Use of the Kolsky Method for Confined Tests of Soft Soils

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ABSTRACT—A modification of the well-know Kolsky method for dynamic tests is described for investigating the dynamic compressibility of soft soils. The modification consists of placing an axial compression soil specimen into a rigid steel jacket that confines its radial strain. Using this modification, experimental results for plasticine and clay are discussed. An automated system for processing the experimental data in order to plot stress-strain curves is also described.

Introduction

The ever-increasing interest in studying dynamic properties of soft soils is explained by the need to solve a number of problems that require quantitative evaluation of behavior of such media under intensive short-term loads. Among these problems are the following: propagation analysis of intensive seismic and explosion waves; their interaction with overground and underground structures; and use of explosion energy in constructing dams, canals, and so on. The collision of solids with soil media analysis and the penetration analysis play special roles in soil dynamics as well.

Mathematical simulations are widely used to analyze such problems. Constitutive equations describing the behavior of soils under the pulsed loads are important. In order to construct the equations of state used in computations and to assess their adequacy, experimental data—based on the dynamic properties of soils in a wide range of load intensities, strain rates and so on—are needed.

The dynamic properties of soils have been studied in the pressure range to 100 MPa and in the strain range to 10^2 s^{-1}.[1-4] One can also find a number of studies on the dynamic compressibility of soils under short-term loads with the stress intensity of over 1 GPa.[5,6,7]

The dynamic load range of 0.1 to 1.0 GPa is the least investigated; experimental data on the behavior of soils in this range are incomplete, inconsistent, and for many soil types totally absent. This fact is explained by experimental difficulties in dynamic investigations. The studies of soil behavior in this range should make it possible to obtain a better insight into the laws and the mechanisms of deformation. The investigation of the mechanical properties of soft soils presents rather a complex problem even for quasistatic loads because the soil properties depend on factors such as multicomponent structure, porosity and humidity. Further, the experimental difficulties increase when high-intensity and short-duration dynamic loads are involved. In national standards there are special procedures and equipment designed for testing the soil quasi-statistically. For the loads of 0.1 to 1.0 GPa and the strain rates of 10^2 to 10^4 s^{-1}, practically every investigator has to design his or her own dynamic testing procedures, construct original loading devices and work out the methods for measuring dynamic loading parameters.

The classical model of dynamic investigations, originally proposed by Kolsky,[8] is a universal one for studying the mechanical properties of structural materials under the strain rates of about 10^3 s^{-1}. Using the split-Hopkinson pressure bar (SHPB) apparatus, Christensen, Swanson and Brown[9] have studied the dynamic properties of rocks, applying a pressure vessel to actively confine strains. Goldsmith and Sackman[10] give an example of using the SHPB to obtain the deformation diagrams for many rocks.

The SHPB method with passively confining radial strains using a rigid jacket (i.e., "jacket-confined tests") was independently used by Felice *et al.*,[11] Gaffney, Brown and Felice[12] and Grushevsky[13] for testing soft soils.

This paper presents the application of the jacket-confined tests to the dynamic testing of soft soils. The experimental results for plasticine and clay are given.

Experimental Apparatus

Loading System

Figure 1 shows the experimental apparatus used at the Research Institute of Mechanics, State University of Nizhny Novgorod for dynamically testing structural materials and soils. Its main components are the following: a pneumatic loading device (gas gun), pressure-measuring bars and recording equipment with a personal computer for the automated processing of experimental results.

The SHPB system was loaded by a striker, 100-400 mm in length, which was allowed to vary the duration of the generated pulses from 40 to 160 μs. The striker velocities could vary from 5 m/s to 30 m/s. Such loading parameters made it possible to obtain strain rates of 5×10^2 to 5×10^3 s^{-1} and maximum stresses in the soil specimens of up to 350 MPa. The passing time of a compression wave along the specimen is about 5 μs, so during the pulse length, the soil specimen experiences multiple reflection of the waves, and its stress-strain state may be considered uniform.

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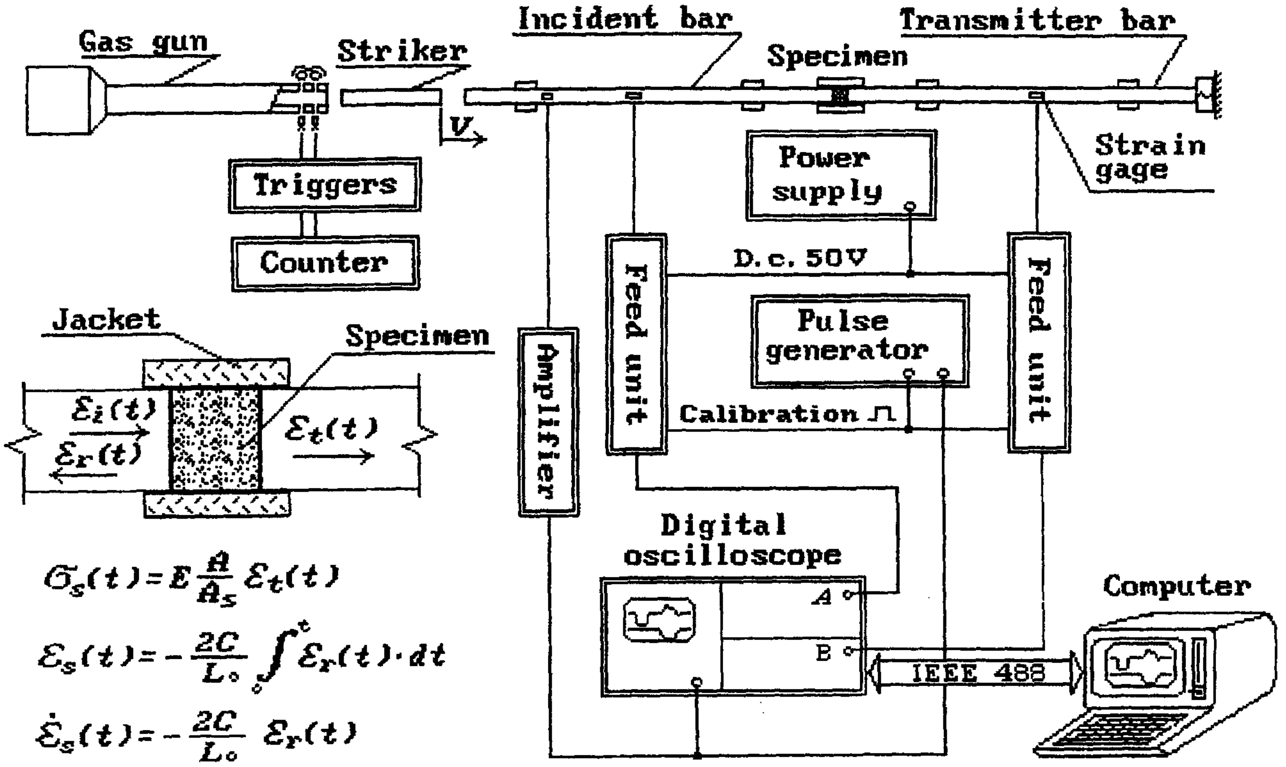

Fig. 1—Schematic of the modified Kolsky apparatus and electronics for testing soils

The pressure-measuring bar system consists of two bars, each 20 mm in diameter and 1 m in length. The bars are made of high-strength steel with a yield strength of 1800 MPa. Elastic strain pulses are measured by small foil strain gages cemented in the middle of the pressure bars.

Confining Jacket

The main difference between the present soft soil test modification and the original SHPB scheme used in compression tests is that a soil specimen is located inside a rigid steel jacket that confines its radial strain. In Malvern's[14] paper, this configuration is named "a passively confined" or "a jacket confined" test. Confining jackets 15 mm in length with a wall thickness of 6 mm or 10 mm were used in the experiments. These were put on the ends of the pressure bars, with a slight gap of 50 μm between the SHPB bars and the inner surface of the steel jacket. The jackets were made of steel, with a yield strength of 1200 MPa. Most of the experiments were conducted using the thicker jackets.

Due to a large difference between the acoustic impedances of the pressure bars and the specimen in a soft soil test, a considerable part of the loading pulse is reflected from the specimen and only a small part of it (about 30 percent) is transmitted to the transmitter bar. Thus, in the experiments, it is technologically difficult to generate axial stresses over 300-400 MPa in the specimens. The yield strength of the jacket material is considerably greater than these values, so the confining jacket elastically deforms in the tests.

Following the analysis of the elastic deformation problem of a thick-walled tube under internal pressure,[15] the maximum values of the radial (ε_r) and circumferential (ε_θ) strains in the confining jacket were calculated for the pressure value of 400 MPa:

for the 6-mm wall jacket, $\varepsilon_r = -0.002$, $\varepsilon_\theta = 0.0046$

for the 10-mm wall jacket, $\varepsilon_r = -0.002$, $\varepsilon_\theta = 0.0033$

The calculated radial strains are considerably lower than the axial strain, which is equal to 0.1 and, for the 6-mm wall jacket, more than 0.1. Thus the deformed state of a specimen may be considered as one dimensional.

Specimens

The clay specimens were made of soil blocks, 140 mm in diameter and 300 mm in height, with intact structure, taken from a depth of about 2 m. To preserve the natural humidity and density, the soil blocks were hermetically sealed with paraffin and polyethylene film. A disc specimen, 20 mm in diameter and 7.5 mm in height, was cut out from the block shortly before the test and placed inside a metal jacket. Upon installation of the specimen inside the jacket, the gap between the rods and the jacket was filled with polytetrafluorethylene film, and the specimen was manually tightened. The tests were conducted under an ambient temperature of 20° ± 2°C. It took no more than 15 minutes to prepare and test a specimen, so the natural humidity of the clay was preserved. The initial characteristics of the clay are given in Tables 1 and 2.

Plasticine is composed of white clay and small additions of wax, paraffin, petrolatum and coloring pigments. Plasticine is widely used as a simulating material in dynamic experiments due to its availability, ease of handling and stability of its physical and mechanical properties.[16] Thus the investigation of its mechanical properties under dynamic

TABLE 1—PHYSICAL-MECHANICAL PROPERTIES OF CLAY

Humidity percentage	Soil Density g/cm^3	Dry Soil Density g/cm^3	Particle Density g/cm^3	Porosity percentage	Plasticity Index	Unrolling Strength	Yield Strength
24.6	1.98	1.56	2.74	43	22	25	47

TABLE 2—PARTICLE SIZE DISTRIBUTION OF CLAY (IN PERCENTAGES)

Fraction Size (mm)						
0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.01	0.01-0.005	<0.005	Total
0.3	1.5	16.1	41.9	10.6	29.6	100.0

loads is of considerable interest. The plasticine was tested under an ambient temperature of 20° ± 2°C. The specimens for the tests were manually formed into tablets, 7.5 mm to 7.8 mm in height, inside the confining jacket, leaving no gap between the specimen and the jacket. The density of the material used in the experiments was 1.36 – 1.44 g/cm^3.

Automation of the Experimental Data Processing

The strain pulses in the pressure bars and in the confining jacket are recorded by digital storage oscilloscopes. Next, the strain data are transmitted from the oscilloscope memory to a PC computer via an IEEE 488 interface. The experimental data-processing computer program allows one to synchronize the selected pulses and to plot true deformation curves, as well as to perform statistical processing of the experimental results, to develop regression models, and so on.

An electric calibration is used to determine the scaling coefficients for converting the oscillogram coordinate points into the strain and time units. This is achieved by adding scale resistors of a known nominal value to the piezoresistor circuits. Calibration precision is controlled by referencing the loading pulse amplitude to the excited wave intensity determined by a one-dimensional theory based on the known striker velocity.

The synchronization of strain pulses and the precise choice of the origins of the pulses are of great importance for obtaining the dynamic deformation diagrams of structural materials using the SHPB method. The suggested soil testing scheme is characterized by a considerable delay (up to 20 μs) of the transmitted pulse relative to the reflected one, even when the registering strain gages are cemented at an equal distance from the specimen. This is explained by the following reasons:

- Substantial difference between acoustic impedances of the pressure bars and the specimen
- Low wave propagation velocity in the soil specimen
- Considerable porosity of the soil material

The latter property leads to the fact that, at the initial stage, the soil deformation process proceeds as a reordering of the particles (grains) as they fill the free pore space. The realization of this process requires moderate load amplitudes (1-2 MPa), which act as the sensitivity threshold of the experimental method for the elastic strain pulses in the pressure-measuring bars (using the strain gages technique). Besides, the weak signals recorded from the strain gages are sometimes accompanied by electromagnetic interference noise. The above factors may lead to possible errors in determining the origins of these pulses.

The pulse synchronization procedure is as follows: the point, after which the registering ray deviates from the zero line for the first time, is taken as the reference point of the incident pulse. Based on the known wave propagation velocity in the pressure bars and the known distance between the specimen and the strain gages, the positions of the reference points for the reflected and transmitted pulses are determined. When the gages are cemented at an equal distance from the specimen, these points are chosen simultaneously. For the chosen reference points, the fulfillment of the main assumption of the Kolsky method is checked during the entire test, namely,

$$\varepsilon^i(t) + \varepsilon^r(t) = \varepsilon^t(t) \qquad (1)$$

where $\varepsilon^i(t)$, $\varepsilon^r(\mathrm{t})$ and $\varepsilon^t(t)$ are the incident, reflected and transmitted strain pulses, respectively. These three pulses are displayed on the screen, together with the sum of the reflected and transmitted pulses (Fig. 2). Special attention is paid to satisfying assumption (1) as closely as possible during the entire pulse length, except for the initial portion (several microseconds) when the stress-strain state of the specimen cannot be considered uniform. The results presented in Fig. 2 show that assumption of force equality at the specimen ends is satisfied reasonably well in the jacket-confined soil tests.

Upon synchronization of the initial pulses, a dynamic deformation diagram and a related strain-rate history are plotted using Kolsky formulas. The processed data are stored in a special database in the form of dynamic deformation diagrams.

Test Results for Plasticine and Clay

Plasticine and clay specimens were tested using the modified SHPB apparatus. The loading amplitudes, strain rates and strain levels in experiments were varied by choosing an impact velocity and a length of the striker. A series of 4 to 5 tests was conducted for each condition, and the results were averaged.

The plasticine test was provided to study behavior both under relatively constant strain rates and under complex

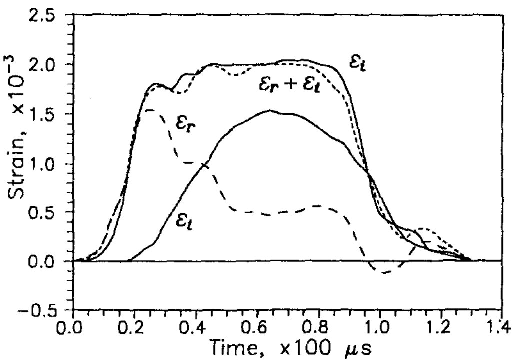

Fig. 2—Synchronization of strain pulses in SHPB

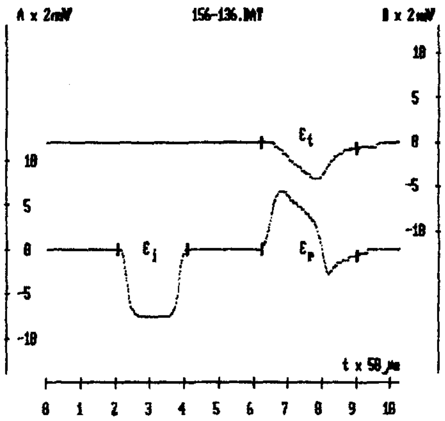

Fig. 3—The oscillogram of strain pulses in the SHPB test of plasticine using a solid striker

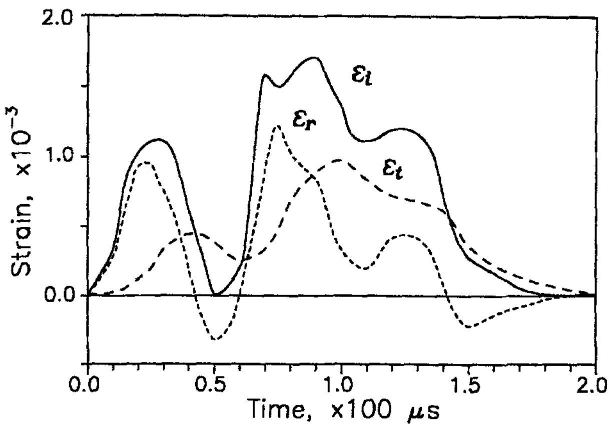

Fig. 4—Strain pulses in the SHPB test of plasticine using a composite striker

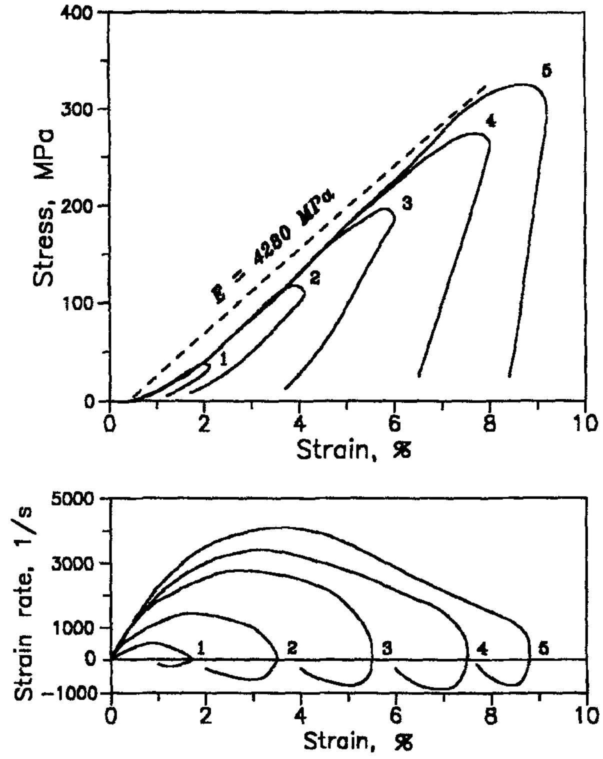

Fig. 5—Deformation curves for plasticine

strain-rate histories. In the former case, the SHPB was loaded by solid homogeneous strikers. To implement a complex strain-rate history, strikers were made, along the length, of two cylinders of materials with different acoustic impedances.[17] The component cylinders were fixed together by easily deformed brackets and had a small gap between them, allowing two pulses of different amplitudes to generate in the loading bar with a delay of up to 30 μs between them. When loading a specimen with such pulses in one of the tests, it was possible to generate a cyclic deformation mode, with different strain rates and a delay between the loading pulses in it. A delay between the loading cycles allows one to analyze the behavior of a material under loading, and unloading with subsequent reloading, for different strain levels.

Strain pulses in the SHPB tests of plasticine, using both solid and composite strikers, are shown in Figs. 3 and 4, respectively. Figure 4 shows clearly that loading the SHPB by a composite striker furnishes fairly complex strain-rate histories, including unloading with subsequent reloading after a certain delay. It is evident from the figures that there is a substantial delay (up to 20 μs) between the transmitted and reflected pulses.

The deformation diagrams for plasticine obtained in the jacket-confined tests are shown in Fig. 5. It is evident that the deformation curves on the loading branch are definitely nonlinear in character. It is worth noting that, for the investigated strain-rate range, all curves agree closely enough in the initial portions of the loading branch. According to the unloading, its character depends greatly on the strain rate and the stress or strain level achieved in the experiment. Further studies are required to determine which of the above factors is dominant. Also, the deformation diagram has, in the region of the transition from active loading to unloading, a portion where the stresses decrease while the strain value continues to increase. Evidently, this may be attributed to the viscoplastic nature of plasticine or due to squeezing of some portion of it into the gap between the bars and the jacket.

Experimental data, obtained in the dynamic cyclic deformation tests in the form of stress, strain and strain-rate

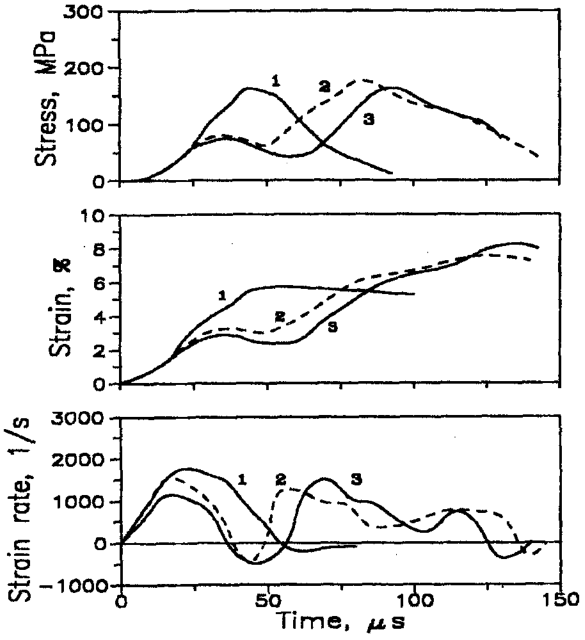

Fig. 6—Stress, strain and strain rate as functions of time

histories, are shown in Fig. 6, and the related deformation diagrams are shown in Fig. 7 (curves 2 and 3), where they are compared with a constant loading rate diagram (curve 1). In tests 2 and 3, stresses in the incident wave drop to zero after the first load cycle; however, complete unloading of the specimen does not take place for the time periods used due to the viscoplastic properties of plasticine. In test 2, time delay between the load cycles is about 10 μs. The time delay, increasing up to 20 μs in test 3, leads to more profound unloading. The secondary loading curve, after partial unloading, practically coincides with the initial deformation curve for single-cycle loading.

In addition to plasticine, clay specimens were tested. Their physical and mechanical properties are summarized in Tables 1 and 2. The experimental results are shown in Fig. 8. It is evident that the deformation diagram has—just as for plasticine—a zero-stress portion. The size of this portion is about 1.7 percent for clay and about 0.5 percent for plasticine. This may be due to a higher porosity of clay as compared to plasticine. It is evident from the above deformation diagrams for clay that the loading branch is nonlinear whereas the unloading is practically linear (its modulus being independent of the experimental conditions). Comparison of the deformation diagrams obtained for plasticine and clay suggests that the behavior of plasticine under active loading is similar to the behavior of natural soil.

In addition to the dynamic diagram, Fig. 8 presents a static deformation diagram for clay obtained in compression jacket-confined tests. Comparison of the dynamic and static experimental results reveals a substantial decrease of clay compressibility under dynamic loading. The difference between the static and dynamic deformation curves apparently results from the different behavior of the components as a function of loading duration. Thus, under static loading, partial squeezing out and removal of the water and air contained in the clay takes place, which does not happen under dynamic loading, where the soil behaves as more of a homogeneous medium, with all the components corresponding to loading. The fact that the dynamic deformation diagrams are close to each other at the active loading stage shows that, for the strain rates of 10^3 to 10^4 s^{-1}, the diagrams reach the limiting dynamic curve, the existence of which was indicated in Ref. 1.

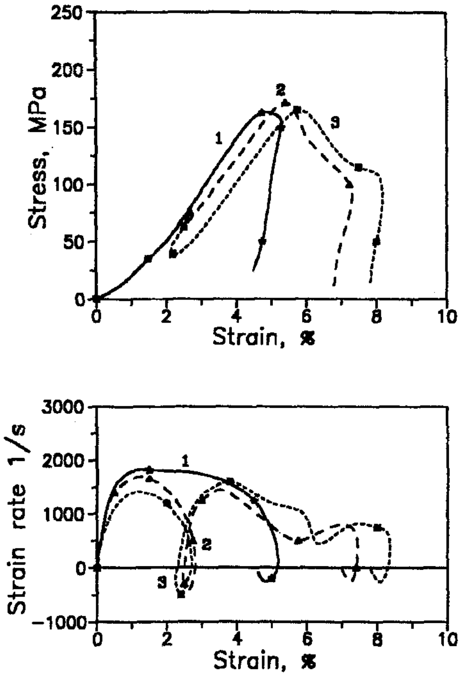

Fig. 7—Cyclic dynamic loading curves for plasticine

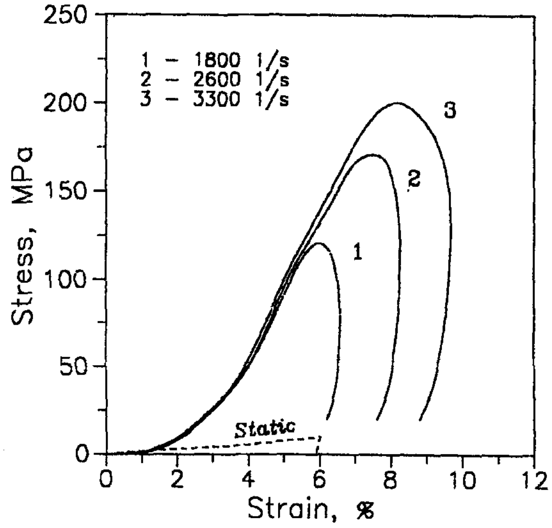

Fig. 8—Dynamic stress-strain curves for clay

Conclusions

The above modification of the Kolsky method can be used successfully when studying the dynamic properties of low-density materials such as soft soils. Using the present SHPB modification, dynamic deformation diagrams for clay and plasticine were obtained. The obtained deformation diagrams are nonlinear when corresponding to active loading. Dynamic compressibility of clay was observed to be considerably lower than static compressibility of clay.

In the future, it appears useful to measure the tangential strains with strain gages fixed on the confining jacket. It would help one calculate a radial component of the stresses acting in the specimen and so obtain more detailed information about the response of the studied material. To analyze in detail the initial portion of the deformation curve, the sensitivity of the method should be increased, which could be achieved by using more sensitive semiconductor gages, rather than foil ones, when measuring strain pulses in the pressure bars.

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