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Yucca Mountain Site Characterization Project

Frictional Sliding in Layered Rock Model: Preliminary Experiments

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ABSTRACT

An important aspect of determining the suitability of Yucca Mountain as a possible nuclear waste repository requires understanding the mechanical behavior of jointed rock-masses. To this end we have studied the frictional sliding between simulated rock joints in the laboratory using the technique of phase shifting moiré interferometry. The models were made from stacks of Lexan plates and contained a central hole to induce slip between the plates when the models were loaded in compression. These preliminary results confirm the feasibility of the approach, and show a clear evolution of slip as function of load.

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1 Introduction

Frictional sliding between simulated rock joints was studied in the laboratory using the technique of phase shifting moiré interferometry. Models were made from stacks of Lexan plates that had been sand-blasted to provide a uniform frictional interface. Each model contained a central hole bored normal to the plane of the plates, so that slip would be induced between the plates near the hole under compressive loading.

The design of the specimen was guided by preliminary experiments performed by Brown [1]. The most significant departure from the original model used by Brown was to increase the length of the model to eight times the diameter of the hole. This change insured a state of uniform far-field stress around the hole.

Diffraction gratings (300 lines/mm) were replicated on the front surface of the models and interrogated with a phase shifting moiré interferometer. During monotonic loading of the models, fringe patterns representing the in-plane surface displacements were recorded at several loads. The relative slip between the plates was determined from these fringe patterns as a function of position along the interface.

The measurements made using the phase shifting moiré interferometer have a precision on the order of 1.67 μm, with a spatial resolution of approximately 0.13 mm (this is based on a viewing width of 60 mm discretized to 512 pixels and 256 gray levels). Because the smoothing provided by phase shifting does not distort the detail near edges and discontinuities, the information right up to the edge of the plates could be used to determine relative slip between plates.

The experimental details concerning the fabrication of the models, the load frame and fixture, and the data acquisition procedures are summarized below. Finally, results for two experiments are presented in the form of color fringe plots and plots of slip versus position along the interfaces around the hole.

The work described in this report is part of the rock mechanics program at Sandia National Laboratories for the Yucca Mountain Site Characterization Program. The laboratory-scale experiments conducted for this work are intended to provide high quality data on the mechanical behavior of jointed structures that can be used to validate complex numerical models for rock-mass behavior. Given the difficulty in obtaining the quality and quantity of data necessary for code validation efforts from field experiments, this work provides essential information for the activities.

2 Experimental Details

2.1 Model Construction

The models were constructed from 12 plates, 2 in. wide by 12 in. long, of 0.25 in. thick Lexan. After cutting and squaring, both sides of all the plates were sand-blasted using a careful procedure to ensure a uniform surface roughness. The plates were then clamped together using threaded round stock inserted through two holes drilled from top to bottom, about 0.5 in. from the sides of the model. The faces of the models were machined flat, and a 1.5 in. diameter hole was bored through the center. The models were then disassembled and finished as follows:

1. The ends of the individual plates were beveled with a grinding wheel to allow them to be secured later with PC-6 epoxy. After grinding, the plates were washed with soap and water to remove grit.

2. The middle plates were temporarily bonded together with silicone to allow an aluminized photoplate diffraction grating to be replicated in epoxy on the resulting surface without epoxy seeping between the Lexan layers by capillary action.

3. After the silicone was cured, the front surfaces of the models were polished flat against a precision granite surface with fine grit sandpaper.

4. After cleaning the front surface with soap and water, a 300 lines/mm grating was replicated onto each model using Photolastic PC-6 epoxy.

5. The plates were then separated so that the silicone could be removed from between them. The edges of the gratings were gently polished with fine sandpaper to remove any "overlap" that would interfere with the sliding of the plates.

6. The models were carefully cleaned and completely reassembled. Finally, the ends of each model were bonded with PC-6 epoxy, which seeped in between the beveled edges to provide a strong yet flexible means to keep the plates aligned properly.

2.2 Load Frame and Fixture

A compact load frame designed for use on an optical table was constructed for this work. Screws and fixtures with a capacity of 500 kN were used to ensure stiffness. Gear boxes were chosen to provide sufficient mechanical advantage to allow the frame to be operated by hand. This avoided potential vibration problems from an electric drive motor. The useful load limit of the frame is determined by the installed load cell, which has a working range of 0–80 kN tension or compression. The load frame design allows a biaxial loading mechanism to be added in the future. The frame is currently being equipped with a linear bearing system to allow translation of the frame (and thus the model) across the field of view of the interferometer.

A custom load fixture for the model was constructed from two 2 in. wide by 12 in. long by 2 in. high steel bars. An additional length of steel bar was used, in conjunction with a pair of dowel pins, to distribute the specimen load evenly. The fixture and the model are shown schematically in Figure 2.

2.3 Material and Interfacial Properties

The wave velocities for Lexan were measured and found to be 2.2 km/sec for compression and 0.92 km/sec for shear. The density of the material is 1.20 g/cm^3, resulting in the following elastic properties: Young's modulus, $E = 2.84$ GPa; Shear modulus, $G = 1.02$ GPa; Poisson's ratio, $\nu = 0.39$.

The coefficient of friction between the sand-blasted plates (as measured by tilting the block) was determined to be 0.47. All of these properties agree with values presented in the report by Brown [1], which contains more information regarding the experimental procedures leading to the determination of this data.

2.4 Phase Shifting Moiré Interferometry

Moiré interferometry [2] is a high-sensitivity method of full-field displacement measurement. The technique directly provides contour maps of the two orthogonal in-plane displacement components, u and v.

Phase shifting [3, 4] is an efficient means for converting the gray-scale fringe pattern information available from moiré interferograms into a digital representation of optical phase. The smoothing provided by the data reduction algorithm is performed in time, not space, so a degree of noise rejection is obtained without loss of spatial detail. This is important when specimens contain edges and discontinuities.

The outputs of the technique are two-dimensional surface maps of in-plane displacement. Strain information can be obtained from the displacement fields via differentiation. The gage length of the strain calculations when using phase shifting is roughly three times the size of a pixel in real data units. Phase shifting moiré interferometry offers an experimental counterpart to the powerful computational methods of solid mechanics, where displacements and strains are also the primary output [5].

2.4.1 Application to the Rock Model Experiment

There were several issues associated with the application of moiré interferometry to this problem that had to be addressed. The first involved how the grating was to be replicated onto each of the plates without introducing large rotations between adjacent pieces of the grating. This technical problem was overcome using the specimen construction method described above.

The second difficulty was a result of each plate having a single isolated grating. Typically, only one continuous diffraction grating is interrogated during a moiré interferometry experiment. In this work, however, the area of interest was covered with multiple diffraction gratings (one per plate), each one slightly rotated relative to the next. The unavoidable slight rotations of the gratings introduced different carrier patterns for each of the plates. Thus, fringe patterns at zero load (null patterns) had to be captured and used as a reference, so that absolute displacement measurements could be made. Fortunately, the video-based phase shifting technique provides an efficient means for accomplishing this.

2.4.2 Description of the Interferometer System

A four beam, fiber optic interferometer was used for this work. This interferometer combines two seperate two beam interferometers to provide both u and v (horizontal and vertical) components of displacement. Central to the system is a four-way fiber optic beam splitter assembly that converts a single, uncollimated beam of Argon-ion laser light into four, equal intensity beams channeled through individual fibers. A schematic illustrating the fiber optic assembly Figure 1.

Four 50 mm diameter camera lenses are located at the end of the fibers and are used to collimate the laser light from the individual fiber sources. The four lenses are mounted on an aluminum bar frame in pairs—two lenses are mounted in a vertical plane, the other two lenses are mounted in a horizontal plane. The entire frame can be rotated to remove any relative rotational misalignment between the interferometer and the specimen.

At any one time, one pair of lenses is capped so that only two lenses project light onto the specimen surface. For example, the vertical pair of lenses can be capped so that the horizontal pair of lenses can be used alone to form fringe patterns representing the in-plane horizontal (u-field) displacements. The angle between the two beams incident on the specimen grating is chosen so that both beams are diffracted into a path normal to the surface of the specimen. This is accomplished by the action of the diffraction grating bonded on the surface of the specimen, and is schematically depicted in Figure 1. When these two beams are recombined using a conventional optical system (lens and camera), they interfere with each other and form a fringe pattern.

Phase shifting is accomplished by stretching one of the selected fibers using a piezoelectric (PZT) transducer. This transducer is under the control of the laboratory personal computer so that the phase shifting can be synchronized with the video image acquisition. This is also illustrated in Figure 1.

Wrapped fringe patterns are obtained by acquiring five images, with 90° phase shifts between the images. These images are then processed using a simple algorithm to produce the wrapped fringe pattern. The wrapped fringe patterns are transferred to a Silicon Graphics workstation and unwrapped using a recursive flood-fill algorithm. A custom software package has been developed for extracting quantitative data from these unwrapped fringe patterns.

3 Experimental Results

Prior to testing, the models were given several cycles of compressive loading to promote uniform frictional properties between the plates. A typical experiment consisted of setting up the model in the load frame, aligning the optics, and taking null patterns at zero load. Load would then be increased gradually, and fringe patterns acquired at predetermined steps.

A typical wrapped fringe pattern obtained during an experiment is shown in Figure 3. These types of images differ from conventional fringe patterns in that the fringes are artificially 'wrapped' every multiple of 2π. This is an artifact of a $\tan^{-1}$ calculation in the data reduction. Before the data in a wrapped fringe pattern can be used, the image must be properly masked and unwrapped. This is accomplished using custom software developed for this purpose.

In addition to unwrapping, it was necessary to subtract the null patterns from the deformed fringe patterns to obtain a measurement of absolute displacements. This leads to what is called a 'nulled' fringe pattern. Once unwrapped and nulled, each pixel in the image provides a measure of the absolute displacement at a given load.

Figures 4 and 5 are color fringe plots of displacement in a Lexan plate model for two levels of compressive load. The colormap used to display these unwrapped images goes from red to yellow to blue (or from black to white in grayscale renderings). The slip between layers can be estimated by noting the difference between the color of the plot above and below an interface. For example, a relatively large amount of slip has occurred near the hole at 0.43 MPa (Figure 4) for interface 1. Figure 5 indicates that at 0.86 MPa, the slip in this region has increased.

The unwrapped fringe plots are useful in that they provide a quantitative representation of the full-field data, but they are not sufficient for quantitative analysis. For this purpose, detailed line scans must be extracted from the unwrapped fringe patterns and processed to produce slip as a function of position along the interface. This is demonstrated in the next set of experiments, where again, fringe patterns were captured at several loads. The results are shown in Figures 6-8, where slip is plotted as a function of position along each interface for three successive loads. The fringe patterns and line scans for this sequence of loading agree well with the previous experiment.

At 0.14 MPa (Figure 6), the slip between the plates appears to be uniformly distributed around the hole. However, at 0.43 MPa (Figure 7), the slip along the first and second interface from the top has increased dramatically. Finally, at 0.56 MPa (Figure 8), the second interface has become the primary location for slip, while the top interface indicates no slip directly above the hole, and a reduced value of slip far from the hole.

4 Conclusions

These preliminary results confirm the feasibility of using phase shifting moiré interferometry for quantifying slip during laboratory experiments with layered rock models. Results for the Lexan model show a clear evolution of slip as a function of load. The trends apparent in these experiments were reproducible between experiments.

The approach can be applied to models made from actual rock or concrete samples with little difficulty. Models can be fabricated and tested that contain an arbitrary combination of holes and/or vertical cuts. Variations in loading can be obtained by modifying the existing load frame. Such variations may include inclined loading and biaxial compressive loading of the model. A linear bearing system is currently under construction to allow a larger field of view to be interrogated during moiré interferometry data collection.

5 Acknowledgments

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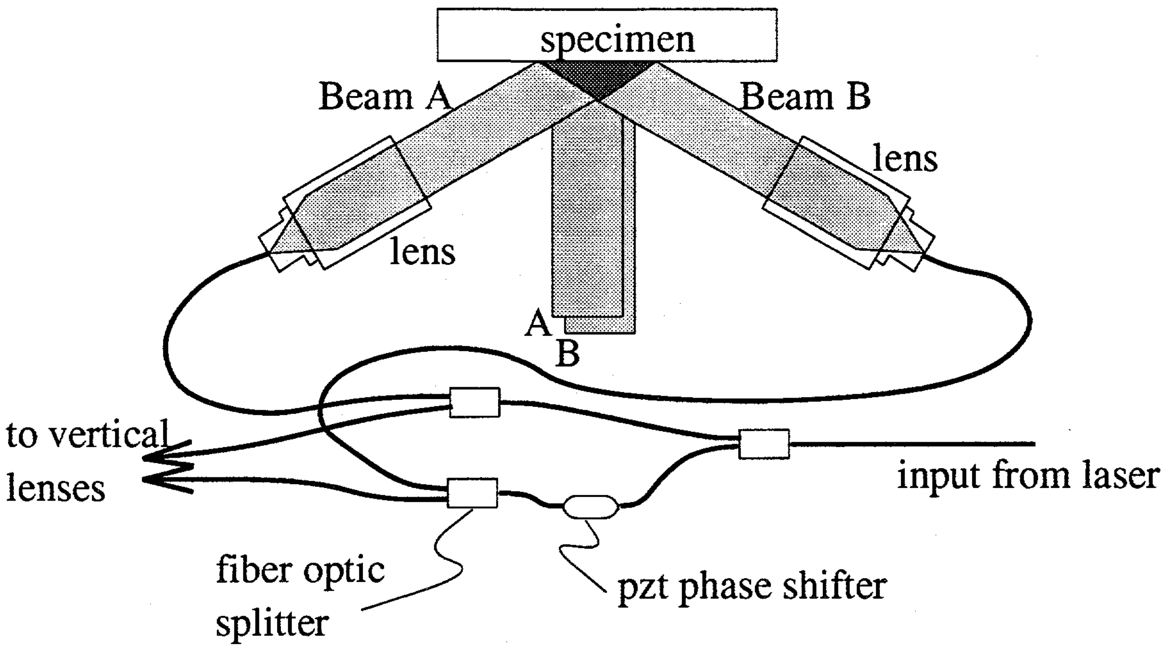

Figure 1: Four beam interferometer schematic, showing how two beams are used to form a fringe pattern.

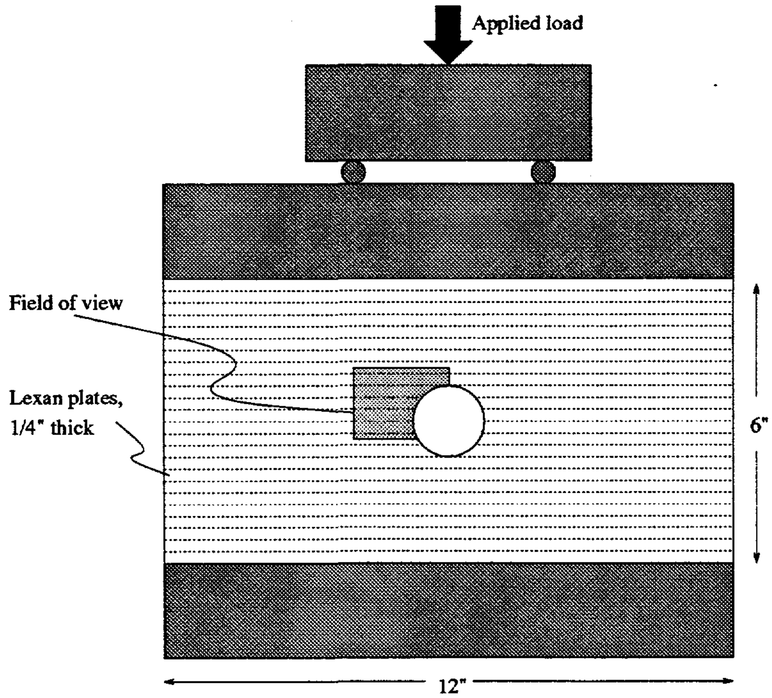

Figure 2: Model and load fixture.

Figure 3: Typical wrapped fringe pattern $\sigma_0 = 0.86\,\text{MPa}$.

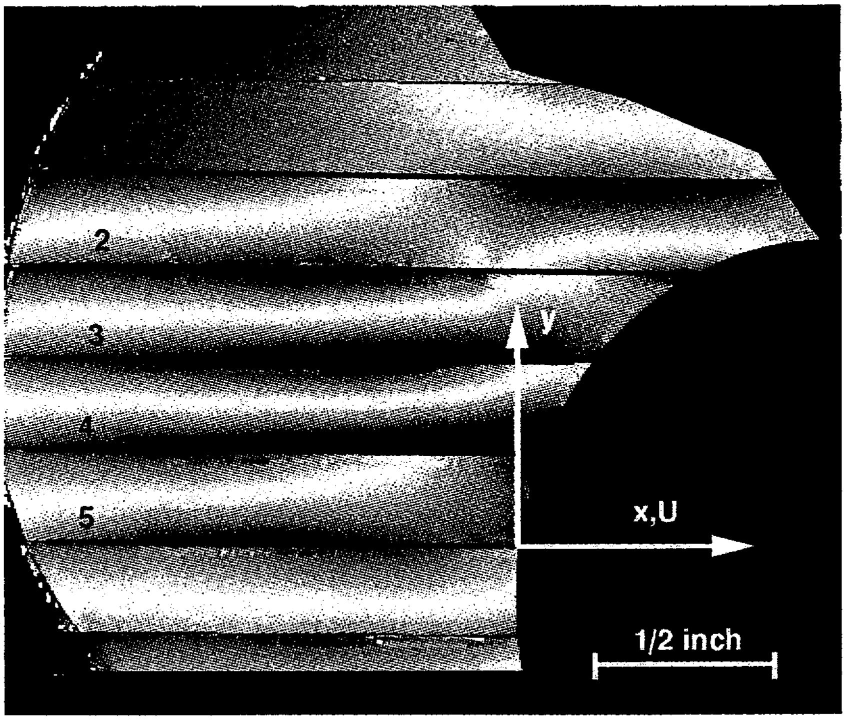

Figure 4: Unwrapped u-displacement field, $\sigma_0 = 0.43\,\text{MPa}$.

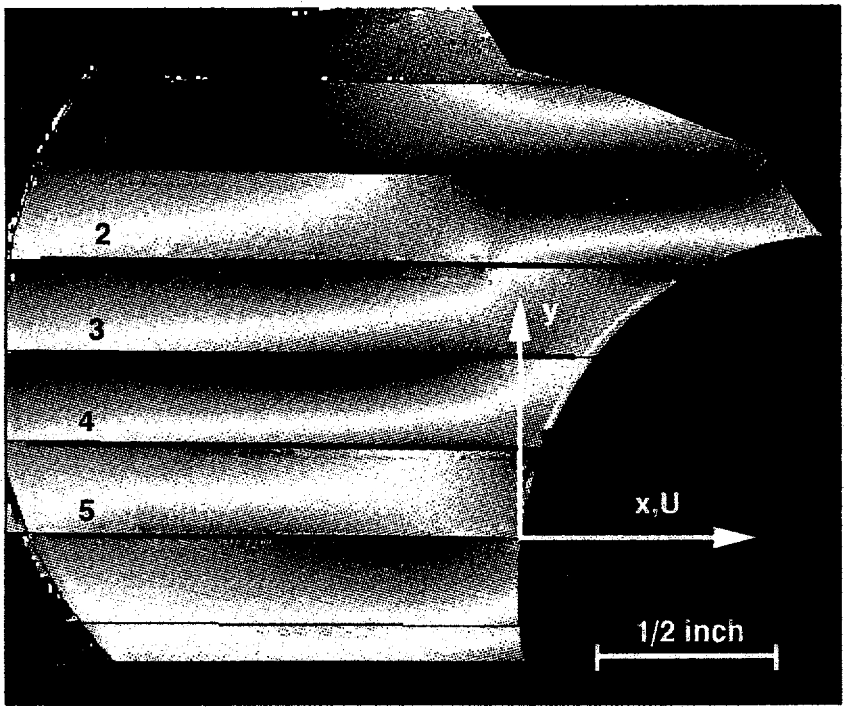

Figure 5: Unwrapped u-displacement field, $\sigma_0 = 0.86\,\text{MPa}$.

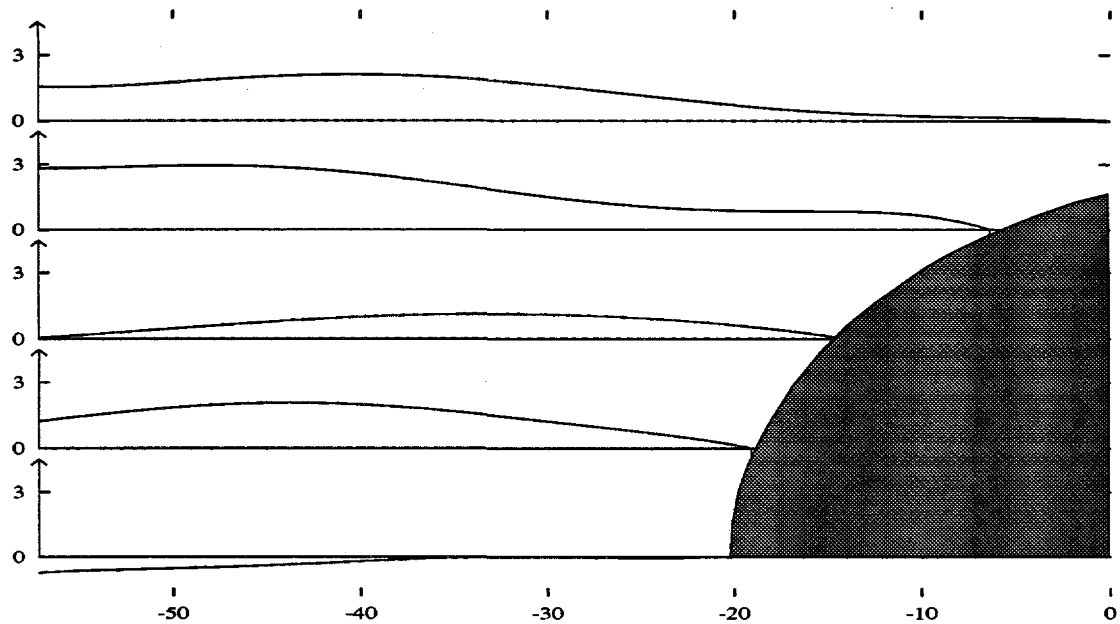

Figure 6: Slip along interfaces at $\sigma_0 = 0.14\,\mathrm{MPa}$. The position scale is in millimeters, and the slip is in microns.

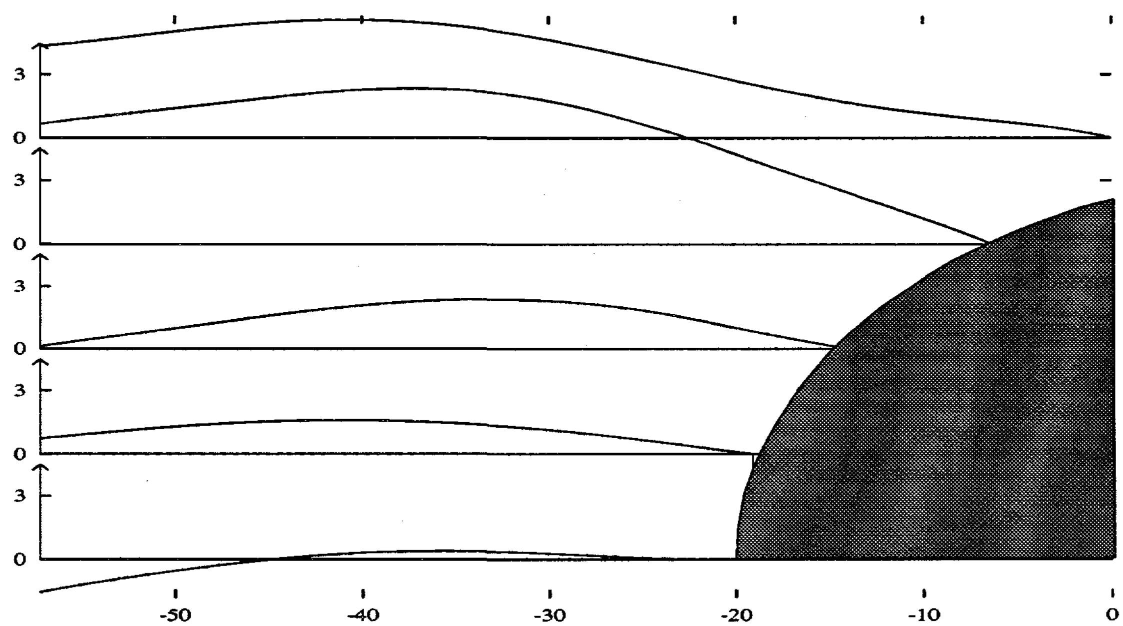

Figure 7: Slip along interfaces at $\sigma_0 = 0.43\,\mathrm{MPa}$. The position scale is in millimeters, and the slip is in microns.

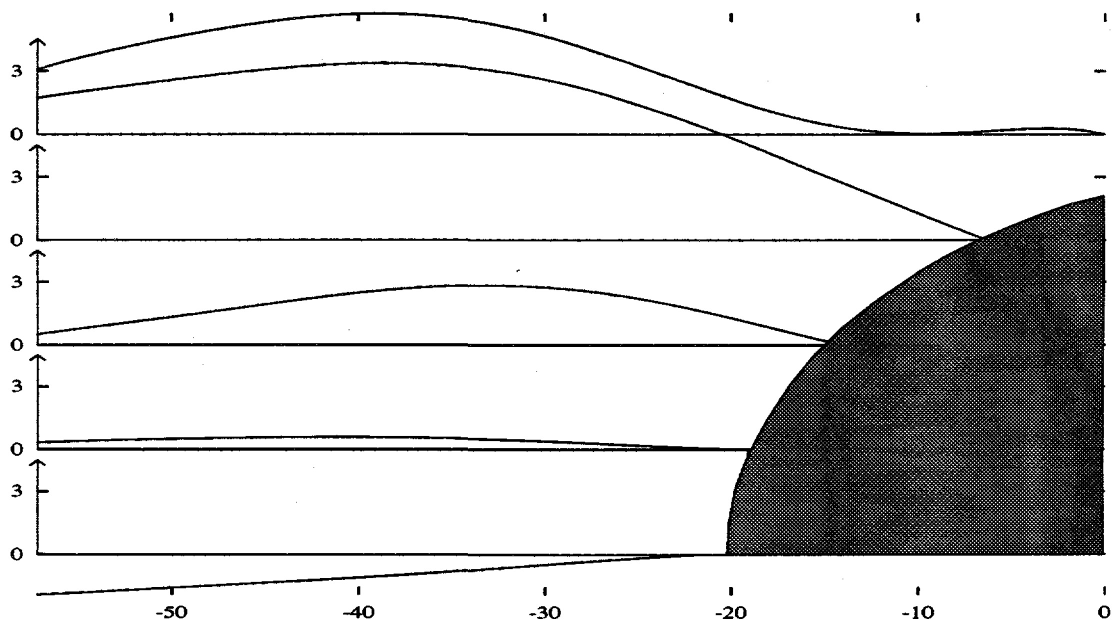

Figure 8: Slip along interfaces at $\sigma_0 = 0.56\,\mathrm{MPa}$. The position scale is in millimeters, and the slip is in microns.

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