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SOILS AS SAMPLES FOR THE SPLIT HOPKINSON BAR

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ABSTRACT

Soils frequently exhibit one or more of the following characteristics which complicate analysis of data from split Hopkinson bar tests or make test setup and execution difficult: low wave speed, high attenuation of acoustic energy, or insignificant structural strength. Low wave speed invalidates the assumption that the sample is deformed uniformly by the load at early times; but, use of a Lagrangian wave propagation analysis permits derivation of useful information from the standard suite of data. Use of gauges within the sample would facilitate this technique. High attenuation requires thin samples, which restricts the strain paths which can be achieved. The weakness of non-cohesive soils presents difficulties in preparation, handling and control of boundary conditions. One simple solution is to support the sample in a rigid sleeve; this results in a uniaxial strain experiment so that the results are directly comparable to shock wave data.

INTRODUCTION

For the past 35 years, the split Hopkinson bar has been used to measure the high-strain-rate mechanical behavior of many materials. Kolsky's pioneering work in 1949 [1] investigated elastomers and metals in very thin discs. Later work treated similar materials in other shapes (e.g. [2]) and extended the work to other metals and to ceramics and rocks (e.g., [3]). Some work has even been reported on very low density foams [4]. In recent years, there has been interest in the possibility of applying the split Hopkinson bar to the determination of the high-strain-rate response of soils. The driving force for most of this interest has been the need to develop predictive methods for estimating structural damage to military systems in or on soil. However, information on the high strain rate deformation of soils is potentially useful in other technical areas such as mining, overburden removal, earthquake engineering, containment of underground nuclear tests, and the study of impact and explosion cratering phenomena.

In the past two years we have conducted over 150 tests of soil specimens in a split Hopkinson bar at Los Alamos National Laboratory. These tests have provided a considerable challenge and a substantial learning process. The purpose of this paper is to share with the community some of the peculiarities of testing soils with the Hopkinson bar and the techniques we have used to overcome of the difficulties. A more detailed discussion of the dynamic behavior of a particular soil is given in a companion paper [5], but most of the examples here are taken from a Los Alamos report describing the dynamic behavior of a dry desert alluvium [6].

THE SPLIT HOPKINSON BAR

A typical arrangement for the split Hopkinson bar, or Kolsky apparatus, is shown schematically in Figure 1. The system consists of two long cylindrical bars: the incident or input bar and the transmitter or output bar. For compression testing, the cylindrical specimen is placed between the two bars and a compressive stress pulse is generated at the end of the incident bar by impact of the projectile or striker bar. The amplitude of the incident stress pulse is determined by the impact velocity and the material properties of the projectile and the incident bar, while the duration of the pulse is dependent on the length and modulus of the projectile.

The stress pulses incident on and reflected from the incident bar/specimen interface are recorded with strain gauges mounted at some point along the incident bar sufficiently distant from either end to prevent overlap of wave trains. The stress transmitted through the specimen is monitored by similarly mounted gauges on the transmitter bar. A momentum-absorbing arrangement at the end of the transmitter bar prevents multiple reflections of the transmitted stress wave. It is assumed that the bars remain elastic during the passage of the stress wave so that, except for the dispersive effects discussed below, the strain gauges accurately reproduce the appropriate stress histories in the bars.

The split Hopkinson bar apparatus operated by the Geophysics Group at Los Alamos National Laboratory consists of incident and transmitter bars as described above supported by a massive reaction frame and includes several other features. The bars are 40.3 mm diameter, 1.22 m long, Vascomax 350 maraging steel heat treated to a yield stress of about 2 GPa (300 ksi). Teflon bushings in the cross members of the reaction frame support the bars at about half meter intervals. For control of specimen pore pressure, each bar is provided with a 3.2 mm diameter axial hole vented radially about 0.3 m from the specimen end. When not required, the cone-shaped openings of these holes at the specimen ends of the bars are plugged with matching cones of the same steel. Stress waves in the bars are monitored by strain gauge pairs mounted 0.61 m from the specimen ends. The pairs are used in a half-bridge configuration to null bending strains.

The incident stress pulse is generated by impact of a projectile from a small gas gun. Projectiles are available to generate pulses with nominal durations of 50, 100, and 200 μs. Projectile velocity is measured just prior to impact by three pairs of diode lasers and photodetectors mounted in the muzzle of the gun.

A static pre-load of up to 200 MPa (30 ksi) can be applied by a hydraulic ram located at the downstream end of the transmitter bar. Finally, a momentum-trapping steel slug is attached to the rear of the ram by a breakaway bolt and allowed to fly off into a rag-filled basket.

Transient signals from the two continuously-powered strain gauge bridges are filtered and preamplified, then routed to the data acquisition and control area in the adjacent room. The signal conditioning amplifiers also have a provision for switching to a calibration signal which verifies the overall gain of the data acquisition system. Further amplification is provided as required prior to digital recording of the signals. The analog bandwidth of the signal recording system is 1 MHz, to prevent aliasing of the digital records.

The data are recorded by CAMAC (IEEE-583) based waveform digitizers. The incident and transmitter bar records are recorded on separate channels with 8-bit resolution. At the usual rate of 0.5 μs per point, a total of 8 ms of data are recorded per channel, and a timing signal derived from the projectile velocity measuring system is used to position the useful data appropriately within this window. The data are automatically read by a small microcomputer and stored on flexible disk for later processing on a larger machine.

In the standard analysis of Hopkinson bar data [3], the stress at the incident bar/sample interface is calculated as

$$\sigma_i = E(I+R),$$

where E is Young's modulus for the bar, I is the incident strain and R is the reflected strain; the stress at the sample/transmitter bar interface is

$$\sigma_t = E(T),$$

where T is the transmitted strain; and the strain rate in the specimen is given by

$$\dot{\varepsilon} = C_o (I-R-T)/l_o,$$

where $C_o^2 = E/\rho$, ρ is the density of the bar, and l_o is the initial sample length. In order to get stress-strain paths for the deformation, the stress is calculated as the average of the stress at the two interfaces and the strain is the time integral of the strain rate.

In the above expressions, all the strain pulses are shifted in time to coincide with the transit time to or from the center of the sample. Propagation of rod waves is dispersive [7,8], so we must correct the measured strain histories for dispersion in addition to shifting them in time. A method has been discribed by Follansbee and Franz [9] which is very easy to implement in a numerical data reduction code. They have approximated the dispersion relation for maraging steel, which is derived in terms of Bessel functions, as a polynomial:

$$\frac{C(\frac{r}{\lambda})}{C_o} = 0.5764 + \frac{0.4236}{22.(\frac{r}{\lambda})^4 + 12.8(\frac{r}{\lambda})^3 + 2.77(\frac{r}{\lambda})^2 + 0.92(\frac{r}{\lambda})^{1.5} + 1}$$

where r is the radius of the bar and λ is the wavelength. In our standard data reduction, we make this correction by transforming the measured pulses to the frequency domain, applying the desired phase shift, and inverting the transform. This procedure also removes the high frequencies in the data which are mostly digitizing noise.

SOILS AS SAMPLES

Soils frequently exhibit one or more properties that make them difficult materials for Hopkinson bar testing. They often have so little strength that even putting them into the bars is not trivial. Soils with substantial fraction of air-filled void volume have very low wave speeds and very high rates of attenuation; these properties limit the sample thickness and/or complicate the data analysis. And, of course, the usual difficulties of getting samples that are characteristic of *in situ* behavior to the laboratory apply to Hopkinson bar tests as to most other laboratory tests of soil samples.

Except for very cohesive, clayey soils or soils that are very well-indurated, it is usually necessary to provide radial support to a soil sample merely to keep it in position for the test. The most obvious choice of support is one that is as compliant as possible in hopes that the lack of radial confinement of the standard Hopkinson bar test could be reproduced. However, when one considers even the flimsiest of sleeves they still provide a radial restraint that would be significant relative to the strength of most soils. The opposite extreme of a very stiff radial support is easy to implement and has the added advantage of providing a strain path that can be easily duplicated at both higher and lower strain rates--uniaxial strain. This strain path also facilitates data analysis, as we shall see below. A third alternative is to provide some intermediate degree of confinement; however, in that case it would be necessary to determine the radial strain and stress histories so that the overall strain path and stress history is known.

For soils with several percent or more of air-filled porosity, it can be shown that radial strain is negligible when a thick-walled metal sleeve is used to confine the specimen. Figure 2 shows the sample holder configuration we have used at Los Alamos. The holder is a cylinder of bronze or steel with an axial hole just slightly larger than the diameter of the bar. The sample is compacted into a disc of the desired thickness at the center of the holder, and then the holder is slipped over one bar and the other bar is moved into the free end. Tests with no sample have shown that the sleeve carries substantially less than 0.1 percent of the pulse during dynamic loading. The radial expansion, Δr, of a tube of modulus E, Poisson's ratio 0.3, inside diameter r, outside diameter R and radial stress P is given by

$$\frac{\Delta r}{r} = \frac{P}{E}\,\frac{(0.7-1.3R^2/r^2)}{(1-R^2/r^2)}$$

For our sample sleeves, this formula gives a radial strain of 1.6×10^{-11}/Pa. This will actually be an overestimate because the internal load is not applied over the entire length of the cylinder. The extreme case occurs when the soil has no shear strength so that the radial stress P is equal to the axial stress measured by the bars. For our typical soils, axial strains of 10 percent or more are attained at only a few tens of MPa so that the radial strain is less than 0.1 percent of the axial strain. In some of the experiments described by Felice *et al.* [illegible], stresses were hundreds of MPa and radial strains may have been as high as a few percent of axial.

The low wave speed and high attenuation in dry soils lead to another sample constraint--that the sample be thin. Because we are deforming the soils in uniaxial strain we do not have to worry about friction effects at the ends of the bars or radial inertia as were considered in detail by Davies and Hunter [2]. The low wave speed limits sample length in two ways. First, thick samples will never reach equilibrium because of the low wave speed; the Hopkinson bar test will then be a wave propagation experiment rather than a homogeneous deformation experiment. Fortunately, for uniaxial strain we can still derive useful information from such a test (see below). The second, and frequently more limiting, result of low wave speed is that the amplitude of the stress wave delivered to the incident bar/sample interface will be very low. If the amplitude of the incident wave in the bar is P_o and the impedence of the bar and soil are $\rho_b D_b$ and $\rho_s D_s$, respectively, the stress of the first wave through the soil will be approximately $P=2P_o\rho_s D_s/\rho_b D_b$. For our dry alluvium [6], we find $P=0.02P_o$. Subsequent reflections between the bars increase the amplitude, but very many reflections would be needed before P approached even half of P_o.

The high attenuation rate of dry soils also limits us to thin samples. The stress incident to the sample, which is already low, will decay as it propagates through the sample. Thus the stress at the sample/transmitter bar interface will be very low and subject to measurement errors. Furthermore, the variability of all these properties makes it difficult to set measurement levels so as to precisely measure transmitter bar signals.

DATA ANALYSIS FOR SOILS

With soil-as specimens, the conditions assumed for the reduction of data from the ideal split Hopkinson bar experiment may not be met. In particular, the wave speeds in dry soils at low stress levels (which may still be large enough to achieve considerable pore collapse) may be very low; values of about 200 to 250 m/s are common. As mentioned above, the deformation is very nearly uniaxial if the sample is confined in a massive sleeve, so we can adopt a data analysis technique originally developed for shock wave experiments which also produce uniaxial-strain loading. In that case, the equations of motion of the soil can be cast into a form wherein the stress is expressed in terms of the velocity and the temporal and spatial derivatives of velocity. Seaman [10] has developed a method which uses Lagrangian measurements of stress or velocity to estimate the temporal and spatial derivatives of the measured quantity. This method, called Lagrangian analysis, is particularly developed for analysis of uniaxial strain waves which attenuate as they propagate. Because the calculation of the stress at the incident interface of the sample involves subtraction of two large numbers, better accuracy can be obtained by analysing the velocity at both sides of the sample than could be obtained with stress data. The velocity calculated in the standard analysis for the incident interface is Lagrangian, but that for the other interface is definitely not. Nevertheless, we can estimate the Lagrangian wave amplitudes from the measured ones if we can determine the reflection properties at this interface.

Consider the experiment in pressure-particle velocity space as illustrated in Figure 3. If the impedence of the wave reflected back into the sample at the transmitted interface is equal to that of the wave incident on that interface, the ratio of the Lagrangian particle velocity, u_L, to the measured particle velocity, u_m, can be calculated from the geometric relations: $(u_L/u_m) = (\rho_b D_b/2\rho_s D_s)+1/2$, where ρ is density, D is wave speed, and subscripts b and s refer to the bar and the soil, respectively. As a check, we can also note that the pressures are related by $(P_L/P_m) = (\rho_s D_s/2\rho_b D_b)+1/2$. If, on the other hand, the impedence of the reflected wave is n times that of the incident wave (as illustrated, for example, by the dashed lines in Figure 3), we find that the ratios are $(u_L/u_m) = (\rho_b D_b/(n+1)\rho_s D_s)+n/(n+1)$ and $(P_L/P_m) = (n\rho_s D_s/(n+1)\rho_b D_b)+1/(n+1)$. It is usually possible to determine the velocity of the first loading wave and the first reflection from the Hopkinson bar data; we have occasionally detected the second arrival at the transmitter bar.

The technique outlined in the preceding paragraph will work well as long as the crush curve of the soil is fairly smooth and the two waves are both compressive. However, in two situations of interest the procedure will break down. First, if the crush curve of the soil is not smooth, the reflection coefficient will not be nearly constant, and a simple multiplicative factor will not represent the true variability of the Lagrangian wave form. This might occur if the soil has a very sharply defined yield point or if all of the gas-filled porosity is crushed out. In the former case the reflection coefficient may decrease dramatically as the yield point is exceeded, whereas in the other case it may increase sharply. Second, if the incident wave has a rarefaction phase, this will likely have a substantially higher impedence than the compression which would occur upon its reflection from the transmitter bar. The result would be a very complicated geometric configuration in the pressure-particle velocity plane. Although a scheme comparable to the one described above could probably be developed, this has not been done to date. Consequently, we present data below only for the initial loading portion of the experiment.

To illustrate this method, consider the data from four experiments on a very dry (about 3 percent water by dry weight) desert alluvium from Luke Air Force Base, AZ, shown in Figure 4. The incident wave amplitudes are all within 2 percent of the same value; two of the experiments used a sample 25 mm thick (22 and 24) and the other two used a 13 mm sample. The data taken from experiments 21, 23 and 24 show that reflections from the transmitter bar interface travel about 1.6 times faster (Lagrangian wave speed) than the wave incident on that bar through the sample so we have used n=1.6 in our data reduction. There are two ways in which the data from the four experiments could be grouped for Lagrangian analysis; we could either analyse each experiment separately or we could analyse both experiments with the same projectile as a unit. We have adopted the latter approach, using the incident interface velocity as the first gauge, the transmitted interface velocity from the 13 mm sample as the second gauge and the transmitted velocity from the companion 25 mm experiment as the third gauge. The amplitude of the second transmitted velocity record was scaled up or down by the amount necessary to bring the incident signal of the second experiment into coincidence with that of the first.

The results of the Lagrangian analysis of the initial loading portions only of the four experiments are shown in Figures 5 and 6. As can be seen from Figure 5, the strain rates actually experienced are 1800 to 5000 sec^{-1}, about twice as great as those determined from the standard analysis. This is because the deformation is not distributed uniformly through the sample during the wave propagation portion of the experiment (which is represented by the initial loading). The differences between the loading paths for the two experiments (Figure 6) are probably not significant.

Figure 7 compares the stress-strain paths for the Hopkinson bar experiments with those from gas gun experiments and a quasistatic uniaxial strain test on the same material. The strain rates for the gas gun tests are in the range of 10,000 sec^{-1} to 30,000 sec^{-1} as compared with 1800 sec^{-1} to 5000 sec^{-1} for the Hopkinson bar. There is apparently a considerable effect on the loading modulus when the strain rate is increased from 5000 sec^{-1} to 10,000 sec^{-1}. The gas gun data were for continuous compression over several microseconds, not for discontinuous shock waves; the gas gun stress-strain paths are, therefore, true loading paths and not just Rayleigh lines connecting some initial and final states. The stress-strain path for loading in the quasistatic test ($\dot{\varepsilon}$=5×$10^{-3}$$sec^{-1}$, 2.8 percent water) is indistinguishable from those of the Hopkinson bar loading over almost all of the range of the data and coincide with the unloading data from the gas gun tests. We conclude, therefore, that the onset of strain-rate effects is rather sudden, affecting the loading path (but not the strain at peak stress) for strain rates above 5000 sec^{-1}. We also note that the dynamic unloading path is considerably less stiff than the quasistatic unloading indicating that the strain-rate effect is also present on unloading for strain rates as low as 2000 sec^{-1}. Our present inability to reduce data for the unloading portion of the Hopkinson bar test prevents us from locating more precisely the lower limit strain rate for which strain-rate effects are important on unloading.

ALTERNATIVE MEASUREMENTS

In addition to the above techniques which we have used to obtain valid data from Hopkinson bar experiments in soils, there are several other techniques which might be applied, but have not yet been (to our knowledge). These include Lagrangian measurements within the sample, use of stress gauges at the interfaces between the bars and the sample, and alternative methods of support.

We have conducted a few experiments with stress gauges embedded in a Hopkinson bar specimen. These experiments have included carbon foils in a thick stack of electrolytic grade mica (muscovite) and strain gauges potted into a cylinder of polymeric material. Both types of experiment yielded good data, but, as of this writing, analysis of these experiments is not complete. Furthermore, neither of these types of gauges could be used in soil with our current massive containment method.

Quartz stress gauges have been used between the specimen and the bar to measure directly the stress at the sample/bar interfaces in Hopkinson bar tests of foam materials [4]. These foams present problems of low wave speed and high attenuation comparable to those encountered in dry soils but do not have the added complication of lack of shear strength. As with the truly Lagrangian measurements of the preceding paragraph, it would be very difficult to combine this approach with the massive containment.

Ways can certainly be found to provide sufficient radial support to keep the sample in place for the dynamic load without resorting to massive containment. As mentioned in a previous section, confinement per se does not invalidate the Hopkinson bar test. If the radial stress and strain can be measured, it would be possible to derive stress-strain relations for strain paths intermediate between uniaxial stress and uniaxial strain. Such information would be very valuable in deriving constitutive models for general deformation paths. There are several possible ways to approach this problem, and we are pursuing some of them. Relaxation of our current massive containment conditions will also facilitate the use of Lagrangian gauges which we have shown in the previous section will permit the use of very powerful analytic tools.

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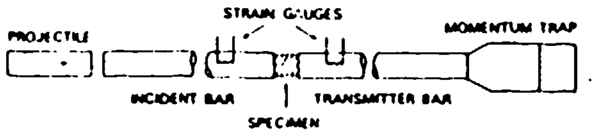

Figure 1. Schematic drawing of split Hopkinson bar apparatus.

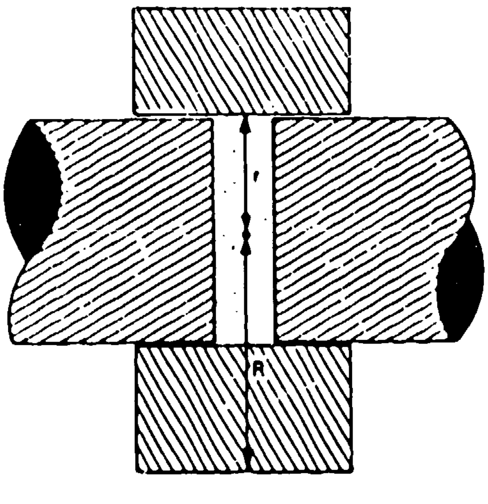

Figure 2. Sample containment scheme used to conduct uniaxial strain tests of soils in the split Hopkinson bar.

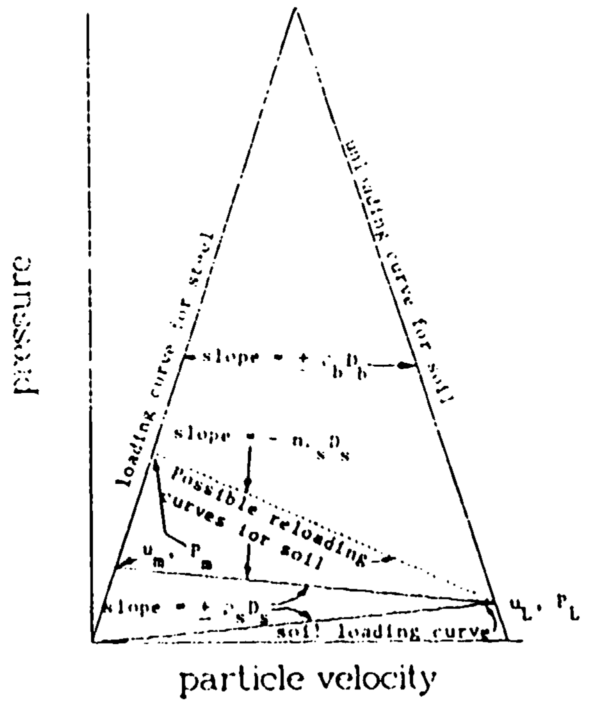

Figure 3. Pressure-particle velocity plot of split Hopkinson bar experiment showing relations used in converting transmitter bar data to free-field Lagrangian equivalent. See text for discussion.

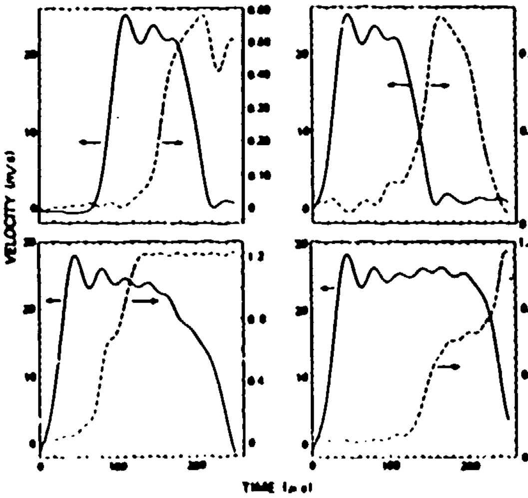

Figure 4. Interface velocity histories for four Hopkinson bar tests of dry desert alluvium [6].

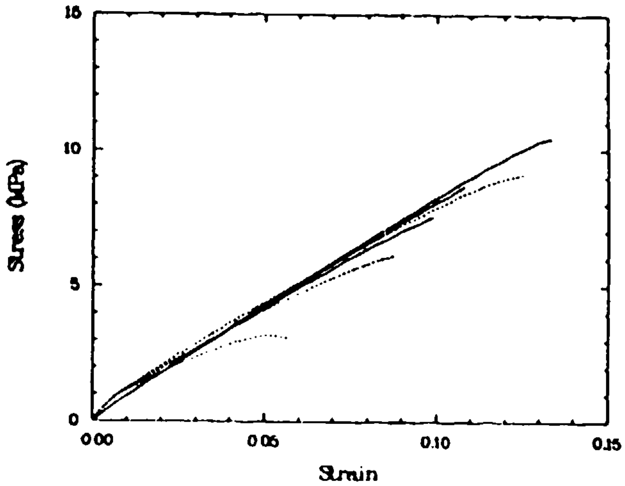

Figure 6. Stress-strain paths derived for initial loading of desert alluvium in Hopkinson bar.

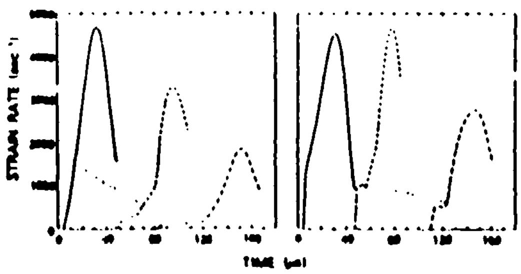

Figure 5. Strain-rate histories derived from data in Figure 4.

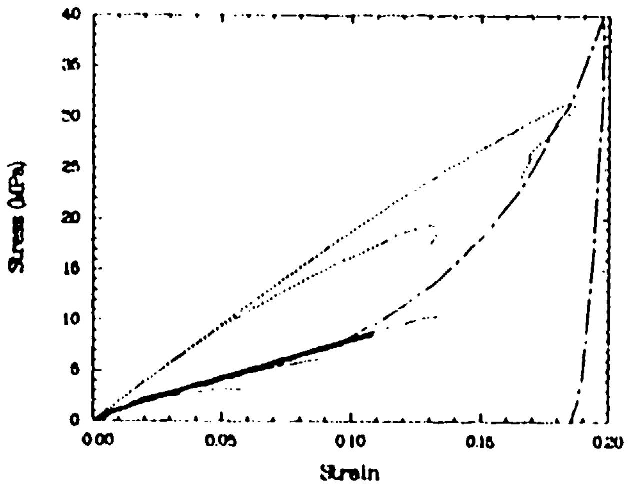

Figure 7. Stress-strain paths for several types of uniaxial strain deformation of dry CARES alluvium: dashed = gas gun, solid = Hopkinson bar, chain dash = quasistatic.