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POTENTIAL FOR GEOPHYSICAL EXPERIMENTS IN LARGE SCALE TESTS

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Abstract. Potential research applications for large-specimen geophysical experiments include measurements of scale dependence of physical parameters and examination of interactions with heterogeneities, especially flaws such as cracks. In addition, increased specimen size provides opportunities for improved recording resolution and greater control of experimental variables. Large-scale experiments using a special purpose low stress (<40 MPa) biaxial apparatus demonstrate that a minimum fault length is required to generate confined shear instabilities along pre-existing faults. Experimental analysis of source interactions for simulated earthquakes consisting of confined shear instabilities on a fault with gouge appears to require large specimens (~1m) and high confining pressures (>100 MPa).

Introduction

The dimensions of many geophysical processes exceed by several orders of magnitude the size of samples employed in laboratory geophysical experiments. Additionally, most measurements of physical parameters of rocks generally have been obtained at essentially the same scale. Because of small absolute size, and limited range of sample dimensions the duplication of standard measurements from conventional tests may, if scaled up, reveal previously unexpected or unverified scale-dependent relationships. Hence, there may be a significant need for laboratory experimentation using large specimens with deminsions on the order of perhaps one meter.

The following summarizes results from a low-pressure experiment to illustrate advantages and disadvantages of large scale experimentation and to demonstrate a specific scale-dependent process associated with fault slip and earthquake instability that requires large specimen dimensions for experimental simulation.

Scale Dependent Processes And Interactions

Scale dependence of physical parameters such as frictional strength, fracture strength, and permeability are taken up elsewhere in this volume and will not be discussed here. A related and insufficiently studied category of geophysical problems pertains to scale dependent processes and interactions. In general, the most likely sources for scale dependent processes and interactions relevant to large scale experimentation are those arising from inhomogeneity over dimensions that exceed grain dimensions and structural complexities such as cracks, faults with gouge, and compositional layering. Examples of scale dependent processes include the displacement dependence of fault strength, effect of fault gouge particle size on fault constitutive properties, nucleation and critical length relationships for unstable fault slip, and wave propagation in inhomogeneous materials.

Detailed Measurement of Processes and Interactions

A second significant area of opportunity presented by experiments using large specimens derives from increased space on the specimen for instrumentation, improved recording resolution, and greater control of experimental variables. Improved measurement capabilities could be realized in situations that are difficult or impractical on small specimens because of limitations on transducer dimensions. Transducer size constraints arise from technological limitations, considerations pertaining to averaging a measurement over several grain dimensions, and by frequency response and timing limitations for high speed processes. Experiments on large specimens in addition greatly expand the opportunity for study of processes involving interactions in inhomogeneous systems. Some examples of such experiments include simulation of tectonic processes such as folding, shear failure and hydraulic fracturing in inhomogeneous or layered rocks, and examination of processes under inhomogeneous stress fields.

A Large Scale Biaxial Experiment

Figure 1 illustrates a special purpose biaxial press developed at the U. S. Geological Survey to study interactions and scaling relations of fault instability processes. The press accommodates specimens with dimensions of 1.5 x 1.5 x 0.4 m. The principal load bearing elements of the apparatus are fabricated from seven 50 mm (2 in.) thick steel plates measuring 2.44 x 3.05m (8 x 10 ft.). The sample is loaded biaxially, normal to the smallest dimension, using pairs of flatjacks giving nominal maximum operating stresses in the major and minor stress directions of 40 MPa and 25 MPa, respectively. These stresses correspond to loads of 24 MN and 15 MN (5.5×10^6 and 3.5×10^6 lbs respectively). The sliding surface is aligned at 45 degrees to the loading axes. Teflon bearings located between the load frame bearing plates and the flatjacks permit the sample to slip with respect to the frame and have proved effective at preventing the buildup of stress inhomogeneities as the blocks displace. Independent programing of the servo-control for the two load axes permits considerable flexibility in the choice of loading path for experiments, including simulation of direct shear loading (constant normal stress).

In contrast to experimentation with small

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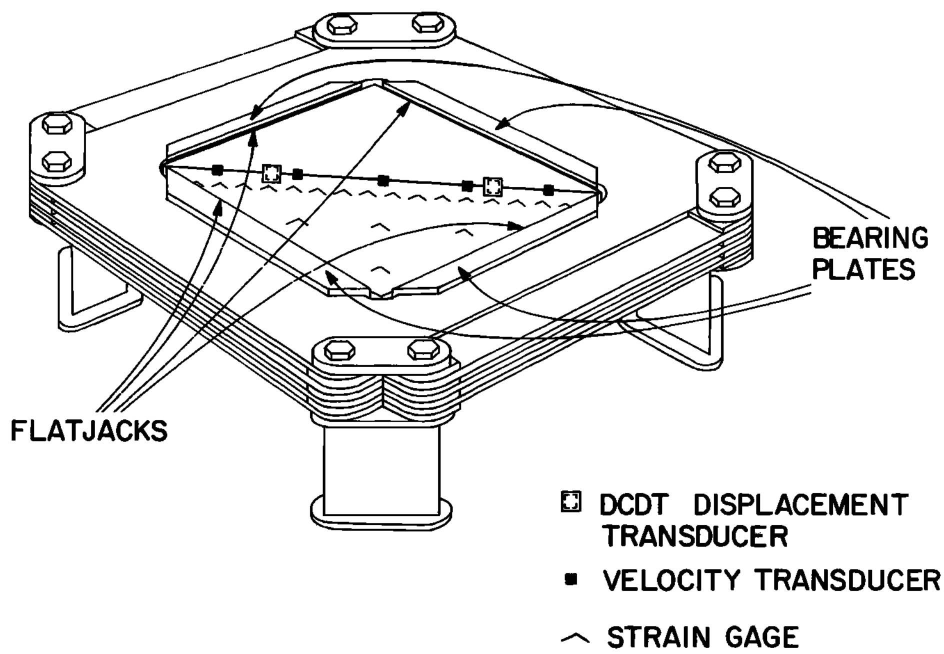

Fig. 1. Diagram of apparatus.

samples, activities pertaining to specimen handling and preparation take on considerably greater complexity in these experiments and represent a principal component of the experimental effort. Presently the samples consist of granitic rock from the Raymond, California, Quarry. The samples are cut to size at the quarry. Final lapping of sliding surfaces to desired roughness is done in the laboratory with a specially constructed lapping frame. Instrumentation attached to specimen is in many cases analogous to field instrumentation for study of active faults and includes semi-conductor strain gages, accelerometers, fault velocity transducers, and fault displacement transducers.

A major element of the experimental program is study of rupture propagation along a fault with known inhomogeneity of sliding resistance and study of processes that determine source dimensions. Experimental control of fault strength by position is accomplished with a series of 25 independently controlled fluid injection/withdrawal holes adjacent to the fault with small feeder holes that conduct fluid to and from the fault surface. By appropriate control of fluid injection pressures and withdrawal of fluid at selected locations along the fault the effective normal stress acting on the fault may be varied as a function of position. Because frictional resistance is proportional to effective normal stress, different patterns of inhomogeneous fault strength may be generated. For example, a seismic gap may be simulated by fluid injection at each end of the fault to cause slip and relax stresses at the ends but not the central portions of the fault, followed by withdrawal of fluid to restore the effective normal stress, and hence strength, to the initial levels. This phase of the experimentation is currently underway.

The coefficient of friction, μ, obtained in these experiments varies from 0.5 to 0.6, where μ is defined as the ratio of shear stress, τ, to normal stress, σ, acting on the slip surface. These values for μ obtained for the large surfaces fall within the range of values obtained from small samples with similar finely lapped surfaces.

The results shown in Figure 2 illustrate details of slip instability obtained from digital recording at 5×10^{-6} sec/sample. The normal stress is 1.4 MPa. Note that unstable slip first begins at displacement transducer D1 (co-located with strain gage S2) with a smoothly accelerating slip rate. As the instability propagates along the surface it acquires a sharp onset. Propagation velocity (rupture velocity) is slow near the point of onset and accelerates to values approaching the shear velocity as the crack traverses the specimen. The peak in stress prior to rapid stress drop arises from the stress concentration in front of the advancing crack tip. The overall form of the records of stress as a function of time including the double peak in stress at gages S4 and S5 appear similar to the results of numerical earthquake source models, especially the model of Andrews [1976]. In those calculations the double peak arises from separation of shear and Rayleigh waves ahead of the advancing crack. Detailed examination of the records reveals that the stress drop at the onset of instability although rapid, is not instantaneous, because finite slip (3-5 microns) is required before the residual sliding strength of the surfaces is reached [Dieterich, 1980]. Note also that the slip rates are relatively constant. The high frequency oscillations on the displacement records arise from mechanical resonance within the displacement transducers.

A result of experiments with this apparatus relevant to possible applications for large scale testing is the confirmation of predicted minimum fault dimension for confined unstable

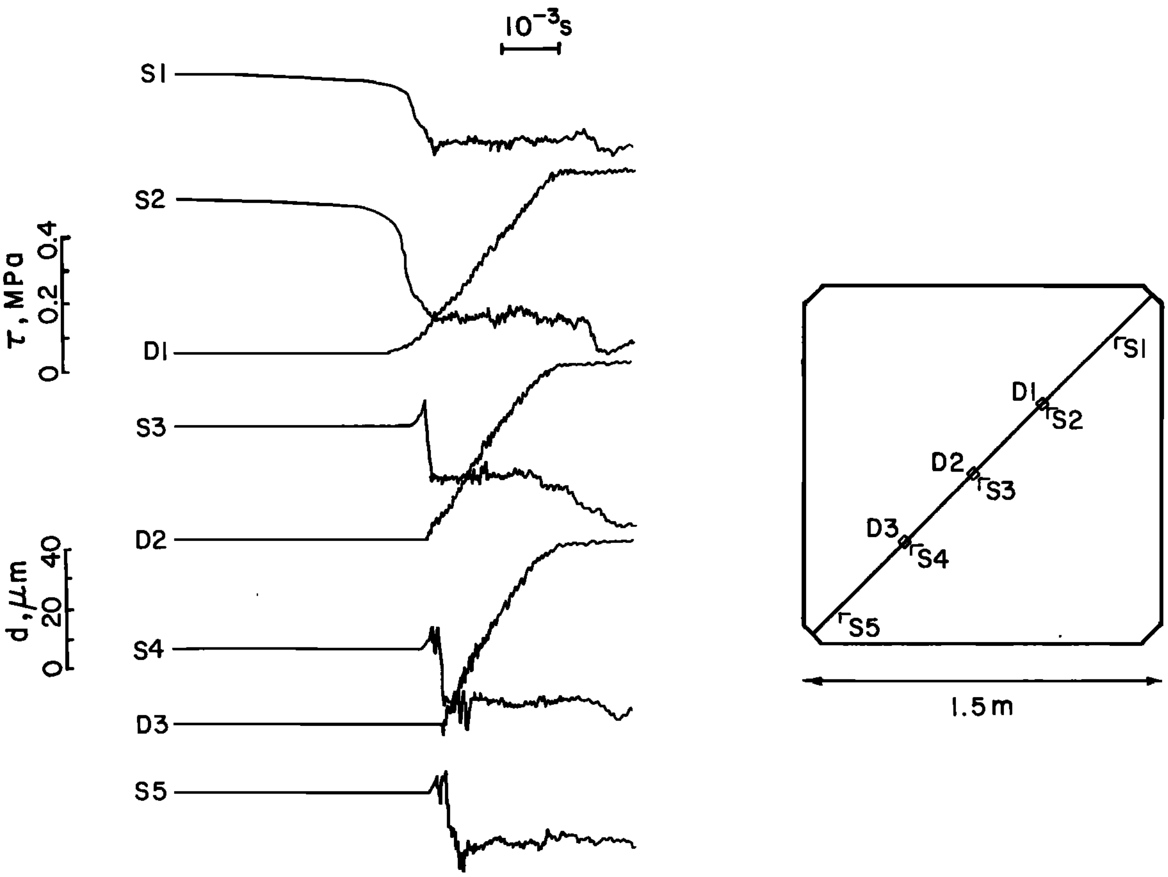

Fig. 2. Details of unstable slip event. Curves D1-D3 give fault displacement and curves S1-S5 give the component shear stress parallel to the fault.

slip [Dieterich and others, 1978]. Slip that affects only the central portion of the sliding surface and does not propagate to the ends of the specimen becomes unstable slip only if the dimensions of the slip patch exceed a minimum length. Because of the close correspondence with earthquake slip, which generally affects only a limited portion of a fault, the experimental generation of confined unstable slip in experiments has particular value for analysis of seismic source processes.

The prediction of a minimum dimension for unstable fault slip is derived from observations of a minimum displacement, d_r, required to reach residual sliding friction at the onset of slip and a related experimental demonstration that the transition from exclusively stable slip to unstable slip depends on the stiffness of the system that applies stress to the sliding surface [Dieterich, 1978]. The boundary between stable and unstable slip in small samples where the entire surface slips more or less uniformly is found by Dieterich [1978] to be given by:

$$K = (\sigma\Delta\mu)/(d_r), \qquad (1)$$

where K is the combined stiffness of the apparatus and sample, expressed as the change of shear stress by fault displacement, and $\Delta\mu$ is the decrease of the coefficient of friction at the onset of slip. If slip is confined to a patch on the fault, change of stress with displacement (stiffness) is not controlled by the stiffness of the apparatus but by the dimensions of the slip patch, L, and the shear modulus, G:

$$\Delta\tau/d = G/(\eta L), \qquad (2)$$

where η is a geometric parameter with values near 1. Taking the effective stiffness of the confined fault slip to be $\Delta\tau/d$ as given in (2) and combining with (1) yields the approximate relationship for the minimum length for unstable fault slip:

$$L = (G\, d_r)/(\eta\Delta\mu\sigma). \qquad (3)$$

The parameter $\Delta\mu$ depends upon several experimental variables, but is commonly in the range 0.02 to 0.05. Parameter d_r depends upon surface roughness and gouge particle size. Direct measurements of d_r [Dieterich, 1980] has yielded values varying from 3 microns for finely lapped surfaces to 225 microns for coarsely lapped surfaces separated by a layer of simulated gouge with particle dimensions of 125-250 microns. For the tests reported here d_r is approximately 5 microns.

Figure 3 taken from Dieterich and others [1978] shows a spontaneous stick-slip event confined to the central part of the block. Note that the slip zone, delineated by the strain

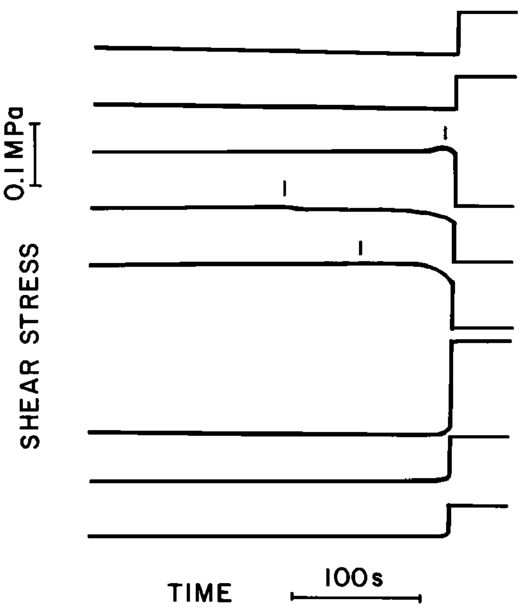

Fig. 3. Confined unstable slip event. Curves give shear stress at equal intervals along the sliding surfaces. The vertical lines indicate the time of onset of premonitory fault slip.

gage records showing a stress drop, has a length of approximately 60 cm. Dimensions for other confined unstable slip events always exceed ~60 cm. Slip on patches with dimensions less than 60 cm consisted of slow, stable events. In addition, similar small-scale biaxial experiments with fluid injection succeeded in producing only stable confined slip on patches a few cm long [Dieterich and Raleigh, 1974].

Figure 4 plots minimum length for confined slip as a function of normal stress from eq. (3) using two values of d_r. The curve for d_r = 5 microns is appropriate to the finely ground surfaces employed in the tests illustrated by Figures 2 and 3. The curve using d_r = 75 microns gives the minimum length predicted

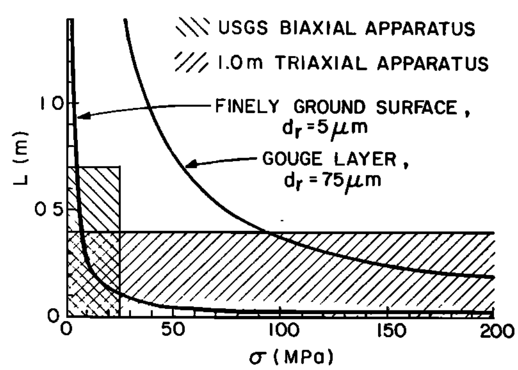

Fig. 4. Predicted minimum dimension for confined unstable slip (L) plotted against normal stress (σ) for a finely ground surface (d_r = 5μm) and a fault with fine gouge (d_r = 75μm). Cross-hatched areas give the approximate operating range of the biaxial apparatus described here and a hypothetical triaxial apparatus.

for a fault with gouge. The value, d_r = 75 microns was obtained from small experiments using a layer of gouge 1 mm to 2 mm thick with particle dimensions in the range <85 microns. The shaded areas in Figure 4 correspond to normal stresses and slip lengths in the USGS biaxial apparatus and a hypothetical high pressure triaxial apparatus employing a sample diameter of about 1 m.

Conclusions

The abbreviated discussion above suggests that a general purpose apparatus for study of geophysical problems would find a variety of applications if it operated under the range of conditions appropriate to the mid- to upper crust. Results from a large-scale biaxial apparatus verify predictions of a minimum dimension for confined unstable fault slip. It is concluded from those results that large sample dimensions are required for experimental study of seismic source processes. Some topics of interest include: scaling of earthquake source motions by stress drop, fault dimensions and fault heterogeneity; relationships between the dimensions of zones of premonitory deformation such as preseismic slip and the dimensions of the earthquake source; processes and interactions that limit earthquake source dimensions and arrest slip including the formation of seismic gaps; variation of rupture velocity with rupture length; and characteristics of stopping phases. The existing U.S. Geological Survey biaxial apparatus is probably adequate to study problems such as these at low normal stresses using finely ground fault surfaces. Studies at higher pressures and applications using faults with gouge would require development of a large, high pressure apparatus.

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