WAVES IN STRATIFIED SOILS

N. Ya. Barlas, V. G. Kravets,
and G. M. Lyakhov

UDC 622.215

A generalization of experimental data on the compression of soil samples and the measurement of stresses during the propagation of blast waves showed that the properties of soils cannot be adequately represented by an elastoplastic model of a medium and that dilational viscosity must be taken into account also. In accordance with this assumption a model of soil as a viscoplastic medium was proposed in [1]. Simultaneous measurements of stresses and strains during the propagation of waves in homogeneous soils confirmed the important effect of viscosity and plasticity on the deformation of soils [2-4].

1. Naturally deposited soils form a complex system of strata which differ in physical properties. These properties may vary continuously or change abruptly at layer boundaries. Among the soil characteristics which may vary from layer to layer are the density of the skeleton, particle size, and moisture content. We study strata which have distinct boundaries and different moisture contents.

The experiments were performed in medium-grained sandy soils in a pit 1.5 m deep, 1 m wide, and 1 m long excavated in dense loam. The layers were produced as the pit was filled, and were separated from one another and from the walls by water-tight polyethylene film which ensured a distinct boundary between layers and constancy of their moisture contents with time. A schematic diagram of the experimental arrangement is shown in Fig. 1: 1) explosive charge; 2) soil tamping; 3, 4) upper and lower soil layers; 5) stress transducers; 6) strain tranducers. The boundary T between layers was at a depth of 0.4 m in all experiments. In some of the experiments the layer of soil with the higher moisture content was on top, and in other experiments it was on the bottom. A high moisture content was achieved by pouring in water and mixing. The soils had the following characteristics: low moisture content, density of skeleton $\gamma = (1.48-1.56) \cdot 10^3$ kg/m^3, moisture content w = 4-8%; high moisture content, $\gamma = (1.48-1.56) \cdot 10^3$ kg/m^3, w = 18-22%. From now on we call soil with a low moisture content dry, and that with a high moisture content moist. Experiments were also performed with the whole pit filled with soil of the same moisture content (homogeneous soil).

The explosive charge consisted of strands of detonating fuse laid in parallel over the whole cross section of the pit and connected at their ends. The charges used had a mass per unit area C = 0.3 and 0.6 kg/m^2. The tamping over the charge consisted of a 0.4-m-thick layer of dry soil.

Stress and strain transducers were positioned in both layers during the filling of the pit. The stress was measured with high-frequency tensometric transducers, and the strain with transducers based on recording the time dependence of the relative displacement of two thin aluminum disks 5 cm in diameter and 5 cm apart. The space between the disks was filled with soil except for a tube 0.6 cm in diameter connecting the disks. This tube contains the tensometric mechanism for recording the time variation of the relative approach

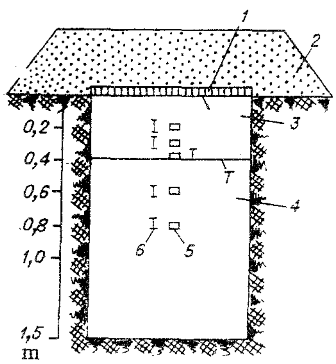

Fig. 1

Kiev. Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 1, pp. 147-153, January-February, 1979. Original article submitted December 15, 1978.

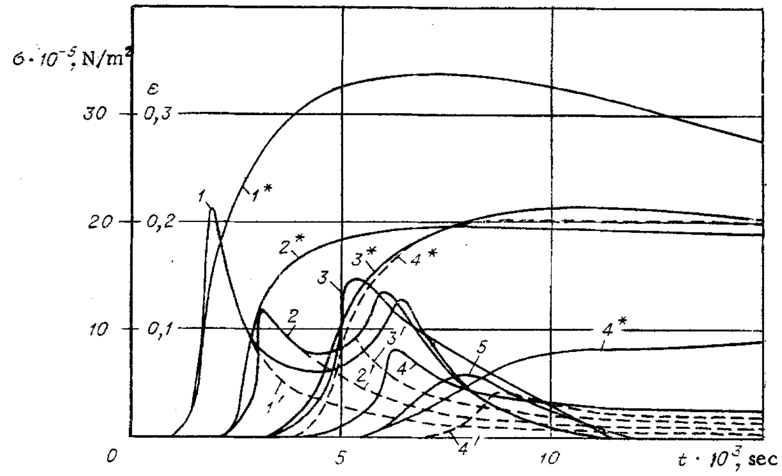

Fig. 2

or separation of the disks and determining the volume strain. The readings of the transducers were recorded on loop oscillographs. A similar method was used in homogeneous soils [2-4]. To ensure identical conditions the pit was cleared of soil after each explosion and refilled. Identical experiments were repeated three times. Because of the high density and low compressibility of the loam the walls of the pit did not permit displacement of the soil in a direction perpendicular to the direction of wave propagation, and thus the process was one-dimensional. This is confirmed by identical values of the parameters recorded at the same depth at the walls of the pit and at the center.

2. We consider the passage of a wave from dry to moist soil. Figure 2 shows traces of the stress component in the direction of wave propagation $\sigma(t)$ reduced to a common scale. For curves 1-5 the mass of the charge was $C = 0.3$ kg/m^2, and the distances r from the plane of the explosion were 0.2, 0.3, 0.4 (dry soil), 0.6 and 0.8 m (moist soil). Curves 1'-4' were obtained in homogeneous dry soil for the same values of C at distances of 0.2, 0.3, 0.4, and 0.6 m respectively. Curves 1 and 2 have two maxima each, associated with the incident and reflected waves. Curves 1' and 2' coincide with curves 1 and 2 up to the instant of arrival of the wave reflected from the boundary.

Figure 2 also shows traces of the strain $\varepsilon(t)$ reduced to a common scale. Curves 1*-4* are for distances $r = 0.2$, 0.3, 0.4, and 0.6 m respectively in stratified soil. Curve 3' was obtained in homogeneous dry soil at $r = 0.4$ m.

The experimental values of the strain are reached considerably later than the stress. In contrast with the stress the arrival of the reflected wave hardly changes the nature of the variation of the strain produced by the incident wave; no sharp increase in strain is observed. At a distance $r = 0.4$ m the maximum stresses in stratified soil are approximately 1.5 times larger than in dry homogeneous soil, but the strains are only 8% larger. At distances of 0.2 and 0.3 m the maximum strains are practically the same in stratified and in dry homogeneous soils. At all distances the strain continues to decrease with time for $60\text{-}100 \cdot 10^{-3}$ sec, i.e., during a period when the stress is zero. The residual strains are 50-80% of the maximum values.

From the graphs of $\sigma(t)$ and $\varepsilon(t)$ of Fig. 2 the curves for $\sigma(\varepsilon)$ in stratified soil are plotted in Fig. 3 for the passage of the incident, reflected, and transmitted waves at distances of 0.2 and 0.3 m (curves 1 and 2), at the boundary between the media $r = 0.4$ m (curve 3), and in the second soil at $r = 0.6$ m (curve 4). Curve 3' for dry homogeneous soil at $r = 0.4$ m is shown for comparison. The slope of curve 4 when the stress is increasing is considerably greater than for curves 1 and 2 in the layer of dry soil. Reloading and subsequent unloading occur along a line with a larger slope than the line of primary loading. The part of the $\sigma(\varepsilon)$ curve for decompression of soil ($\sigma = 0$) coincides with the $O\varepsilon$ axis and is not shown in Fig. 3.

Figure 4 shows the maximum stress as a function of distance $\sigma_m(r)$ for $C = 0.3$ and 0.6 kg/m^2, and T is the boundary between the layers. Curves 1 and 2 are for a wave in homogeneous dry soil (for $r \leq 0.3$ m they correspond also to the incident wave in a layer of dry soil above a layer of moist soil), 1' and 2' are for the transmitted wave in moist soil, and 1" and 2" are for the reflected wave in dry soil. Curves 1, 1', and 1" were obtained for $C = 0.3$ kg/m^2, and 2, 2' and 2" for $C = 0.6$ kg/m^2. The deviation of individual experimental points from the average values is 20-30%.

This results from the impossibility of obtaining completely identical soil properties in each repacking and moistening. In addition to the spread of extreme values there is a spread in the times at which they are

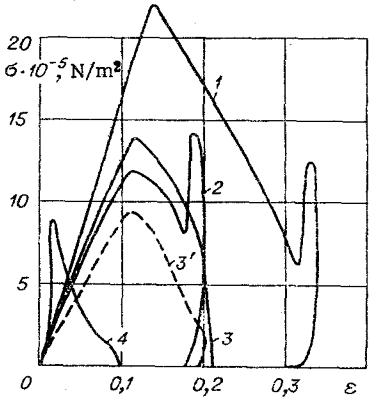

Fig. 3

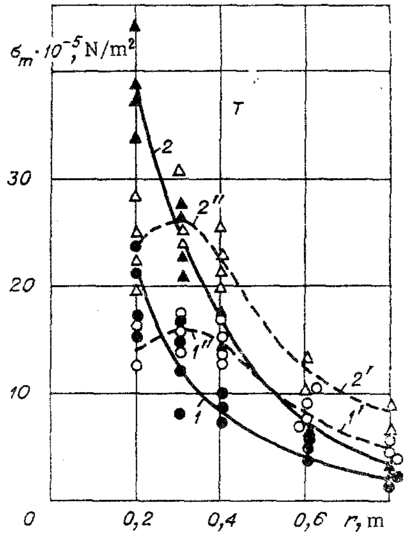

Fig. 4

TABLE 1

No.	0,2–0,3 m	0,3–0,4 m	0,4–0,6 m	0,6–0,8 m	0,4–0,2 m
1	80	70	70	65	—
2	85	70	70	70	—
3	80	60	210	150	270
4	85	60	220	150	260
5	220	210	70	60	—
6	240	210	75	70	—

reached. The spread is accounted for by curve 3 of Fig. 2 passing above curve 2. The wave of maximum stress is attenuated appreciably more slowly in moist than in dry soil. The average value of the reflection coefficient at the boundary is 1.5 for C = 0.3 kg/m^2, and 1.4 for C = 0.6 kg/m^2. The maximum stress at the boundary is reached (1–2) · 10^{-3} sec later than at the same distance in homogeneous dry soil.

The values of the velocity (m/sec) of propagation of the stress maximum of the incident, reflected, and transmitted waves are listed in Table 1. The rows refer to the following soils: 1) dry homogeneous, C = 0.3 kg/m^2; 2) dry homogeneous, C = 0.6 kg/m^2; 3) stratified, C = 0.3 kg/m^2; 4) stratified, C = 0.6 kg/m^2; the distances 0.4–0.2 m apply to the reflected wave. In passing from dry to moist soil the wave velocity increases. The velocity of the maximum of the reflected wave is four to five times higher than that of the incident wave. An appreciable increase in the velocity of the maximum for the reflection from a concrete wall of a wave in loess and sandy soils was observed in [4, 5].

3. We consider the passage of a wave from moist to dry soil. Curves 1–5 of Fig. 5 are for stresses $\sigma(t)$, reduced to a common scale, at distances r = 0.2, 0.3, 0.4, 0.6, and 0.8 m respectively, and curves 2*–5* are for strains, also reduced to a common scale, at r = 0.3, 0.4, 0.6, and 0.8 m respectively. The mass of the charge C = 0.3 kg/m^2. At all distances the maximum strain lags the maximum stress. As the wave enters dry soil the stress is decreased, the strain increases, and the rise time of the stress and strain is increased. A wave in dry soil reflected from the boundary with a less compressible soil results in a compression wave which causes a second increase in stress (Fig. 2). In moist soil the arrival of a rarefaction wave from the boundary with dry soil does not lead to a sharp decrease in stress as is the case in inviscid media such as water. The rarefaction wave also has no appreciable effect on the character of the strain variation.

Figure 6 shows plots of $\sigma(\varepsilon)$ constructed from traces of $\sigma(t)$ and $\varepsilon(t)$ for the passage of a wave from moist to dry soil. Curve 1' is for r = 0.2 m (moist soil) and curve 3' is for r = 0.4 m (boundary), with the transducer in dry soil. The mass of the charge in both cases was 0.6 kg/m^2. Curves 2 and 3 are for distances of 0.3 and 0.4 m with C = 0.3 kg/m^2. Both transducers were in moist soil. Curves 4 and 5 correspond to the layer of dry soil at distances of 0.6 and 0.8 m with C = 0.3 kg/m^2.

In contrast with dry soil (Fig. 3) the graphs of $\sigma(\varepsilon)$ for stress relief in moist soil are concave toward the origin over a certain portion. The maximum strains are substantially smaller, and the slopes of the curves for increasing stresses are substantially larger than in dry soil.

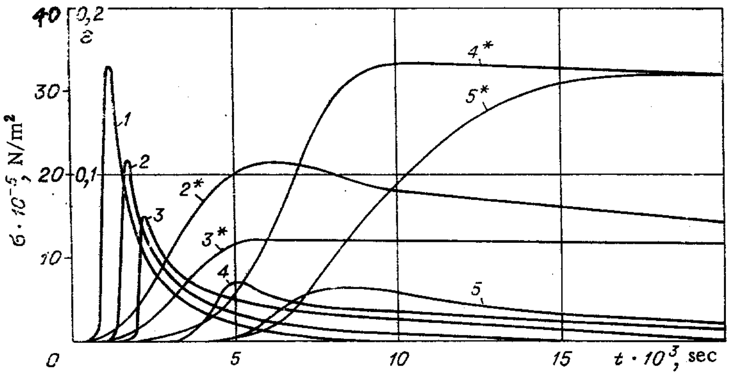

Fig. 5

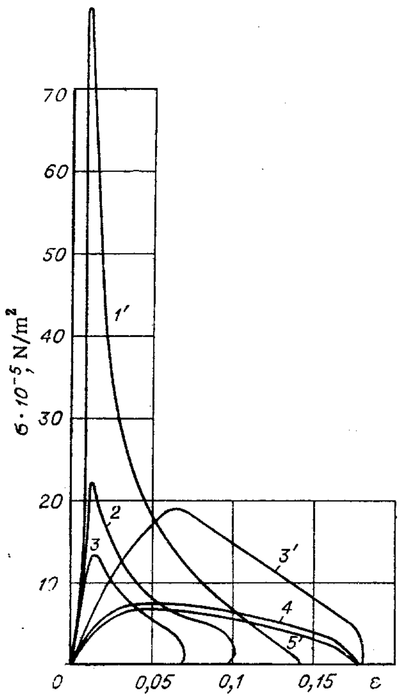

Fig. 6

In Table 1 rows 5 and 6 give the values of velocity of propagation of the stress maximum when the upper layer of soil is moist and the lower layer is dry. For row 5 C = 0.3 kg/m^2, and for row 6 C = 0.6 kg/m^2. The values of the velocity at distances of 0.4–0.6 m in homogeneous dry soil (rows 1 and 2) and after the passage of the wave from moist to dry soil are practically identical. At these distances loading conditions are established which are close to the limiting (equilibrium) values, when the velocity of the maximum has a minimum value.

The experimental results show that an increase of moisture content from 4–8 to 18–22% causes significant changes in soil properties: The attenuation of the maximum stress with distance is decreased, the maximum and residual strains decrease, the velocity of propagation of the stress maximum increases, and the leveling out of the wave and the time by which strain lags stress are decreased.

In stratified soil when the first layer is dry and the second is moist, the rules correspond to the passage of a wave into a less compressible medium: At the boundary the stress and strain increase, and a reflected compression wave leads to a second increase in stress. There is practically no second increase in strain. The velocity of propagation of the stress maximum is appreciably higher than in the incident wave.

In stratified soil when the first layer is moist and the second is dry the rules correspond to the passage of a wave into a less compressible medium: The stress and strain in the first medium decrease at the boundary, and in the second medium the velocity of propagation of the stress maximum and also the strain and the rate of leveling out of the wave increase. The wave reflected from the boundary does not give rise to an appreciable change of the strain in the first medium.

The compaction of stratified soils by an explosion is determined primarily by the action of the incident wave. The reflected wave has an appreciable effect on the strain only in the region where the primary stress loading has not yet stopped. At a greater distance from the boundary, where unloading has begun before the arrival of the reflected wave, its effect is negligible. This is accounted for by the larger slope of the $\sigma(\varepsilon)$ curve for reloading and unloading than for primary loading.

LITERATURE CITED

1. G. M. Lyakhov, Principles of the Dynamics of Blast Waves in Soils and Rocks [in Russian], Nedra, Moscow (1974).
2. S. S. Grigoryan, G. M. Lyakhov, and P. A. Parshukov, "Spherical blast waves in soils inferred from stress and strain measurements," Zh. Prikl. Mekh. Tekh. Fiz., No. 1, (1977).
3. A. A. Vovk, V. G. Kravets, G. M. Lyakhov, V. A. Plaksii, V. I. Salitskaya, and K. S. Sultanov, "Experimental determination of the blast-wave parameters and viscoplastic characteristics of soil," Prikl. Mekh., No. 1 (1977).

4. G. M. Lyakhov, V. A. Plaksii, and K. S. Sultanov, "Investigation of a wave in soil with an obstruction from the records of stress and strain," Zh. Prikl. Mekh. Tekh. Fiz., No. 3 (1976).
5. Z. V. Narozhnaya, "Experimental determination of the rate of stress relief in soils during dynamic processes," Fiz. Goreniya Vzryva, No. 1 (1965).

STRUCTURE OF SHOCK WAVES IN ELASTOPLASTIC RELAXING MEDIA

V. G. Grigor'ev, A. S. Nemirov, and V. K. Sirotkin

UDC 534.222.2

At the present time shock and explosive loads are being more and more widely used in various technical processes. In this case, an adequate description both of the process of the propagation of a shock wave and of the change in the medium as a result of the shock action is of great importance.

Elastoplastic waves have been discussed earlier in a number of pieces of work [1-3], taking account of the behavior of dislocations at the front of the shock wave. In [1] a model was developed for the description of the inelastic behavior of iron and low-carbon steel in a wide range of change in the deformation rates. A solution is given to the problem of the plane collision of plates. In [2], along with a numerical solution of the problem of the porpagation of an elastoplastic wave, a stationary wave is discussed. It is shown that the front of a shock wave has a multiwave structure. However, as an expression for the velocity of the dislocations the authors of [2] used only an exponential dependence on the intensity of the tangential stresses and did not consider the important case of a power dependence. In [3], on the basis of the dynamics of dislocations, the theory of a fully established wave profile is discussed; numerically calculated profiles are compared with experimental profiles, obtained by the methods of laser interferometry. It is shown that the velocity of the dislocations with the shock-wave compression of aluminum is well described by a power dependence. In addition, it is shown that for aluminum the density of mobile dislocations increases linearly with a rise in the value of the plastic shear γ_p.

In the present article the question of the structure of the waves of the load in elastoplastic media is discussed; a dislocation model of the dynamic plasticity is used [4-6]. Within the framework of this model, it is possible to describe not only the dynamics of the plastic deformation, but also to consider the structural changes which take place in a material under the action of dynamic loads.

The analogous problem of the structure of a shock wave, using a phenomenological approach to a description of the relaxation of the tangential stresses, was discussed in [7]; however, in this article there was no detailed discussion of the role of the nonlinearity of the process of the relaxation of the stresses, and effects connected with the change in the density of the dislocations were not taken into consideration.

Let us consider a shock wave, whose width Δ is small in comparison with the curvature of the front and the distance at which appreciable damping of the shock wave takes place. In this case, the structure of the wave will be determined by the solution of the steady-state plane problem [8].

Going over to a moving system of coordinates in which the front is motionless, the equations of motion can be written in the form [7]

$$\rho u = \rho_0 u_0,\ \sigma_1 - \sigma_{10} = (\rho_0 u_0)^2 (1/\rho - 1/\rho_0), \tag{1}$$

where ρ is the density; u is the velocity; σ_1 is the stress along the axis of propagation; ρ_0, u_0, σ_{10} are the corresponding values ahead of the front.

We shall consider not-too-strong shock waves, so that the temperature behind the front of the wave does not exceed the melting temperature. In this case, the thermal components of the pressure can be neglected [8] and the equation of state can be written in the form

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 1, pp. 153-161, January-February, 1979. Original article submitted February 17, 1978.