Journal of Mining Science, Vol. 33, No. 1, 1997

ROCK MECHANICS

ANOMALOUSLY LOW FRICTION IN BLOCK MEDIA

M. V. Kurlenya, V. N. Oparin,
and V. I. Vostrikov

UDC 550.834+622.831

1. In investigating the mechanism by which pendulum-type waves (μ waves) appear, we discovered the disappearance of friction between interacting geological blocks at certain levels of pulsed perturbation in models of block media [1]. This is observed in directions orthogonal to the line of action of the external pulse. We have suggested that this effect may be due to apparent loss of contact between the surfaces of the interacting blocks. Analysis in terms of standing soliton waves provides estimates of $(2\text{-}5)\cdot 10^{-6}$ m for the apparent distance between the surfaces in the cases considered in [1].

This is one of those rare cases where a seemingly incidental result has broader significance [1-3]. The potential importance of this result was noted in [1, 3]. In this context, a number of questions arise regarding the mechanical conditions and other circumstances associated with the appearance of anomalously low friction in block media. Interested primarily in possible applications of this effect in geomechanical prediction and in explosive and drilling work near mineshafts, we have focused on the following topics in the initial research cycle reported here:

1) the relation between the absolute transverse displacement of the geological blocks in bilateral constrained conditions under the action (in different energy ratios) of a vertical pulsed excitation on the block system and a horizontal force (in pulsed and static approximations) on the working block;

2) the influence of the time delay between the horizontal and vertical pulsed excitations on the character of the transverse displacements of the working blocks.

2. To answer these questions, research is undertaken on two models.

Model 1 is a vertical system of six organic-glass blocks (250 × 125 × 85 mm; mass 3.25 kg).

Model 2 is a vertical system of six silicate-brick blocks (250 × 125 × 85 mm; mass 5.43 kg). The velocity of longitudinal waves is ${}^1V_p$ = 2814 m/sec in the organic glass and ${}^2V_p$ = 2662 m/sec in the silicate bricks.

Two experimental schemes are considered.

In scheme 1 (Fig. 1), we investigate the transverse pulsed reaction of block 3 under a static horizontal force, with a vertical pulse applied to the surface of block 1. A platform with a dynamometer is rigidly screwed to block 4. A screw connected to the dynamometer by means of a force regulator is attached to block 3. The necessary horizontal force for block 3 relative to blocks 2 and 4 is created by means of this regulator. A brace on the platform prevents the motion of block 2 with block 3. The center of a hardened screw is placed at point *a* of block 1 and serves as the point of vertical pulsed excitation. The vertical pulsed excitation is provided by a tempered steel pin of mass m = 82.71 g. To specify a different level of energy input to the block system, the pin is dropped from different heights with respect to point *a* of block 1. Taking account of skewing, the proportion of kinetic energy transferred from the pin to the block system is calculated.

In scheme 2 (Fig. 2), the transverse pulsed reaction of block 3 (absolute shear) under the action of a horizontal pulsed excitation (in contrast to the static horizontal force in scheme 1), with a vertical pulsed excitation at the surface of block 1 (as in scheme 1). In this case, the force regulator with the dynamometer is eliminated. The dynamic horizontal excitation of block 3 is specified by a steel ball (m = 226.9 g) suspended on a thread. By changing the angle of ball deviation, the energy of the pulsed horizontal excitation may obviously be changed. At point b of block 3, the same screw as in block 1 is inserted and

Institute of Mining, Siberian Branch, Russian Academy of Sciences, Novosibirsk. Translated from Fiziko-Tekhnicheskie Problemy Razrabotki Poleznykh Iskopaemykh, No. 1, pp. 3-16, January-February, 1997. Original article submitted October 7, 1996.

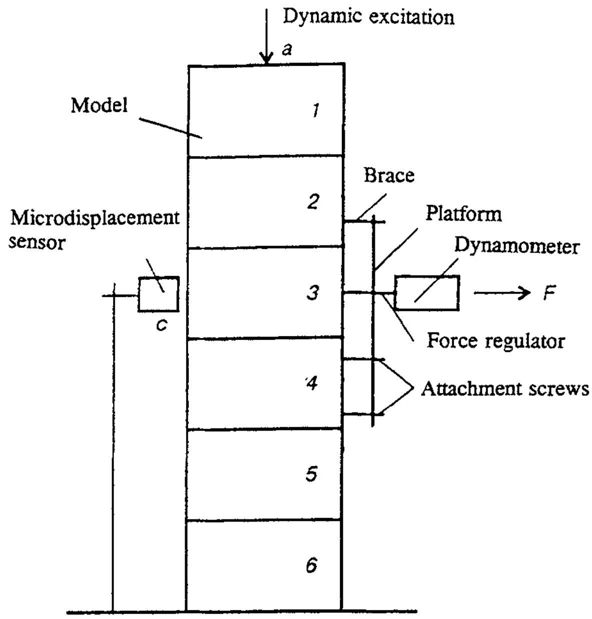

Fig. 1. Experimental scheme 1 for studying the transverse pulsed reaction of block 3 under the action of static horizontal forces, with vertical pulsed excitation of the surface of block 1.

serves as the point of horizontal pulsed excitation. Electromagnets EM-1 and EM-2 hold the pin and the steel ball in the initial state and are controlled by a special time-delay circuit, which specifies the delay Δt between the onset of free fall of the cylinder and the onset of steel ball motion, i.e., between the vertical and horizontal pulsed excitations.

3. The absolute displacement of block 3 is recorded by an optical displacement sensor specially developed in the laboratory of mine geophysics at the Institute of Mining, Siberian Branch, Russian Academy of Sciences. This sensor is a photooptical system placed in a mechanical structure for precise adjustment to the zero point. The operating principle of the sensor is explained in Fig. 3. An L-shaped arm made of thin opaque material is attached to the object (in this case, block 3). Part A of the arm is placed between the radiator and receiver of a photooptical system attached to the bracket of the mechanical system. A strip of shadow is projected by the arm in the IR flux of the source.

The receiver incorporates an FDK-12 photosensor based on a disk divided into four sectors made of photosensitive material. Using the mechanical system, the photooptical system is centered relative to the shadow from the arm. In the course of the measurements, displacement or deformation of the object produces a change in position of the shadow relative to the sectors of the receiver. The output signals from these sectors change accordingly and are analyzed by the measuring system.

A functional electrical diagram of the sensor is shown in Fig. 4. Radiator VD1 creates an IR flux at receiver VD2. The signal from the receiver is sent to amplifier 1 with a large input impedance and a transmission ratio of around 30 dB. Then the signal is sent to differential amplifier 2 with a transmission ratio of one. The use of the differential measuring scheme increases the conversion coefficient of the sensor and considerably reduces the effect of external noise. Low-frequency filter 3 eliminates parasitic high-frequency components of the signal. The conversion coefficient of the sensor is 4 V/mm.

Data analysis is by means of the measuring and computing complex (MCC) described in [2].

4. Now let's turn to the experimental results. In the first stage of the experiments, the threshold values of the static horizontal force F^0 required to set block 3 in motion in models 1 and 2 is measured, in conditions where there is no vertical pulsed excitation of the block system. The corresponding results are shown in Table 1. In Table 1a, block 3 (organic glass, silicate brick) is shifted together with the adjacent block 2 or blocks 2 and 1; in Table 1b, block 2 is attached to the platform and hence to block 4 (that is, block 3 moves between blocks 2 and 4). As may readily be established, the ratio between the forces required to overcome friction for silicate-brick and organic-glass blocks, in the case of motion of types 1-5 in Table 1, is as follows: 1) 3.08; 2) 3.13; 3) 2.70; 4) 2.82; 5) 2.95. The mean is approximately 2.94.

Thus, the frictional coefficient between the silicate blocks is approximately three times that for organic-glass blocks. The relative spread of the data with respect to the mean is no more than 7%. This large difference in the friction coefficients for the blocks is primarily due to the relief of the contacting surfaces.

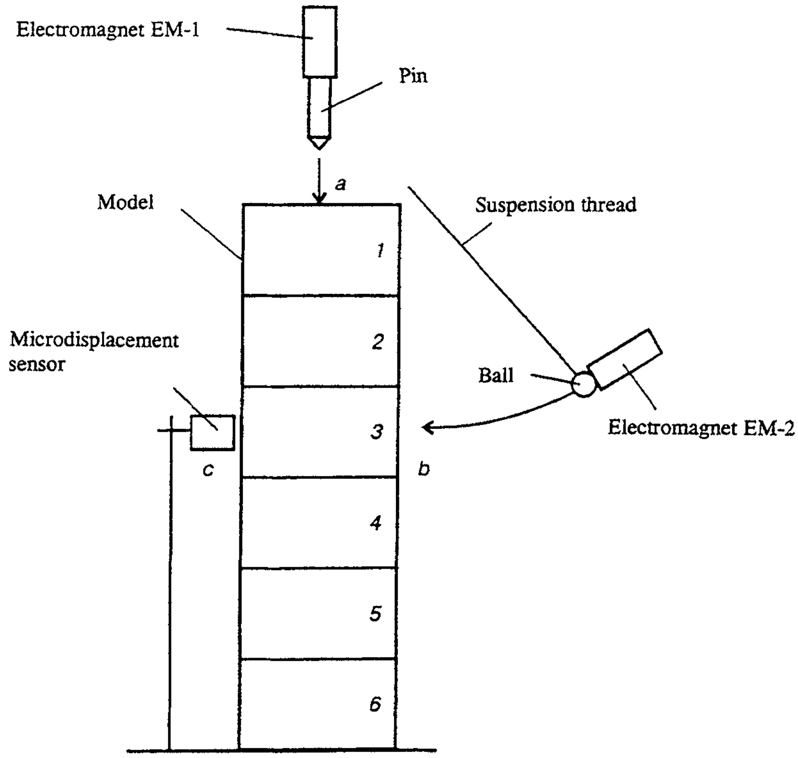

Fig. 2. Experimental scheme 2 for studying the transverse pulsed reaction of block 3 under the action of horizontal pulsed excitation, with vertical pulsed excitation of the surface of block 1.

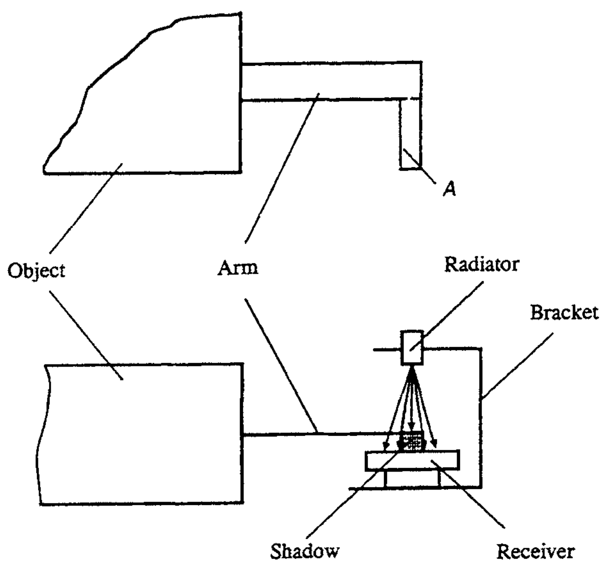

Fig. 3. Operating principle of optical absolute-displacement sensor.

In the second stages of the experiments, the shift values of block 3 for models 1 (organic glass) and 2 (silicate brick) under the action of a static horizontal force F and a vertical pulsed excitation of energy W are recorded (scheme 1). The results are shown in Fig. 5 for organic glass and model 1 and in Fig. 6 for silicate bricks and model 2. The absolute displacement of block 3 in the transverse direction is shown in Figs. 5 and 6 for specified F, with several energy characteristics of the vertical pulsed excitations.

TABLE 1

Model / Material	F^0, kg				
	(a) with no platform			(b) with a platform	
	1	2	3	4	5
Blocks:					
of organic glass	1,2	2,3	3,7	3,4	6,6
of silicate brick	3,7	7,2	10,0	9,6	19,5

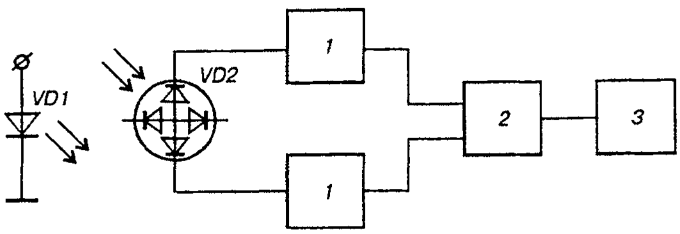

Fig. 4. Functional electrical diagram of optical absolute-displacement sensor.

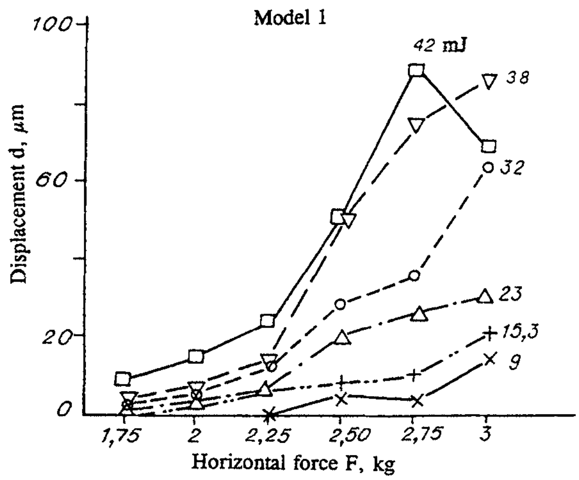

Fig. 5. Dependence of the transverse displacement of block 3 under the action of a static horizontal force F and a vertical pulse of energy W for model 1 (organic glass).

First consider Fig. 5 in comparison with the data in column 5 of Table 1 for model 1. Note that the first notable displacement of block 3 is observed when F is significantly less than F^0. For example, when $W_{ex} \cong 42$ MJ, displacement d $\cong 10$ μm occurs when F $\cong$ 1.75 kg, whereas $F^0 \cong 6.6$ kg, i.e., $F^0/F \cong 3.8$. There is a significant improvement in the force characteristics when the blocks are moved in constrained conditions.

The general properties of the transverse displacement d of block 3 in Fig. 5 for different levels of the vertical pulsed excitation W_{ex} (9-42 MJ) in the block system are:

1) practically monotonic increase in the force on the working block 3 with increase in energy of the vertical pulse W_{ex} for fixed F;

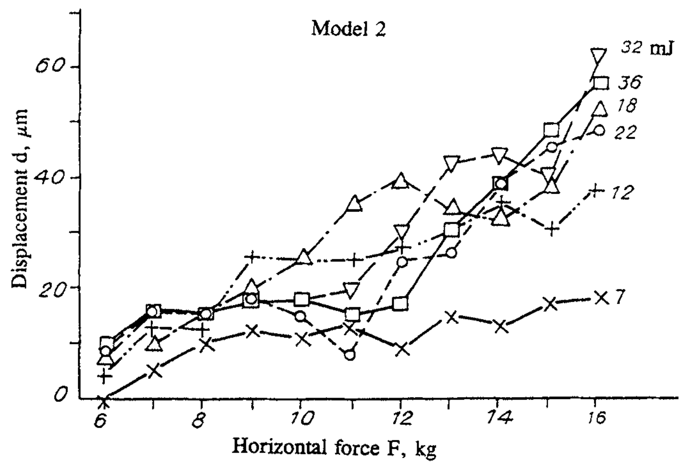

Fig. 6. Dependence of the transverse displacement of block 3 under the action of a static horizontal force F and a vertical pulse of energy W for model 2 (silicate brick).

2) a practically parabolic relation between the increase in d for the working block and the increase in lateral (horizontal) force F.

Thus, in the case when F = 2.75 kg, it is evident that increasing the energy of the vertical pulse from 9 to 42 mJ increases the lateral displacement of block 3 from 5 to 90 μm, i.e., by a factor of 18. At the same time, the pulse energy increases by a factor of no more than 4.7. On the other hand, if the influence of F on the displacement of block 3 is considered with a fixed energy of the vertical pulse (say, $W_{ex} \cong 42$ mJ), increase in F from 2.25 kg ($F/F^0 \cong 0.34$) to 2.75 kg ($F/F^0 \cong 0.42$) increases the displacement d of block 3 from 24 to 90 μm, i.e., by a factor of 3.75, whereas F increases only by a factor of ≅1.24.

Let's compare Fig. 6 with column 5 in Table 1. The basic features of the displacement of the silicate block are analogous to those of the organic-glass block. Perhaps the only difference is the scale of the abscissa. If the abscissa in Figures 5 and 6 is converted to the ratio F/F^0, even this difference practically disappears. The influence of the increased surface roughness of the silicate blocks is apparent in the quasi-monotonic structure of the displacement curves in Fig. 3. This, of course, must lead to increase in the value of F/F^0 corresponding to the same transverse shift d of the block with the same energy W_{ex} of the vertical pulsed excitation. For example, according to Figs. 5 and 6, F/F^0 is 0.45 and 0.82 for blocks of organic glass and silicate brick when $W_{ex} \cong 32$ MJ and d ≅ 63-65 μm. In view of the difference in F/F^0 for organic glass and silicate brick, we may conclude that the mean amplitude roughness characteristics of the corresponding surfaces may differ approximately twofold. This is realistic in view of the manufacturing technology used for the model blocks. The results of the third stage of the experiment confirm this conclusion.

In the third stage of the experiments, the deformation of block 3 at point c is recorded for models 1 and 2 under the action solely of a vertical pulsed excitation. The corresponding results are shown in Fig. 7 for model 1 made of organic glass and in Fig. 8 for model 2 made of silicate brick: the absolute displacements are shown in Figs. 7a and 8a and their spectra in Figs. 7b and 8b. For comparison, the absolute displacements of the same blocks in the same measurement scheme but with the additional action of a horizontal force on block 3 are shown in Figs. 7c and 8c.

Combined analysis of Figs. 7 and 8 shows that, in fact, the amplitude of the displacement of the silicate-brick and organic-glass blocks in the direction orthogonal to the pulsed excitation differs by about a factor of two (low-frequency oscillations for time segments t ≥ 75 msec must be considered). In addition, according to Figs. 7b and 8b, the fundamental carrier harmonics in the high-frequency (537.11 ± 4.9 Hz for organic glass and 285.2 Hz for silicate) and low-frequency (19.5 ± 4.9 Hz for organic glass and 13.7 Hz for silicate) regions also differ by a factor of approximately two for silicate and organic-glass blocks in the given measurement schemes. Given the similar longitudinal wave velocities for the materials employed, these features of the dynamic displacement of blocks of the same size may only be due to the analogous ratios of the linear roughness dimensions of the contacting block surfaces. Finally, note the ratio between the sharp spectral maxima for model 1 (${}^1f_U = 537.11 \pm 4.9$ Hz and ${}^1f_L = 19.5 \pm 4.9$ Hz in Fig. 7b) and model 2 (${}^2f_U = 285.2$ Hz and ${}^2f_L = 13.7$ Hz in Fig. 8b). It may readily be established that

$$\frac{{}^if_U}{{}^if_L} \cong \chi = (\sqrt{2})^9.$$

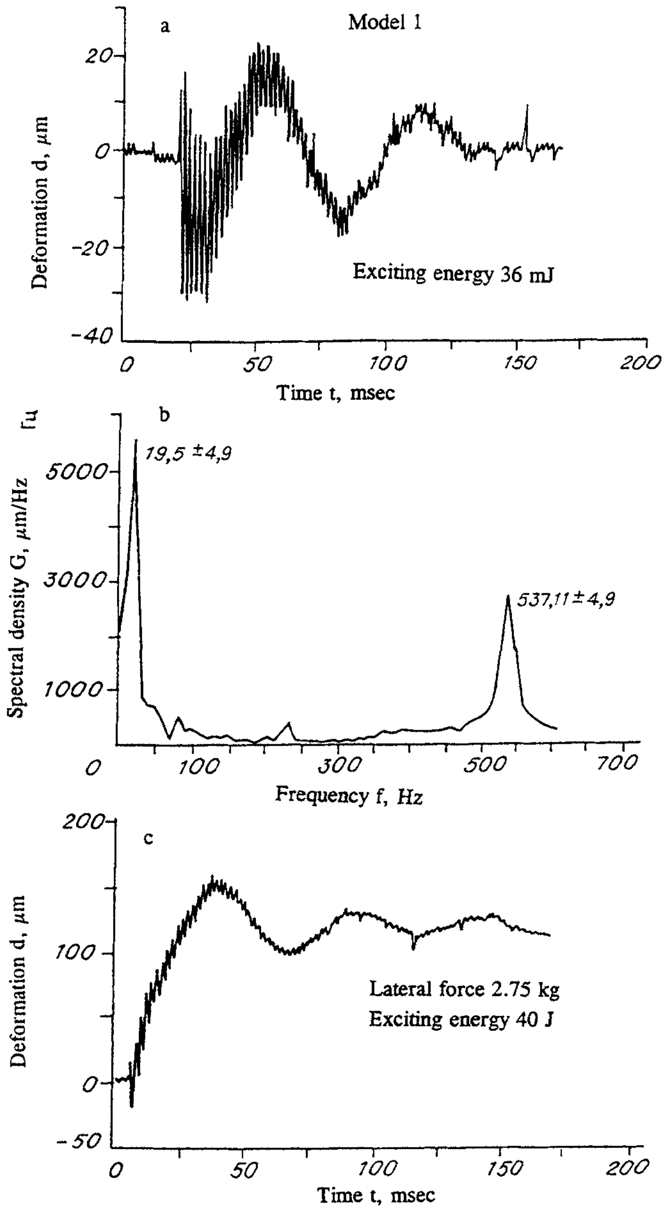

Fig. 7. Transverse deformations over time (a) and their spectra (b) under the action of a vertical pulsed excitation in model 1 (organic glass, recording at point c); c) transverse displacements in model 1 under the combined action of a vertical pulsed excitation and static horizontal force F.

The coefficient χ was first introduced in [2] on the basis of structural analysis of the spectral filling of the elastic wave packets with pulsed excitation of block media on the basis of acoustic measurements.

In the final stage of the experiment, scheme 2 is used. In this case, experiments are only conducted on model 2 made of silicate blocks; the combined action of vertical and horizontal pulsed excitations of different energy on block 3 is investigated. The displacement of this block is shown in Fig. 9a solely as a function of the action of horizontal pulsed excitation of energy W_h = 42 mJ for a series of 29 experiments in a particular sequence (after each experiment and excitation, block 3 is returned to its initial position). The displacement of block 3 under the combined action of vertical and horizontal pulsed excitations of energy W_v = 37 mJ and W_h = 24 mJ is shown in Fig. 9b as a function of the delay Δt between these pulses. The transverse displacement of block 3 is shown in Fig. 10a for a series of 123 experiments under the action solely of horizontal pulsed excitations, each of energy 16 mJ (after each pulse, the block is returned to the initial state). The displacement of block 3 is shown in Fig. 10b as a function of the time delay between vertical and horizontal pulses of energy W_v = 73 mJ

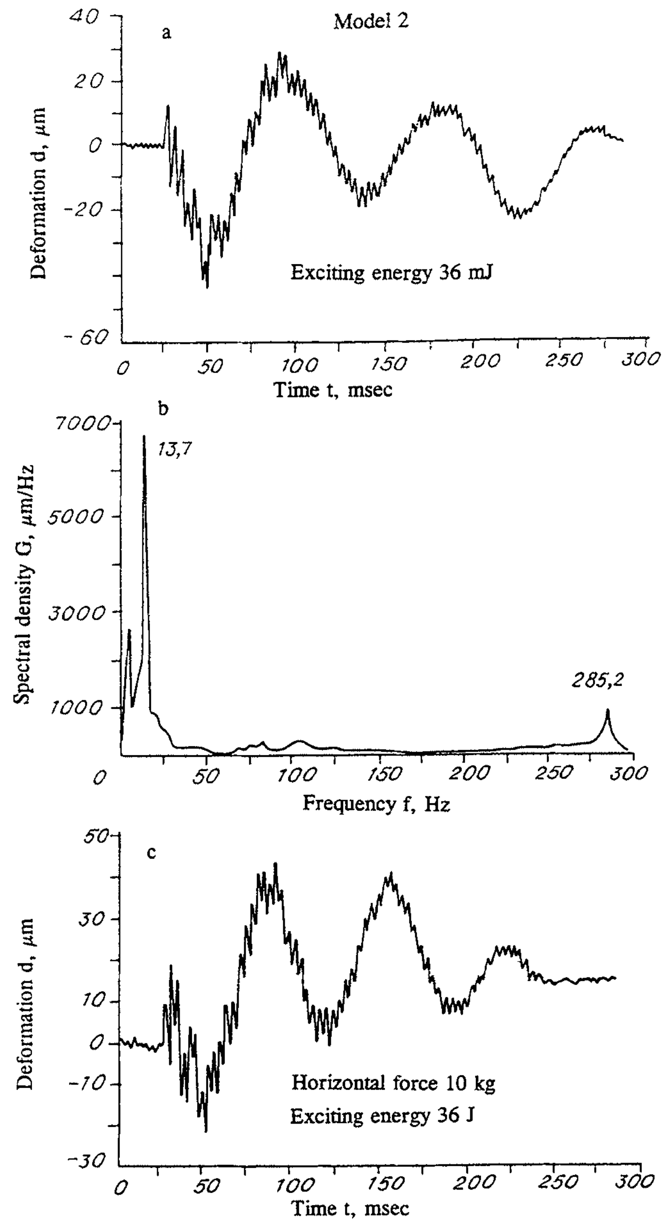

Fig. 8. Transverse deformations over time (a) and their spectra (b) under the action of a vertical pulsed excitation in model 2 (silicate, recording at point c); c) transverse displacements in model 2 under the combined action of a vertical pulsed excitation and static horizontal force F.

and W_h = 16 mJ for 20 individual experiments. In Fig. 11a, the transverse displacement of block 3 is shown for a sequence of 41 experiments under the action only of horizontal pulses, each of energy 106 mJ (block 3 is returned to the initial state after each pulse). The displacement of block 3 is shown in Fig. 11b as a function of the time delay between vertical and horizontal pulses of energy W_v = 73 mJ and W_h = 106 mJ for 31 individual experiments.

Analysis of the experimental data in 9-11 is undertaken to answer the following questions:

1) What is the reproducibility of the transverse displacements of block 3 at several specified energies of the horizontal pulse if there is no vertical pulse? What are the mean transverse displacements of the blocks in that case?

2) What is the structure of the relation between the transverse displacements of block 3 at several specified energy levels of the vertical and horizontal pulses and the time delays between them?

3) How much do the mean transverse displacements of block 3 differ for the case when block 3 is subject only to a horizontal pulse of specified energy and to the horizontal pulse and an additional vertical pulse?

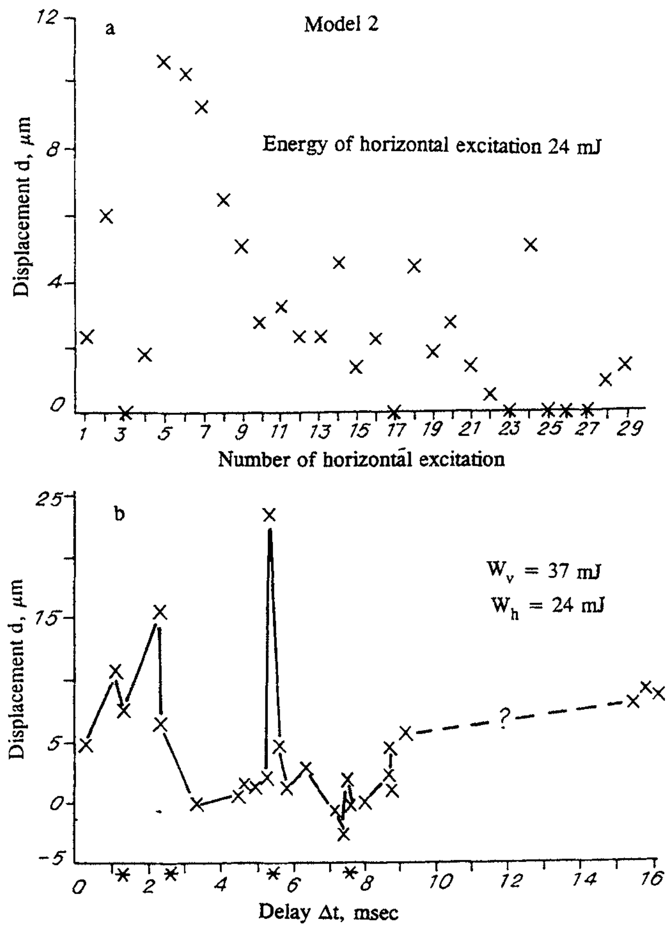

Fig. 9. (a) Reproducibility of experiments on the transverse deformations of block 3 under the action of a horizontal pulsed excitation of energy $W_h = 24$ mJ for 29 experiments; (b) canonical relation — with modulus $(\sqrt{2})^i$, $i = 0, \pm1, \pm2, \ldots$ — of the time delay between the vertical and horizontal pulsed excitations with $W_v = 37$ mJ and $W_h = 24$ mJ.

Let's look at the first question. Analysis of Figs. 9a-11a permits the calculation of the mean absolute displacement d_{me} of block 3 under the action of horizontal pulses of energy 24.16 and 106 mJ. Thus, when $W_h = 24$ mJ, $d_{me} = 3.2$ μm ($d_{max} = 10.7$ μm); when $W_h = 16$ mJ, $d_{me} \cong 2$ μm ($d_{max} \cong 8.8$ μm); when $W_h = 106$ mJ, $d_{me} = 29.5$ μm ($d_{max} = 66$ μm). Hence, with increase in energy from 16 to 106 mJ (by a factor of ~ 6.63), there is a corresponding increase in transverse displacement by a factor of 14.75; i.e., for the given energy range, the rate at which the displacement of block 3 increases is twice the rate of energy increase. Comparison of d_{me} and d_{max} for the given energy levels according to the formula $\delta = d_{max}/d_{me}$ shows that the parameter δ characterizing the reproducibility of the experiments may vary in the range 2.3-4.4.

Now consider the second question. Careful analysis of the structure of Figs. 9b-11b reveals a very important feature: the canonical dependence of the significant local maxima of the transverse displacement of block 3 (with modulus $\sqrt{2}$) on the relative time delay of the vertical and horizontal pulses. If the basic value $\Delta t = 5.4$ msec (which corresponds to the clear maximum $d = 23$ μm in Fig. 9b), the canonical values of the series (msec) are as follows: $\Delta t_0 = 5.4$; $\Delta t_1^- = \Delta t_0/\sqrt{2} \cong 3.8$; $\Delta t_2^- = \Delta t_0/2 \cong 2.7$; $\Delta t_3^- = \Delta t_0/2\sqrt{2} \cong 1.9$; $\Delta t_4^- = \Delta t_0/4 = 1.4$; $\Delta t_8^- = \Delta t_0/8 \cong 0.7$; $\Delta t_1^+ = \sqrt{2}\Delta t_0 \cong 7.6$; $\Delta t_2^+ = 2\Delta t_0$; $\cong 7.6$; $\Delta t_3^+ = 2\sqrt{2}\Delta t_0 \approx 15.3$. These values agree (with a relative accuracy no worse than 5%) with the significant local maxima of d as a function of Δt (marked by asterisks at the abscissa) in Figs. 9b-11b, even though the energy characteristics of the pulses are significantly different in these cases. This indicates that the relation between Δt and d is a fundamental property, which is of particular importance in terms of specifying the optimal pulse conditions to generate anomalously low friction in various contexts. Another intriguing conclusion from Fig. 9b is that, when $\Delta t \in 7.0$-7.3 msec, the block reaction is the opposite of what is expected; i.e., in that range, block 3 begins to move in the opposite direction to the horizontal-pulse vector. This is a seemingly paradoxical case. Unless we consider the role of the rough block surfaces and

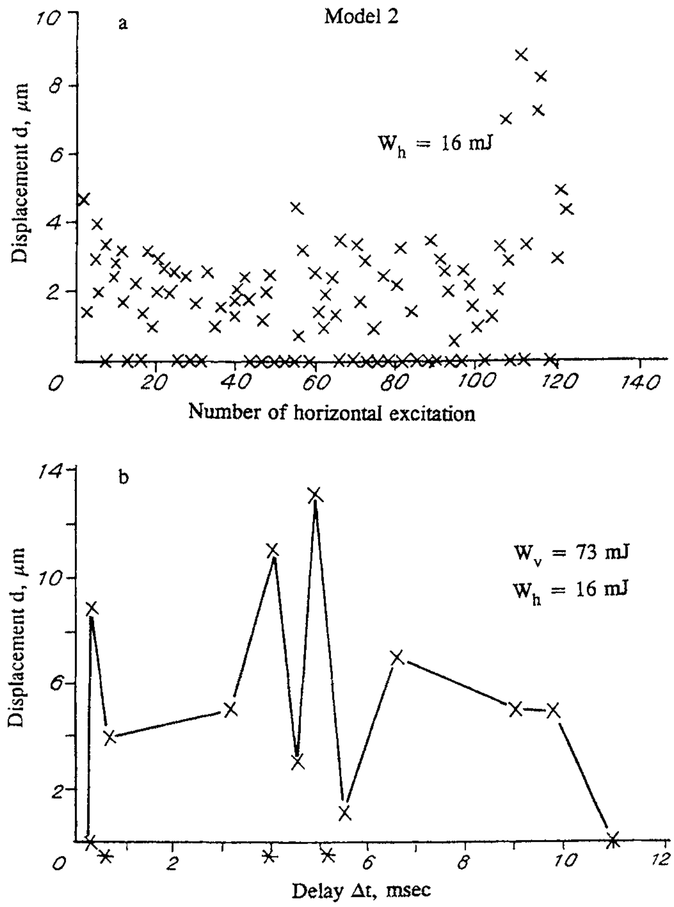

Fig. 10. As in Fig. 9, but for W_v = 73 mJ, W_h = 16 mJ.

a resonant mechanism for the appearance of anomalously low friction between the blocks, we would be at a loss to explain this phenomenon.

Finally, let's turn to the third question, it is simple to calculate the mean transverse displacement of block 3 from Figs. 9b-11b for the case with horizontal and vertical pulses. Thus, for the conditions in Fig. 9b (W_v = 37 mJ, W_h = 24 mJ), we have d_{me} = 4.8 μm (d_{max} = 23 μm); for the conditions in Fig. 10b (W_v = 73 mJ, W_h = 16 mJ), we have d_{me} = 6 μm (d_{max} = 13 μm); for the conditions in Fig. 11b (W_v = 73 mJ, W_h = 106 mJ), we have d_{me} = 29.5 μm (d_{max} = 66 μm). In considering the first question, we gave the corresponding values of d_{me} (d_{max}) for the same values of W_h when W_v = 0. It is of practical interest to compare the case with different W_v at fixed W_h (on the basis of Figs. 8-11). Comparison of the corresponding data in Fig. 9a,b for W_h = 24 mJ indicates that increasing W_v from 0 to 37 mJ increases d_{me} from 3.2 to 4.8 μm (a factor of 1.5), while d_{max} increases from 10.7 to 23 μm (a factor of ~2.2). Comparison of the data in Fig. 10a,b for W_h = 16 mJ indicates that increasing W_v from 0 to 73 mJ increases d_{me} from 2 to 6 μm (a factor of 3), while d_{max} increases from 8.8 to 13 μm (a factor of ~1.47). Comparison of the data in Fig. 11a,b for W_h = 106 mJ indicates that increasing W_v from 0 to 73 mJ increases d_{me} from 36.3 to 29.5 μm (a factor of 1.23), while d_{max} increases from 62 to 66 (a factor of 1.07). As is evident from the last example, analysis in terms of d_{me}, without taking account of Δt, may lead to inaccurate conclusions regarding the relation between the real block displacement d and the pulse energy. The situation is different when this relation is considered in terms of the canonical relationship of the significant local maxima of d with Δt. Averaging the significant local maxima leads to a characteristic for d that already has a monotonically increasing dependence on the energy parameters, as may be established by direct estimates on the basis of Figs. 9-11.

The functional approximation of the dependence of d on W_h, W_v, and Δt discussed here for various geological materials requires independent investigation. As our present study indicates, this is a pressing problem.

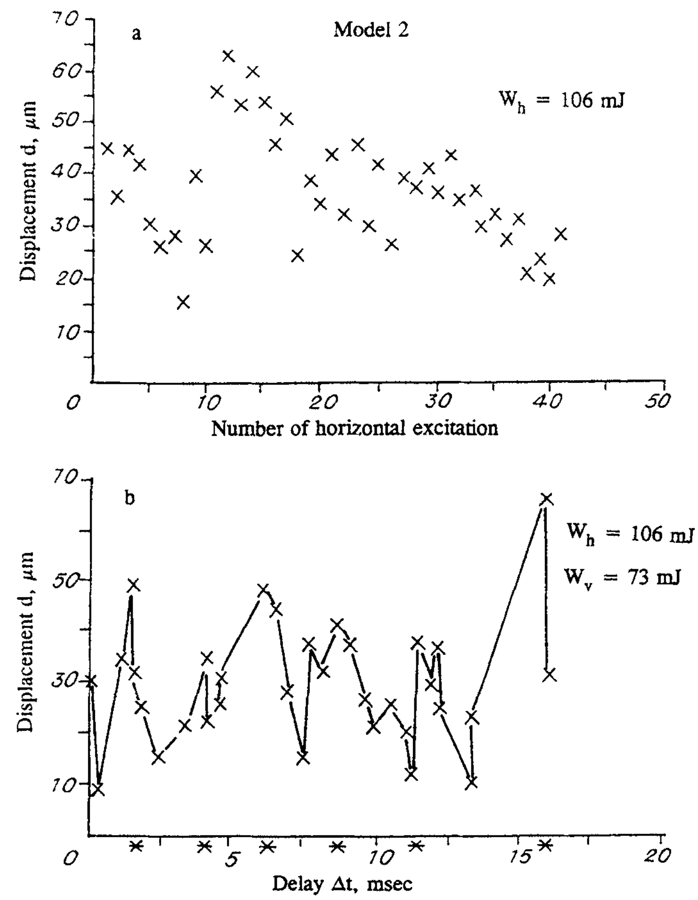

Fig. 11. As in Fig. 9, but for $W_v = 73$ mJ, $W_h = 106$ mJ.

CONCLUSIONS

1. Under the combined action of a static horizontal force F on the working block and a vertical pulsed excitation with energy W_v on the block system as a whole, horizontal (transverse to W_v) displacement of the working block occurs at values of F much less than F^0, the threshold value of the static horizontal force to overcome the static friction of the working block in constrained conditions when $W_v = 0$.

2. The following general properties may be stated for the transverse displacement d of working blocks of geological materials:

– practically monotonic increase of d with increase in energy of the vertical pulse W_v at fixed horizontal force F;

– a near-parabolic dependence of the increase in d on the increase in F at fixed W_v.

3. Analogous properties may be formulated for the case when a vertical pulsed excitation acts on the block system and a horizontal pulsed excitation acts on the working block; in this case, there is a canonical relation (with modulus $\sqrt{2}$) of the time delay between the vertical and horizontal pulses

$$\delta t_i = (\sqrt{2})^i \times \delta t_0, \quad i = 0, \pm 1, \pm 2, \ldots; \quad \delta t_0 = \frac{V_p}{\chi 2\Delta}; \quad \chi = (\sqrt{2})^9 \cong 22{,}63,$$

where Δ is the characteristic linear dimension of the working blocks; V_p is the longitudinal wave velocity in the block material. This conclusion is an obvious consequence of the data in [1] and a comparison of the fundamental carrier harmonics in the high-frequency (285.2 Hz) and low-frequency (13.7 Hz) regions of the spectrum of transverse displacements of silicate blocks with a basic frequency $f_0 = V_p/2\Delta$.

4. Comparison of the amplitude values of d in the present study confirms the hypothesis in [1] that the anomalously low friction in block media is a resonance phenomenon and indicates that the theoretical estimates in [1] for the relative adhesion of the blocks on the basis of standing soliton waves are correct.

This work was conducted with financial support from the Russian Fund for Fundamental Research (grant 96-05-66052).

REFERENCES

1. M. V. Kurlenya, V. N. Oparin, and V. I. Vostrikov, "Pendulum-type waves. II. Experimental method and basic results of physical modeling," Fiz.-Tekh. Probl. Razrab. Polezn. Iskop., No. 4 (1996).
2. M. V. Kurlenya, V. N. Oparin, and V. I. Vostrikov, "Pendulum-type waves. I. State of the problem and measuring and computational resources," Fiz.-Tekh. Probl. Razrab. Polezn. Iskop., No. 3 (1996).
3. M. V. Kurlenya, V. N. Oparin, V. I. Vostrikov, et al., "Pendulum-type waves. III. Data of full-scale observations," Fiz.-Tekh. Probl. Razrab. Polezn. Iskop., No. 5 (1996).
4. M. V. Kurlenya and V. N. Oparin, "Scale factor in the zonal disintegration of rock and canonical series of atomic—ionic radii," Fiz.-Tekh. Probl. Razrab. Polezn. Iskop., No. 2 (1996).