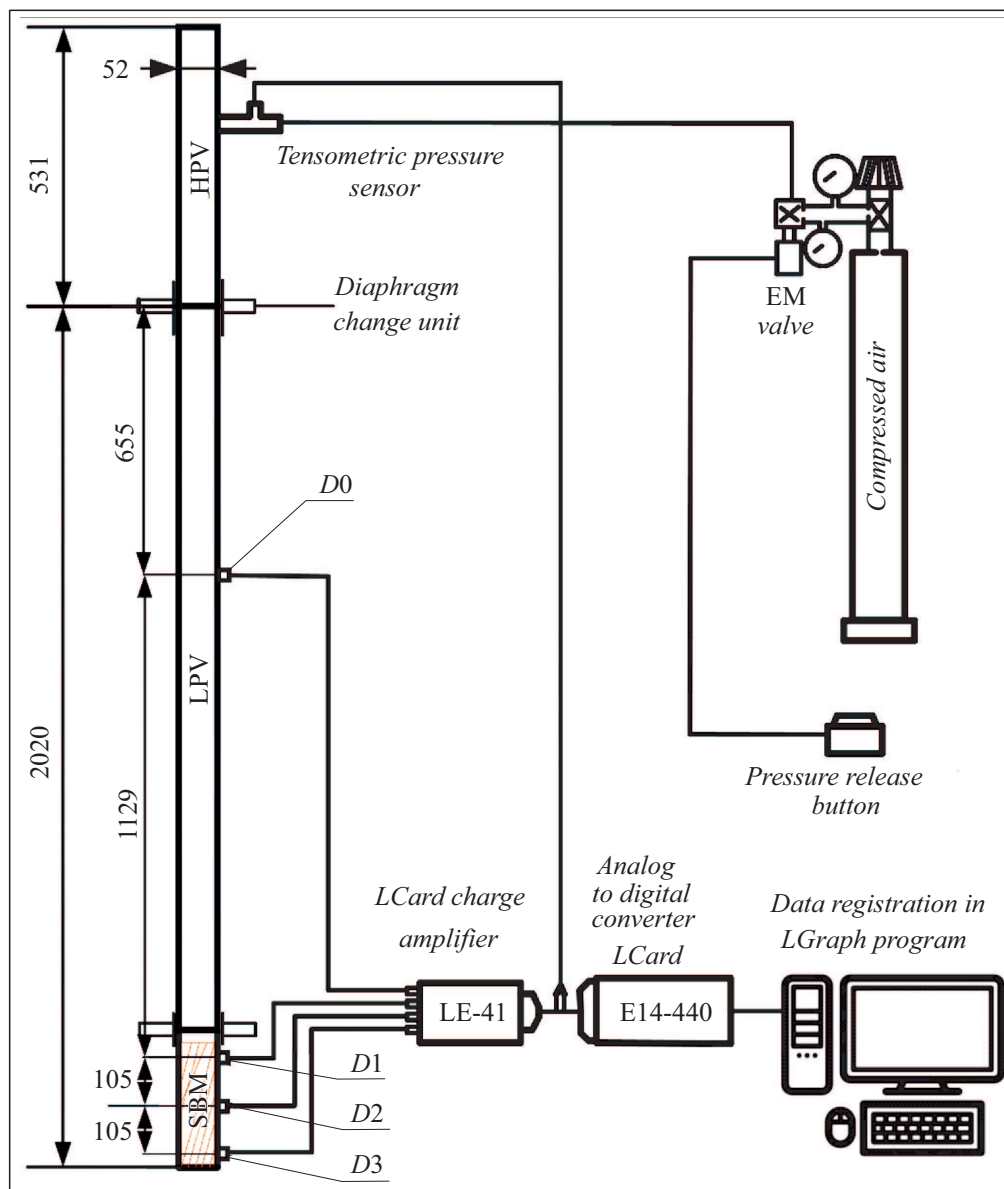
The study of propagation of shock wave pulses (SWPs) in porous media is of considerable applied interest and is relevant to such issues as explosion safety of technological processes [1], design of structures for protection against dynamic loads [2,3], and advancement of seismic exploration methods [4]. Experimental studies into the dynamics of SWPs in porous media are traditionally carried out in shock tubes, which allow one to record the parameters of incident and reflected waves [5]. The approach proposed in [6] involves the use of reflected pulses to probe changes in the medium after the initial SWP impact. This technique revealed a paradoxical phenomenon: the amplitude of the reflected pulse in a sand fill may be 3–4 times higher than that of the main pulse, and the maximum pressure shifts to the leading edge of a wave as it penetrates deeper into the medium [7].

Although the study of acoustic properties of porous media has a long history, the effects associated with shielding of porous media with metal membranes remain unexplored. The present study is the first to analyze the influence of aluminum foil fit tightly to a sand fill on the characteristics of the main and reflected pulses in this fill. The obtained results are compared with the data from earlier experiments [6,7] with an open sand surface.

Experiments were carried out in a shock tube (Fig. 1) consisting of high- and low-pressure chambers separated by a diaphragm (the rupture of this diaphragm forms a shock wave) and a section of bulk media [6]. When air was forced into the high-pressure chamber, the diaphragm made of oiled paper (either tracing paper or „Snegurochka,“ which is xerographic office paper) got ruptured. The pressure profiles of the formed and propagating pulse were recorded by LKh 610 acoustic piezoelectric sensors with a frequency range of 3–10 000 Hz [7]. The shock wave amplitude is related unambiguously to the diaphragm rupture pressure. The section of bulk media was filled layer by layer with

sand (grain sizes ranged from 160 to 650  $\mu\text{m}$ ; the average arithmetic size was 390  $\mu\text{m}$  [6]) with strong compaction and moderate ramming; the porosity of the resulting compacted sand fill was 39.2%, which corresponds to a density of 1590  $\text{kg}/\text{m}^3$ . In the shock tube with the section of bulk media, the wave is repeatedly reflected from the surface of the examined bulk medium and the upper end of the shock tube. The shape of the first reflected pulse, which reaches the surface of sand 13 ms after the main one and propagates within the sand fill, differs qualitatively from the shape of the main pulse at the corresponding depth. Since these changes are caused by a short-term transformation of the sand structure after the impact of the main pulse, the reflected pulse affected by these structural changes is called the probing one [6].

The amplitudes of shock wave pulses generated with the use of diaphragms made of tracing paper (15 kPa) and „Snegurochka“ paper (30 kPa) differed by a factor of two on the average. Steepness [6]  $P_i = (\Delta p / \Delta t)_{\text{max}}$ ,  $[P_i] = \text{kPa}/\text{ms}$ , where  $i$  corresponds to the chosen diagram, is a convenient parameter for characterizing the leading edge of pulses. Its value is determined at the point of maximum pressure rise at the leading edge. The steepness values are indicated on the pressure diagrams to the left of pulses (Fig. 2). Depending on the rupture conditions of different diaphragms, the steepness of the main pulse in sand at the level of sensors  $D1$  and  $D2$  varies from 200 to 1000  $\text{kPa}/\text{ms}$  in experiments with an open fill. The steepness of the probing pulse is noticeably lower (less than 200  $\text{kPa}/\text{ms}$ ), which is a sign of loosening of the bulk medium. Propagation over a distance of two centimeters of sand (from the surface to sensor  $D1$ ) results in a slight reduction of amplitude and steepness of the leading edge. The steepness of the main pulse at sensor  $D1$  is  $P_{1a} = 250 \text{ kPa}/\text{ms}$ . The probing pulse reaches sensor  $D1$  13 ms after the impact of the main pulse; its edge steepness



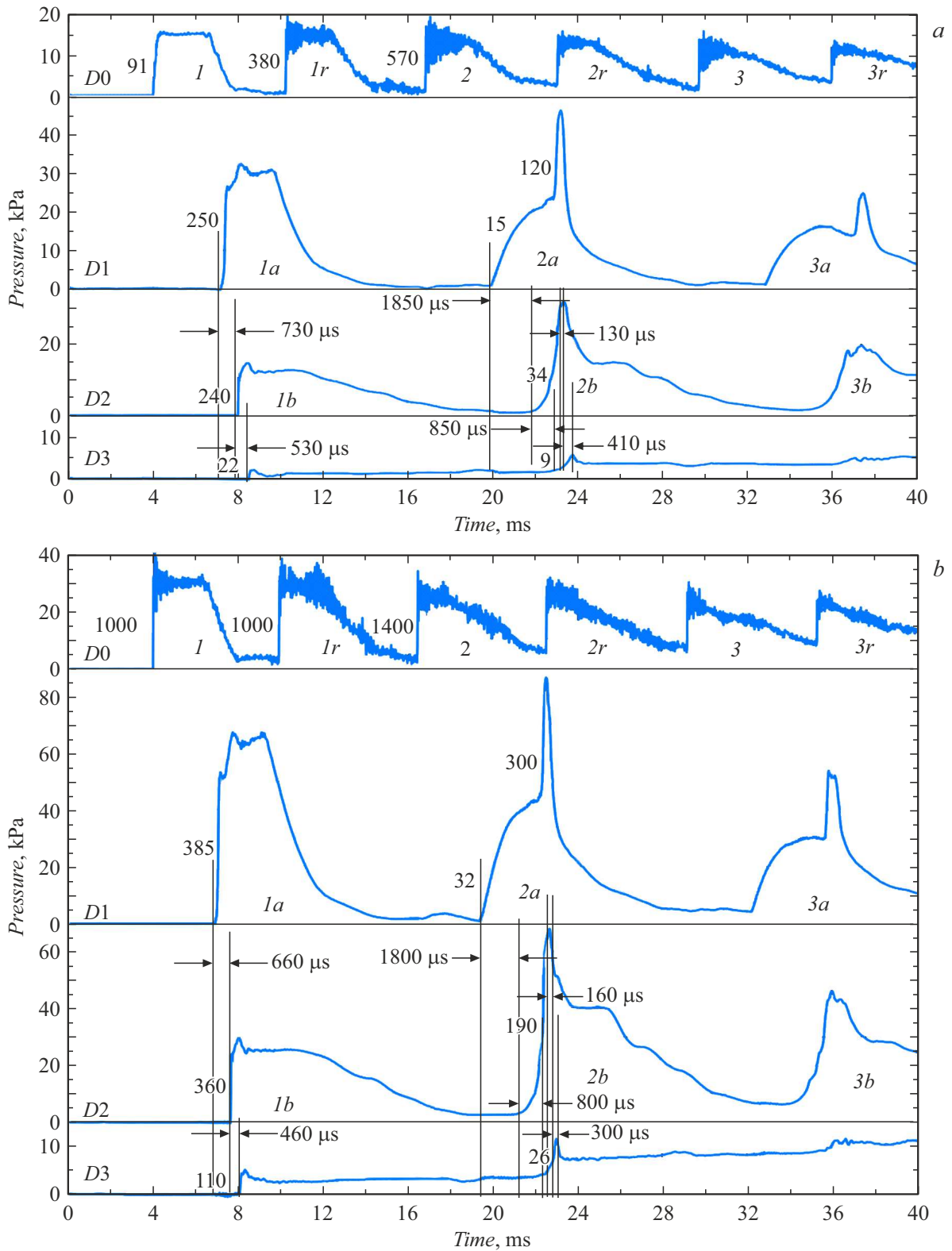
**Figure 1.** Shock tube; geometric dimensions (in mm) and positions of the diaphragm, the bulk medium, and piezoelectric pressure sensors  $D0$ ,  $D1$ ,  $D2$ , and  $D3$ . The internal diameter of all sections is 52 mm [6].

is low ( $P_{2a} = 15$  kPa/ms; diagram 2a), which is apparently attributable to loosening of sand as a result of reflection of the main pulse from the surface. A peak [6] with an amplitude 1.5 times greater than the amplitude of the main pulse and a considerable steepness of 120 kPa/ms is formed at the trailing edge of the probing pulse. The second probing pulse (diagram 3a) has a similar shape with a peak at the trailing edge. Notably, the formation time of the peak of the probing pulse at sensor  $D1$  is virtually the same as the formation time of the peak at sensor  $D2$ ; the tops of peaks are formed almost simultaneously.

With the SWP amplitude increased by a factor of 2 to 30 kPa (Fig. 2, b), the edge steepness values of incident and reflected pulses formed in air are several times higher

than the values at a low amplitude (Figs. 2, a, b). Note that the edge steepness values of pulses passing through the sand layer are higher at a larger amplitude (Fig. 2, b,  $D1$ – $D3$ ). A peak on the leading edge forms at sensor  $D2$  at the same time as the peak at sensor  $D1$ ; the time distance between the peaks is 160  $\mu$ s, which corresponds to a velocity of 660 m/s.

In the sand fill after the impact of the main pulse [6,7], peaks ( $D1$  and  $D2$ ) form on the probing pulse with amplitudes exceeding the amplitude of the main pulse (Figs. 2, a, b). There are two main hypotheses for the formation of peaks. According to the first one, the bulk medium is compressed during the passage of the incident main shock pulse and unloaded after the pulse is



**Figure 2.** Main and probing shock wave pulses in the bulk sand medium (sensors  $D0$ – $D3$ ). Panels  $a$  and  $b$  correspond to the diaphragms made of tracing paper and „Snegurochka“ paper (the steepness values in kPa/ms are indicated at the leading edges of pulses).

reflected. The upper layer of the fill relaxes, the medium becomes looser than in the initial state, and all this affects the behavior of the probing pulse: it travels through a looser medium, which results in the formation of a peak. According to the second hypothesis, the passage of an incident pulse through the upper layer of the sand fill is accompanied by gas filtration into this layer. When the pulse impact ceases, penetrating gas is released from the sand fill, inducing loosening of its top layer.

To test these hypotheses, aluminum foil  $8.0 \pm 0.5 \mu\text{m}$  in thickness with a mass of 0.046 g was fit tightly to the sand surface. The foil diameter was 4 mm larger than the diameter of the tube. The foil edges were bent into a trough shape; this structure shields almost completely the bulk medium from air flow penetration under the SWP influence. It follows from the comparison of characteristics of the main pulses in Figs. 2 and 3 that the pulse steepness values at sensor *D1* in the sand fill covered with foil (diagram *1a* in Fig. 3, *a*) are almost twice as large as the corresponding values in sand with an open surface (diagram *1a* in Fig. 2, *a*), while the pulse amplitude is 17% lower than in open sand. This significant increase in steepness is indicative of the fact that foil-shielded sand behaves like a stiffer medium.

Note that the probing pulse rise in the shielded fill is two-stage; within the first  $400 \mu\text{s}$ , the leading edge behaves as it would in a soft medium and is characterized by a low steepness of 10 kPa/ms (diagram *2a* in Fig. 3, *a*, *D1*), which is even smaller than the leading edge steepness of the first probing pulse in open sand (diagram *2a* in Fig. 2, *a*, *D1*). The pulse then rises sharply within  $90 \mu\text{s}$  at a rate of 670 kPa/ms, reaching an amplitude that exceeds the one of the main pulse by a factor of almost 2. After the impact of the first probing pulse, the second probing pulse is formed in the same shape as its predecessor with the same stepwise growth at rates of 8 and 680 kPa/ms (diagram *3a*, Fig. 3, *a*, *D1*). This feature is probably attributable to the formation of a top layer of loosened sand under the foil in the process of reflection of the main pulse. The signals at sensor *D2* are characterized by a sharp pulse rise; the values of steepness (230, 490 kPa/ms, diagrams *2b*, *3b*) and amplitude of the probing pulses are significantly higher (160 kPa/ms) than the corresponding parameters of the main pulse (*1b*). This indicates that the bulk medium under the foil becomes significantly stiffer than the medium with an open surface. An incident probing pulse propagates at a low velocity within the loosened layer and accelerates sand grains in it. Deeper layers are compacted, and accelerated sand grains together with the impact pulse form a peak at the leading edge on this stiff bulk medium.

The shape of the main pulse diagrams remains essentially unchanged when the same compacted bulk medium with the same shielding foil is exposed to an SWP with an amplitude (Fig. 3, *b*) two times higher than the previous one (Fig. 3, *a*). The probing pulse is formed without peaks with an edge steepness of 660 kPa/ms, which is two times lower than the main pulse steepness (1050 kPa/ms). An

incident pulse with twice the amplitude does not establish the conditions needed for loosening of the top layer of sand upon reflection. Following compaction by the main pulse, the skeleton returns to its original state within 13 ms, and the second and third probing pulses propagate in the same way as the main one.

A qualitative difference is revealed: the propagation of the probing pulse resulted in the formation of a peak (on the leading edge instead of the trailing one) with a greater steepness upon reflection of a small-amplitude SWP (Fig. 3, *a*). It should be noted that with a doubled SWP amplitude (Fig. 3, *b*), the mentioned peak is not formed and the edge steepness of the probing pulse is two times lower than that of the main pulse, while the edge steepness in the case of a small amplitude increased from pulse to pulse. If the peak height is neglected, the ratios of amplitudes of the main and probing pulses corresponding to two amplitudes differ little.

Thus, the peak at the trailing edge and its amplification with depth at small and large SWP amplitudes vanish in the case of shielding with foil. This confirms the validity of the second hypothesis, which states that the amplification effect is attributable to penetration of the gas phase into the compacted bulk sand medium exposed to an SWP.

In conclusion, we note the following.

— A shielding foil membrane has virtually no effect on the shape of the main pulse propagating in a bulk sand medium, but the amplitude of the pulse transmitted into sand is 15% lower than the amplitude of the pulse in an open bulk medium. This is attributable to the fact that SWPs do no longer propagate through the pore space of the bulk medium and pulsed filtration of gas into compacted sand is excluded.

— The main pressure pulse compresses the bulk sand medium and induces the formation of a thin loosened layer under the shielding foil upon SWP reflection; the state of compression is preserved until the arrival of the probing pulse.

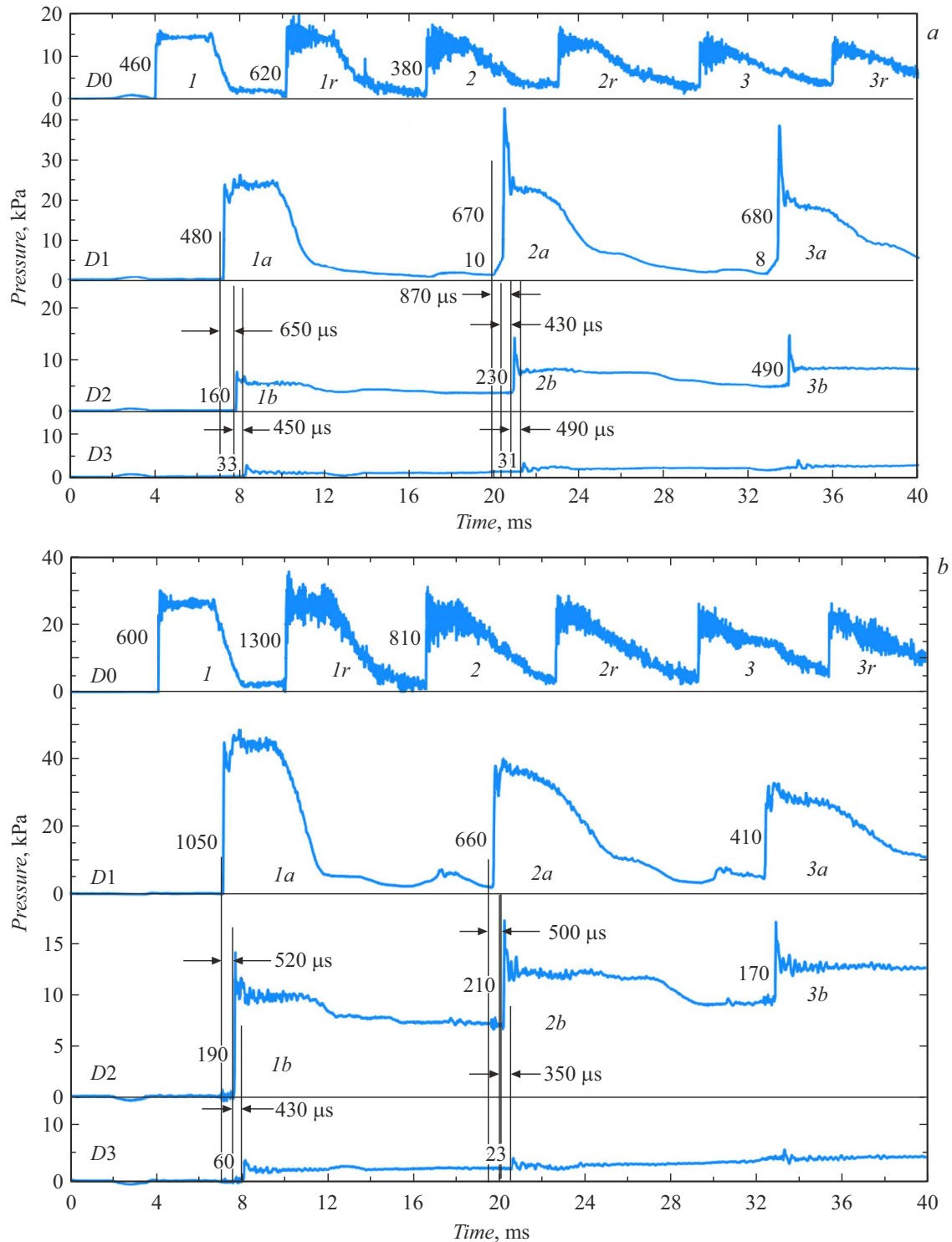
— The two-stage rise of the probing pulse is caused by the shock compression of the loosened sand layer above the compressed (stiffer) and compacted bulk medium; the peak is many (6) times steeper than the peak of the probing pulse in the open bulk medium.

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## Conflict of interest

The authors declare that they have no conflict of interest.



**Figure 3.** The same as in Fig. 2; the sand surface is shielded by aluminum foil (membrane).

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