EFFECT OF STATIC PRESSURE ON THE MOTION OF SAND FOLLOWING AN EXPLOSION

O. S. Kolkov, V. I. Kulikov,
A. M. Tikhomirov, and A. F. Shatsukevich

In [1, 2] sand motion resulting from the spherically symmetric subsurface explosion of a chemical explosive and an electrical explosion was experimentally investigated. Complete pictures of the motion were obtained for both sources and compared. It was shown that the wave pictures are qualitatively the same and, moreover, with a certain degree of accuracy, the explosions may be assumed similar. This makes the electrical explosion a convenient source for the experimental investigation of the phenomena associated both with the properties of the explosion source and the mechanical properties of the soil. We have attempted to determine how static pressure affects the motion of dry sand in the presence of chemical and electrical explosions. We have obtained the spatial distribution of the mass velocity of sand compressed by an excess pressure $\Delta p = 1$ kgf/cm^2 and its variation in time. The results are compared with those obtained for loose ($\Delta p = 0$) sand.

1. Experimental Method. In the experiments the sand was subjected to omnidirectional compression under a pressure of about 1 kgf/cm^2 ("reinforced" sand). The bulk density of the sand $\rho_0 = 1.55$ g/cm^3 and remained almost unchanged when a pressure of 1 kgf/cm^2 was applied. As explosion sources we used spherical charges of PETN weighing 2.5 g at a density of 1.4 g/cm^3 and a powerful spark discharge (electrical explosion) produced by a device developed at the Institute of Geophysics of the Academy of Sciences USSR. For comparison we used the experimental results previously obtained by the authors in experiments on loose sand [1, 2].

The experimental setup is shown schematically in Fig. 1. The discharge was initiated at the bottom of the tank 1 (solid brass plate), at the end of a coaxial discharger 2 measuring 20 mm in diameter. The energy released (8.5 kJ) was monitored in each experiment by oscillographing the current and voltage in the discharge gap. The mass velocity of the different layers was measured directly as a function of time. The measurement method was based on the registration of the emf induced in probe 3 as it moved together with the sand in the constant inhomogeneous magnetic field created by an external source. The method is described in more detail in [1]. In order to create omnidirectional compression the sand was placed in a rubber bag 5, from which the air was evacuated. Thus, the sand was compressed by an excess pressure of about 1 kgf/cm^2. A similar means of creating external pressure has been employed by a number of American investigators studying the propagation of plane compression waves in cylindrical sand samples. An extensive bibliography may be found in [3].

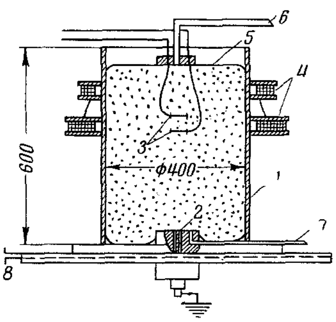

Fig. 1

In the experiments with explosive charges the discharger was replaced by a brass insert containing the charge. In other respects, the experimental conditions were the same as for the electrical explosions.

The experiments showed that the effect of "reinforcement" on the motion of the sand was much more strongly expressed in the case of an electrical explosion. Accordingly, the results presented below chiefly relate to electrical explosions.

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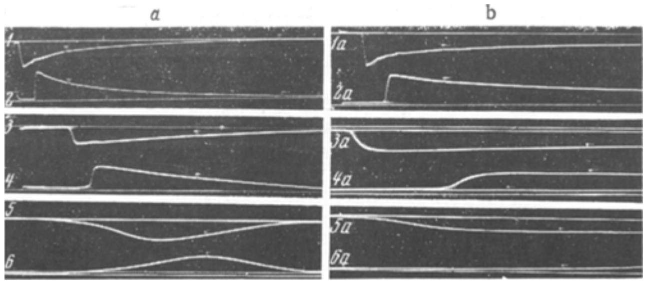

Fig. 2

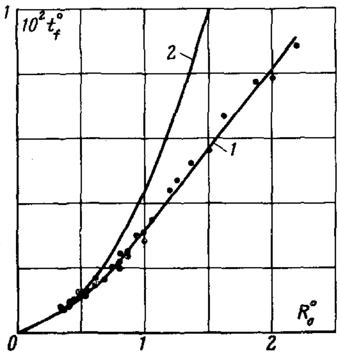

Fig. 3

Special experiments were performed to ascertain the effect on sand motion of the presence of air at the electrical explosion center. The air was evacuated from the entire volume except for a zone immediately adjacent to the discharger. The results of these experiments coincided with the results obtained by evacuating the entire volume

2. Experimental Results. For convenience of comparison with [1, 2] we employ the reduced distances $R^\circ = R/C^{1/3}$ and times $t^0 = t/C^{1/3}$. Here, R is the distance from the explosion center (m), t is time reckoned from the instant of explosion (sec), and C is twice the weight of the charge of TNT equivalent in energy to the explosion in question (kg). For an energy of 8.5 kJ $C = 4.08 \cdot 10^{-3}$ kg.

In Fig. 2 oscillograms of the mass velocity of the soil for electrical explosions in "reinforced" (a) and loose (b) sand at the same energy are presented for the following initial distances R_0 of the probes from the center of the explosion:

a)	b)
$1 - R_0 = 0.07$ m	$1 - R_0 = 0.09$ m
$2 - R_0 = 0.09$ m	$2 - R_0 = 0.11$ m
$3 - R_0 = 0.14$ m	$3 - R_0 = 0.16$ m
$4 - R_0 = 0.16$ m	$4 - R_0 = 0.22$ m
$5 - R_0 = 0.30$ m	$5 - R_0 = 0.30$ m
$6 - R_0 = 0.35$ m	$6 - R_0 = 0.35$ m

The interval between time marks is 1 msec. A comparison of the oscillograms obtained at the same distances shows that "reinforcing" the sand has an important influence on the development of the motion in time. Both the rise time of the mass velocity to a maximum and the total duration of the positive phase are reduced. With distance from the explosion center the mass velocity rise time increases, whereas the time in which it subsequently decays to zero decreases. The total duration of the positive phase decreases with distance and can be approximately described by the equation

$$\tau^+ = 0.98 \cdot R_0^{-0.2} \quad (0.06 \leqslant R_0 \leqslant 0.35) \tag{1}$$

Here, R_0 is in meters and τ in msec.

The time of arrival of the front (mass velocity maximum) is plotted against the initial distance from the explosion center in Fig. 3, where 1 corresponds to an electrical explosion in "reinforced" sand and 2 to an electrical explosion in loose sand. The curves begin to diverge almost at the very beginning of the measurement interval. Below we present values of the propagation velocity of the front obtained by graphic differentiation of curve 3 and the corresponding values for loose sand:

R_0° m/kg$^{1/3}$ =	0.4	0.6	0.8	1.0	1.5	
D m/sec =	400	280	220	200	200	(a)
D m/sec =	300	190	120	92	75	(b)

It should be noted, however, that the constancy of the velocity at $1.0 \le R_0^\circ \le 2.2$, obtained as a result of plotting a linear relation on that interval in Fig. 3, is not completely convincing. In fact, at a sufficient distance from the explosion center the propagation velocity of the front should tend to a constant value equal to the speed of sound (about 400 m/sec). Thus, the propagation velocity, after reaching a certain minimum, probably increases again, i.e., curve 1 (Fig. 3) should have a point of inflection. However, it is not possible to plot such a curve because of the experimental scatter.

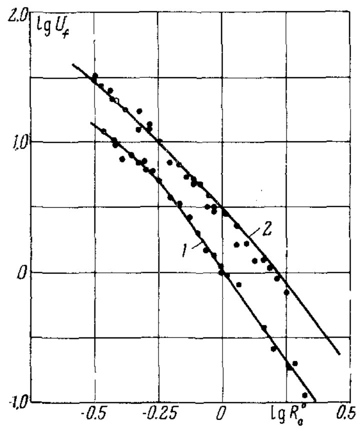

Fig. 4

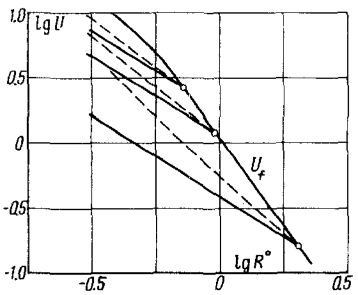

Fig. 5

In Fig. 4 the maximum mass velocity (particle velocity at the front) is shown as a function of the reduced initial distance from the explosion center for an electrical explosion 1 and a chemical explosion 2. The experimental points are for "reinforced" sand; the curves are based on the data of [1, 2] for loose sand. As follows from the figure, when the sand is "reinforced" with a pressure of 1 kgf/cm^2 there is practically no change in the maximum mass velocity for either an electrical or a chemical explosion. To compare the nature of the deformation of the soil behind the wave front in loose and "reinforced" sand, it is interesting to construct the mass velocity distribution behind the front with respect to the Euler coordinate:

$$R = R_0 + \Delta R$$

where R_0 is the initial coordinate of the probe, and ΔR is the displacement. The U(t) relations for various R_0 are obtained directly from the oscillograms. Having a set of such relations, it is easy to obtain the mass velocity distributions with respect to the initial coordinate for various instants. The transition to the Euler coordinate distributions is effected by taking the displacements into account. In Fig. 5 these relations are given for three positions of the front in the case of electrical explosions in "reinforced" (solid lines) and loose (dashed lines) sand. The circles in Fig. 5 represent the position of the front, the line drawn through them corresponds to the maximum mass velocity. As follows from the figure, the velocity distributions behind the front are essentially different for loose and "reinforced" sand. Whereas with propagation of the front the distribution law for loose sand tends toward the law

$$U = U_f \left(\frac{R_f}{R}\right)^2$$

where R_f is the coordinate of the front, for "reinforced" sand a power law with an exponent that does not depend on time,

$$U = U_f \left(\frac{R_f}{R}\right)^{1.25} \quad (0.3 \leqslant R^\circ \leqslant R_f^\circ), \tag{2}$$

is satisfied over the entire range investigated.

The existence of such a law indicates that the fall in density behind the front is much more intense in the "reinforced" as compared with the loose sand.

Thus, even a relatively small (1 kgf/cm^2) increase in static pressure sharply changes the motion of the sand behind the wave front. At the same time, the maximum mass velocity is practically unaffected by the "reinforcement" of the sand.

A comparison of the results obtained with those of [4] and numerous investigations recently carried out by Grigoryan and co-workers showed that within the limits of error of the individual series of experiments the laws of attenuation of the maximum mass velocity are in fairly good agreement, although the media compared (loose and "reinforced" dry sand, moist sand, loess, clay, and frozen loam) actually cover the entire range of soft soil types. However, further research is required to account for this fact.

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