# STUDY OF THE EFFECT OF EXPLOSIVE SHOCK LOADS ON SOFT SOIL

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Soft soils are complex multiphase media consisting of solid granules, water, and air, with the latter two constituents found in the intergranular space. The study of the behavior of such soils when subjected to high-intensity shock loads is of both scientific and practical interest.

Systematic experimental study of the mechanical property of soft soils subjected to explosive shock loading was begun at the end of the 1950s (see [1-6], for example). However, the measured pressure was no greater than 75 MPa in almost all of the studies. The investigations [2, 4] examined the properties of sand during shock-wave loading in the high-pressure region. Lagunov and Stepanov [2] obtained the Hugoniot curve of dry sand with the density $\rho_{00}$ = 1.66 g/cm³ within the stress range from 100 MPa to 5 GPa. Also found was the dependence of particle mass velocity in the unloading wave upon exit of the plane shock wave (SW) at the free surface $u_1$ on the mass velocity in the incident SW u within the interval 50-800 m/sec. It turned out that $u_1/u = 1.36$ throughout this interval. Dianov et al. [4] obtained the Hugoniot curves of four fractions of dry sand within the stress range from 1 to 6 GPa and two fractions of water-saturated sand in the range from 2 to 12 GPa.

Below, we report certain results from the measurement of the compressibility of piled sand (at its natural moisture content) in transmitted and reflected SWs created by the detonation of a plane layer of explosives. The measurements were obtained for the stress range 6-230 MPa. We also present results of measurements of the mass velocity of particles in the unloading wave when the SW reaches the free surface.

The propagation of plane SW's in piled sand of the density $\rho_{00}$ = 1.66 g/cm³ and moisture content w = 4-5% was studied on the unit shown in Fig. 1. The sand 1 was poured into a segment of a thick-walled steel tube 4 (internal diameter 75 mm, wall thickness 40 mm, height 4, 8, 12, and 16 cm) set on a steel slab 6. The sand was loaded by the explosion of a disk of explosive 2 of the thickness $\Delta_{EX}$ = 1.5, 3.0, and 4.5 mm. The explosion was initiated at the center of the sand. A striker plate 3, made of aluminum alloy AMg6 of thickness 2 mm, was placed between the explosive and the sand. The striker was 2 mm thick. The normal stress in the sand was measured with piezoelectric pressure gauges 5 [7] placed in the sand at distances x = 2, 4, 8, and 12 cm from the striker. The normal stress in the SW reflected from the steel slab was measured by a pressure gauge embedded in the slab flush with its surface.

To exclude the effect of lateral pressure on the piezoelement, an air gap of about 0.5 mm was left between the piezoelement of the gauge and its body (made of titanium alloy VT-4). Thus, the gauge measured only the stress normal to the gauge's surface. The diameter of the

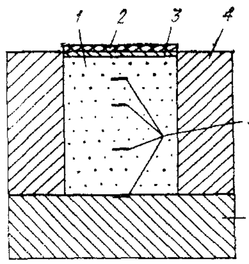


Fig. 1

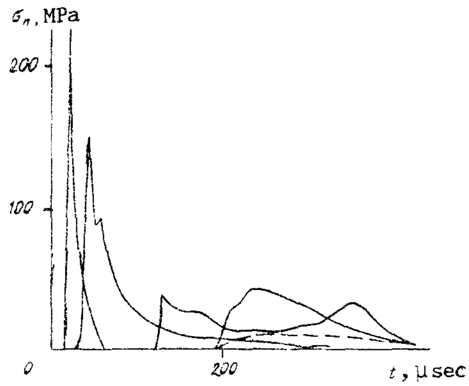


Fig. 2

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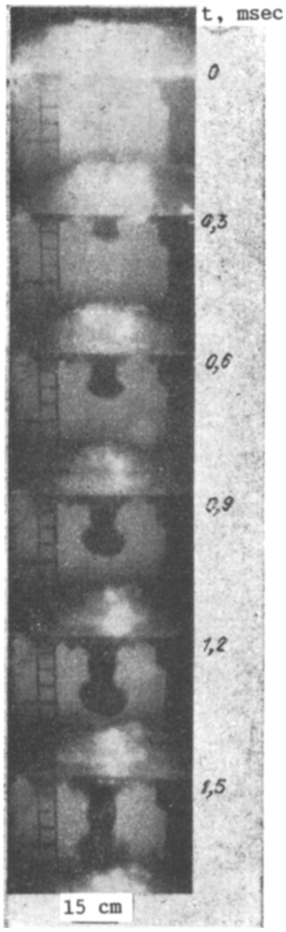


Fig. 3

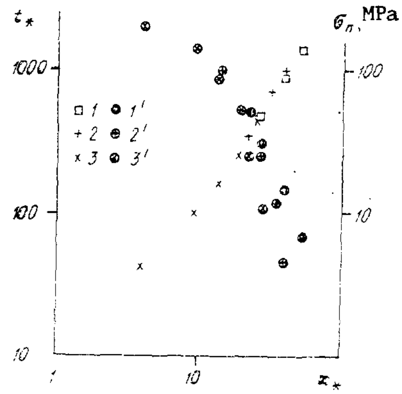


Fig. 4

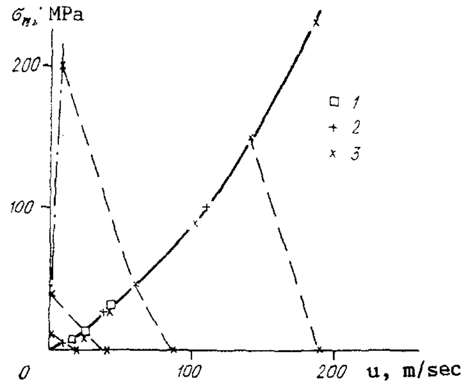


Fig. 5

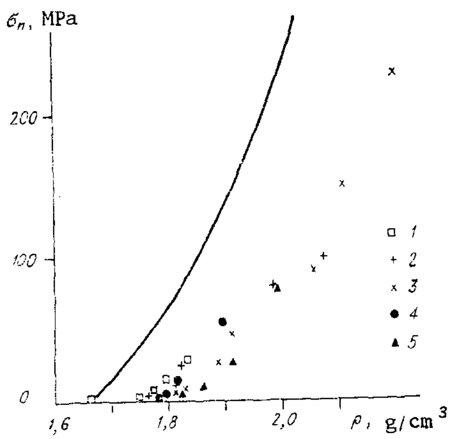


Fig. 6

gauge was 14 mm, its thickness was 4 mm, and mean density was about 3 g/cm³. As a result, the gauges were easily extracted from the sand and there was little distortion of the sand's movement. Pressure in the piezoelement equalized over a period of time <5 μsec. The measurement errors were as follows: <8% for time intervals: <15% for pressure. The maximum measurement time was 80 msec.

Figure 2 shows typical records of the normal stress $\sigma_n$ in the transmitted (curves 1-3) and reflected (curve 4) waves. In this test, the steel slab was set at the distance x = 12 cm from the striker, while $\Delta_{EX}$ = 4.5 mm. The gauges were positioned at the distances x =

TABLE 1

| $\sigma_n$, MPa | u, m/sec | $\sigma_r/\sigma_n$ | $u_1/u$ |
|---|---|---|---|
| 150 | 139 | — | 1,37 |
| 45 | 60,25 | 4,44 | 1,44 |
| 11 | 25,5 | 2,73 | 1,57 |

2, 4, 8, and 12 cm (lines 1-4). For comparison, the figure also shows the record of $\sigma_n$ in the transmitted wave at the distance x = 12 cm (dashed line) from another experiment with $\Delta_{EX}$ = 4.5 mm and the slab located x = 16 cm from the striker.

To record the dispersion velocity of the free surface of the sand, we set a thick-walled tube on the steel slab. The internal section of the tube contained a hole covered by a thin polyethylene film to keep the sand in the tube. As before, loading was done by the explosion of a disk of explosive ($\Delta_{EX}$ = 4.5 mm) driving a striker plate. Dispersion velocity was recorded with an SKS-1M camera positioned 3 m from the target. Thus, the objective lens and the lower edge of the tube were at the same level. A typical picture of the dispersal of the sand is shown in Fig. 3.

Figure 4 presents diagrams illustrating the propagation of the SW in dimensionless coordinates ($x_* = x/\Delta_{EX}$, $t_* = t/\Delta_{EX}$). Points 1-3 and 1'-3' show the results of tests with $\Delta_{EX}$ = 1.5, 3.0, and 4.5 mm, respectively, while 1-3 show the x–t diagram and 1'-3' show the $\sigma_n$–x diagram. Using known values of $\sigma_n$ and D (the velocity of the SW, D, was determined from the x–t diagram of SW propagation by graphical differentiation) and relations for the SW front, we can find the mass velocity and compression in the transmitted SW:

$$u = \sigma_n/\rho_{00}D,\ 1 - \rho_{00}/\rho = u/D.$$

Figure 5 shows the relation $\sigma_n$–u for sand (points 1-3 correspond to $\Delta_{EX}$ = 1.5, 3.0, and 4.5 mm) and the Hugoniot curve of the steel (the dot-dash line). Also shown are the stresses in the reflected wave and the dispersion velocity. The dashed lines join points corresponding to the parameters of the transmitted and reflected SW's and the velocity of the sand at the distances x = 2, 4, 8, and 12 cm from an explosive disk of the thickness $\Delta_{EX}$ = 4.5 mm. Values of the reflection coefficient $\sigma_r/\sigma_n$ and the ratio $u_1/u$ are shown in Table 1 ($\sigma_r$ is the maximum normal stress in the reflected wave). It should be noted that the reflection coefficient is substantially greater than 2 – the value typically seen at such pressures for most solids [8] – and it agrees with the value $\sigma_r/\sigma_n$ = 2.56 found in [9] at $\sigma_n$ = 9 MPa for alluvium. Meanwhile, the values of the ratio $u_1/u$ lie between 2 ("velocity-doubling rule") in the acoustic approximation [8] and 1.36 [2].

Figure 6 compares the $\sigma_n$–ρ relation we obtained for sand with the results of other authors who have studied the shock-wave [2] and explosive [3] loading of sand (points 1-3 correspond to $\Delta_{EX}$ = 1.5, 3.0, and 4.5 mm, the line shows data from [2] ($\rho_{00}$ = 1.66 g/cm$^3$, w = 0), and points 4 and 5 show data from [3] ($\rho_{00}$ = 1.74, w = 6% and $\rho_{00}$ = 1.76, w = 7.5%). The discrepancy seen can be attributed both to the different compositions and moisture content of the sand and to the difference in loading conditions.

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# DYNAMIC PROBLEM OF THE INTERACTION OF A CIRCULAR DIE WITH SOIL REGARDED AS AN ELASTOVISCOPLASTIC HALF-SPACE

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A numerical solution is obtained for an axisymmetric two-dimensional problem concerning the interaction of a circular die with soil regarded as an elastoviscoplastic half-space and subjected to a dynamic load. The problem of the motion of a circular die on an elastic half-space subjected to dynamic loading was solved in [1, 2]. In [3], a two-dimensional formulation was used to numerically solve the problem of the impact of a flat bar-shaped die against a half-space modeling an elastoplastic medium.

In the present study, soil is regarded as an elastoviscoplastic medium with constitutive equations [4] accounting for the effect of strain rate on volume compressibility. Shear strains are described within the framework of an elastoplastic theory of flow [5]. The results are compared with elastic and elastoplastic calculations, as well as with experimental data [6] indicating the need to allow for the viscosity of soil when calculating loads on bodies undergoing dynamic interaction with soil.

1. The deformation of an elastoviscoplastic medium is described by the following system of governing equations [4]:

$$\frac{\partial \varepsilon}{\partial t} = \frac{1}{E}\frac{\partial \sigma}{\partial t} + g(\sigma - f(\varepsilon)), \tag{1.1}$$

$$E = E(\varepsilon), \quad \partial\sigma/\partial t > 0; \quad E = E_*(\sigma, \varepsilon), \quad \partial\sigma/\partial t \leqslant 0;$$

$$2G\dot{e}_{ij} = \frac{d\tilde{S}_{ij}}{dt} + \lambda S_{ij}, \quad \dot{e}_{ij} = \dot{\varepsilon}_{ij} - \frac{1}{3}\dot{\varepsilon}\delta_{ij}, \quad \dot{\varepsilon} = \dot{\varepsilon}_{kk}; \tag{1.2}$$

$$J_2 = \frac{1}{6}\mathscr{F}^2(\sigma), \quad \sigma = \frac{1}{3}\sigma_{kk}. \tag{1.3}$$

Here, $\sigma_{ij}$ and $\varepsilon_{ij}$ are components of the stress and strain tensors; $J_2 = (1/2)S_{ij}S_{ij}$ is the second invariant of the deviator of the stress tensor; $S_{ij} = \sigma_{ij} - \sigma\delta_{ij}$; $\dot{\varepsilon}_{ij} = \partial\varepsilon_{ij}/\partial t$; $g(z) > 0$ at $z > 0$; $g(z) \equiv 0$ at $z \le 0$; $f(\varepsilon)$ is the statistical compression diagram of the medium; $E(\varepsilon) = \varphi'(\varepsilon)$ is a function characterizing the instantaneous loading of the medium at $\dot{\varepsilon} \to \infty$; $\varphi(\varepsilon)$ is the limiting dynamic compression diagram; G is the shear modulus; $d\tilde{S}_{ij}/dt = dS_{ij}/dt - S_{ik}\Omega_{jk} - S_{jk}\Omega_{ik}$ is the derivative of the stress-tensor deviator in accordance with Jaumann [5].

The plasticity function in (1.3) was written in the form of the following linear relation, in accordance with available empirical data [4]

$$\mathscr{F}(\sigma) = k\sigma + b \tag{1.4}$$

(k and b are empirical coefficients characterizing internal friction and cohesion in the soil).

We now introduce the cylindrical coordinate system i, j, k = x, r, θ. The problem will be solved in an axisymmetric formulation. In this case, the parameters of motion and the stress—strain state of the medium are independent of the angle θ. The x axis coincides with

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