IGPP Proposal Number 324

**A Specialized Boundary Element Algorithm Developed
to Calculate the State of Stress in the Anza Gap,
San Jacinto Fault Zone, Southern, CA.**

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1. Introduction

The San Jacinto fault zone (SJFZ) is a major right lateral splay of the San Andreas fault system in southern California (Figure 1). A significant slip gap has been identified on the SJFZ between Anza and Coyote Mountain using an number of slip events (Abe, 1988, Thatcher *et al.* 1975). This approximately 40 km-long gap is believed to be capable of producing an earthquake with a magnitude as large as $M_L = 7$ (Vernon, 1989). In addition, the SJFZ near Anza is characterized by highly clustered seismicity patterns that clearly define a seismicity gap within the northern half of the Anza slip gap (Scott, 1992; Sanders and Kanamori 1984).

Principle stress orientations and ratios obtained from the inversion of focal mechanism data display a significant amount of variability throughout the region, as shown in an earlier IGPP-supported study (Hartse *et al.*, 1994). The observed orientations of the principle stresses for the Anza region are generally those expected for a San Andreas oriented strike slip system; the most and least compressive stresses are nearly horizontal and the intermediate stress is nearly vertical. However, the most compressive stress direction rotates in a clockwise fashion by 25° across the region from east to west and a systematic reverse to normal oblique component of slip trends from the northwest to the southeast.

Because seismicity and slip gaps such as these are considered to be excellent

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Figure 1: The region surrounding the San Jacinto fault zone showing major fault zones, 3846 seismic events recorded by the Anza seismic network (open circles) and the Anza slip gap. The area where the study is focused lies within the box outline.

natural laboratories for studying the earthquake process, much work has been done on understanding their origins and physical conditions. In an attempt to understand this observed variability in the stress field, a boundary integral computer code for simulating the stress in a homogeneous thin plate cut by a vertical fault system has been written based upon the algorithm of Crouch and

Starfield (1990). In our modified formulation, the original system of equations is rearranged using boundary conditions which are more consistent with faults: given shear strength and normal stress and displacement continuity. Results based upon this code have been shown to correlate well with previous analytic state of stress calculations for simple fault geometries (eg. Chinnery, 1963). A number of gap models of varying complexity are presently being analyzed in order to model the observed state-of-stress for the Anza gap.

II. Progress During the Reporting Period

A. Major Findings

The FY94 IGPP investigation into the state of stress near the Anza gap has yielded a number of interesting results to date. At the end of the last reporting period (FY93), the algorithm used for the calculations was taken directly from Crouch and Starfield (1990). This method has been used by a number of researchers for their calculations of stress (Billham and King 1989; Gombert 1991; Stein *et al.* 1992). This method works well for standard boundary value problems such as a known displacement field along a fault. Under close scrutiny the application of this algorithm to a mixed value problem (a known stress and a known displacement) was found to be numerically unstable (Figure 2). In this figure, an antisymmetric distribution of stress relative to the solitary fault is expected, however variability occurs both on either side and on either end of the fault.

The orientations of the principle stress for a solitary fault should also be antisymmetric. These are plotted on an azimuthal color wheel (Figure 3). In this representation, red colors correspond to approximately east and west azimuths, purples through blues to the northeast and southwest azimuths, and yellows through greens to the northwest and southeast azimuths. Degree measurements are in X-Y coordinates where zero degrees corresponds to east. The color wheel representation was chosen in order to maintain exacting detail on the 81 x 81 grid of orientations without overwhelming the plot with directional indicators. Reduction of the number of orientation points plotted yields an unsatisfactory loss of resolution.

Models calculated using the original Crouch and Starfield algorithm allow material to strain parallel to the fault only. This behavior induces an unrealistic build-up of the component of strain normal to the fault, which is akin to placing a fixed barrier within a plastic medium. This instability becomes

Figure 2: Most compressive stress magnitude (upper) and orientation (lower) for a zero-strength fault under 100 MPa uniaxial N-S compression extending from the X-Y coordinates (-20,20) to (20,-20) calculated using the standard algorithm of Crouch and Starfield (1990). The magnitude of the stress ranges from approximately - 125 MPa (purple) to - 75 MPa (red) and should be anti-symmetric about the fault. The

Azimuth by Color

Figure 3: Azimuthal color wheel where the colors on the wheel denote principle stress orientation and where opposite azimuths have the same color. The overlying vectors point roughly towards the direction represented by each color. The color method was chosen over vectors

Figure 4: Double sided boundary element. The fault zone is exaggerated from its infinitesimal size to emphasize the two-sided nature of the element. The positive and negative shear and normal axes are labeled. Pairs of such elements can be oriented at any angle with respect to the X-Y axis to construct fault systems of arbitrary complexity.

unacceptably large as the complexity of the fault model increases through the addition of features such as slip gaps, changes in strength, and/or fault bends. In our new foundation, the original boundary conditions are replaced by double-sided conditions of stress and displacement continuity across the fault and known along-fault shear strength:

$$\left. \begin{aligned} u_n^{(+)} &= -u_n^{(-)} \\ \sigma_n^{(+)} &= \sigma_n^{(-)} \end{aligned} \right\} \text{calculated (characterizes normal stress} \\
 \text{and displacement discontinuity)}$$

$$\left. \begin{aligned} \sigma_s^{(+)} \\ \sigma_s^{(-)} \end{aligned} \right\} \text{known (characterizes shear strength)}$$

where the positive and negative signs correspond to opposite sides of the fault (Figure 4).

This new system was tested by placing a zero-strength fault which extends from the X-Y coordinates (-20,20) to (20,-20) under 100 MPa of compressive stress in a Poisson solid where Young's modulus is 54,000 MPa. The stress distribution off-fault is propagated for a 81 x 81 grid extending from the lower-left X-Y coordinate of (-80,-80) to the upper right coordinate of (80,80). Plots of the most and least compressive principle stress directions and orientations clearly overcome the instability problem (Figure 5). These results were next

validated by comparing them to the results of Chinnery (1963) which provides an analytic formulation for the stresses associated with a right lateral strike-slip dislocation surface. The shear stress drop parallel to the fault (Figure 6) and the normal stress (also termed the hydrostatic compression or tension) (Figure 7) also correlate well with this result. However, the shape of the zero stress drop contour varies from the straight fault model of Chinnery as it has four lobes which connect to the crack tips. This arises because our boundary integral equation model allows for the natural tendency of the crack tips to rotate into the direction of the regional stress field (Hanson et al. 1971).

Curiously, the zero shear stress strength condition along the fault is adhered to in an unexpected manner. It is typically believed that a fault would meet this condition by principle stress rotation to relieve the fault parallel shear stress. However, our solution tends to meet this condition by placing the near fault region in a state of isotropic stress.

B. Summary and Conclusions

- The widely-used algorithm of Crouch and Starfield is unstable when used to solve our mixed boundary equation problem of interest. Altering the boundary conditions and correspondingly rearranging the system of equations to utilize double-sided boundary elements overcomes this drawback.
- The new algorithm is more physically realistic as it allows for rotation of the fault segments in the strain field resulting from satisfying the fault static shear strength condition.
- It presently appear that simple gap models will not approach the complexity observed by Hartse *et al.* (1994).
- Preliminary results indicate that a fault trifurcation gap model may describe the non-strike slip components to some of the seismicity.
- The equilibration of the principle stresses has broad implications towards stress near faults that will be further investigated.

C. Equipment Obtained and Facilities Used

No new equipment has been obtained for the reporting period of this project. The majority of the analysis was done using the New Mexico Tech Geophysics Facility.

Figure 5: Principle stress magnitude (upper) and orientation (lower) estimated using the new double-sided boundary element formulation (Figure 4) for a zero-strength fault extending from the X-Y coordinates (-20, 20) to (20, -20) under 100 MPa uniaxial N-S compression. These

Figure 6: The shear stress change (MPa) parallel to a 45° zero-strength fault which extends from the X-Y coordinates of (-20,20) to (20,20) under a regional stress of 100 MPa. Areas with negative values denote regions of stress dissipation whereas positive values are stress accumulation.

D. Tangible Results

Papers Completed

Hartse, Hans E., Richard Aster, Michael Fehler, Jennifer Scott, and Frank Vernon, Evidence for Small-Scale Stress Heterogeneity in the Anza Seismic Gap, Southern CA, JGR Vol. 99, No. B4, 1994.

Papers in Preparation

Flores, R.A., R.C. Aster, and M.C. Fehler, Title in Preparation, in preparation for submission to Bulletin of the Seismological Society of America.

Abstracts and Presentations

Flores, R.A., R.C. Aster, and M.C. Fehler, Stress Calculations for the San Jacinto Fault Zone, Southern CA, Using a Specialized Boundary Element Algorithm for the Strike-Slip Mixed Value Problem, abstract submitted to Fall, 1994 AGU Meeting.

Flores, R.A., R.C. Aster, and M.C. Fehler, State of Stress Calculations Based upon Fault Geometry on the San Jacinto Fault Zone, Southern CA, abstract, Seismological Research Letters 65, Pp. 70, 1994.

E. Intangible Results

This research has continued to encourage collaboration between scien-

Figure 7: The normal stress associated with a zero strength fault which extends from the X-Y coordinates of (-20,20) to (20,-20). Areas with negative values are zones of compression and positive values are zones of dilation.

tists at the Los Alamos National Laboratories, New Mexico Tech, and The Scripps Institution of Oceanography.

III. Future of the Project

During the next few months, we will finalize the analysis of the state of stress for slip gaps and synthesize this knowledge into a model for the ANZA region. We will also extend the region that is under investigation to include larger portions of the San Jacinto fault zone as well as portions of the nearby San Andreas system. A package of boundary element and visualization programs that constitute a valuable tool set for the analysis of stress in a number of geophysical situations has been developed. It is our intent to develop additional items for this package in order to continually improve its capabilities. Primarily, we would like to allow for non-homogeneous initial conditions including regional driving stress, Poisson's ratio, and Young's modulus. We believe that the addition of these features could increase the resolution of the package and thus make it applicable to an even more diverse set of geophysical scenarios.

IV. Funds Received

Initial IGPP-LANL funding (\$11,500) was made available in October, 1991. To continue the project into the last half of Fiscal Year 1992, we received a funding supplement totaling \$9,000 from IGPP-LANL.

\$20,500 was awarded from IGPP-LANL (\$15,500 to NMT and \$5,000 to LANL) to continue the project during Fiscal Year 1993, and Fiscal Year 1994 funding totalled \$22,000 (\$17,000 to NMT and \$5,000 to LANL).

Rick Aster has obtained additional funding for Anza-related studies from the USGS National Earthquake Hazards Reduction Program (NEHERP). Research and equipment purchases associated with the NEHERP project will assist in this project due to overlapping software and data processing interests.

V. Los Alamos Facilities Used

The EES-4 Sun network was used for testing the stability of the computer program.

VI. References

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