BEHAVIOR OF A TUNNEL DURING A RAPID EARTHQUAKE FAULTING EPISODE

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A symposium on Recent Advances in Geotechnical Centrifuge Modeling was held on July 18-20, 1984 at the University of California at Davis. The symposium was sponsored by the National Science Foundation's Geotechnical Engineering Program and the Center for Geotechnical Modeling at the University of California at Davis.

The symposium offered an opportunity for a meeting of the International Committee on Centrifuges of the International Society for Soil Mechanics and Foundation Engineering. The U.S. participants also met to discuss the advancement of the centrifuge modeling technique in the U.S. A request is being transmitted to the American Society of Civil Engineers to establish a subcommittee on centrifuges within the Geotechnical Engineering Division.

BEHAVIOR OF A TUNNEL DURING A RAPID EARTHQUAKE FAULTING EPISODE

by P. B. Burridge*

INTRODUCTION

The Southern California Rapid Transit District plans to construct a subway system known as Metro Rail for the Los Angeles area. A portion of the proposed tunnel passes through the 45° dipping Hollywood fault at approximately right angles and, as shown in Figure 1, lies on sandstone bedrock 60 feet below the alluvium surface. Probable fault displacement is estimated at 3.7 feet of vertical offset. Since there have been no documented occurrences of the behavior of a modern tunnel subjected to fault displacements, information is lacking as to the interaction of tunnel and soil, the stress levels to be expected in the tunnel and the length of tunnel that will be affected. To help answer these questions, a limited series of rapid fault displacement tests was conducted on a scaled model tunnel imbedded in soil in the geotechnical centrifuge at the California Institute of Technology. This paper presents: a) the faulting mechanism used for the fault displacement tests, b) the results of two tests, and c) the results of a one-dimensional finite element analysis of the tunnel.

FAULTING MECHANISM

A device had previously been constructed to simulate the action of a 45° reverse fault on the centrifuge (1). As shown in Plates 1 and 2, the device consists of a test container with a false floor, the right-

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hand side of which, together with the end wall, is capable of moving down at 45° to the left side which is stationary. The moving portion is kept in place until activated by a toggle control supported in a position beyond top dead center (TDC). In its initial position the floor is level, as seen in Plate 1, and the model tunnel is placed on it and covered with soil. When the centrifuge is running with the test container at the appropriate g-level, and the data acquisition system is turned on, the toggle is released by a push from a hydraulic cylinder controlled by the operator. Once it passes over TDC, the weight of the moving portion of the box plus soil (with the in-flight acceleration level of approximately one hundred g's, this amounts to more than one ton) propels it downward to the stops, to the position shown in Plate 2. The fault is thereby activated and propagates through the soil to the surface. The tunnel and superincumbent soil are displaced as they would be in a fault rupture event.

The vertical offset of the false floor shown in Plate 2 is 1/4 inch and represents a 2 foot fault displacement at 100 g. Although the geologically expected vertical displacement of the Hollywood fault is 3.7 feet, an offset of only 2 feet was modeled for the centrifuge tests since calculations indicated that the full geological offset would permanently damage the instrumented model tube.

MODELING OF THE PROTOTYPE TUNNEL

The proposed tunnel construction consists of a number of precast reinforced concrete slabs bolted together to make one 3-1/2 foot long "ring" section, as shown in Figure 2. These "rings" in turn bolt together along the tunnel axis to form the complete tunnel. Since the bending properties of the slab units vary along the tunnel axis and circumferentially around the cross-section, an equivalent uniform prototype section was chosen and a uniform aluminum tube used for the centrifuge model. The most important property of the prototype tunnel to be modeled was the in-plane "ring" stiffness, that is, the stiffness associated with deformation of the circular tunnel cross-section. Consequently, the inside diameter and the EI per unit length of the tunnel were the quantities used to correctly scale the centrifuge model tube. The aluminum model tube is shown in Plate 3, instrumented with strain gauges for longitudinal flexure (i.e., bending of the tunnel as a beam) and transverse flexure (i.e., deformation of the circular cross-section).

FAULT TEST PREPARATION OF THE MODEL TUBE

The ends of the model tube were covered to prevent the entrance of sand and the tube was placed at right angles to the fault in the test container, with the false floor in the raised position. A hard plastic sleeve extending to the wall which moves with the fault was placed over the rigid end of the tube to accommodate shortening of the box with fault displacement and prevent axial compression of the tube. At the left end of the tube was a 3/4 inch gap between the tube and end wall, which became filled with sand once the model overburden was placed over the tube for the fault displacement tests. Plate 4 shows the model tube placed in the test container prior to filling with sand and Plate 5 shows the test container after completion of a test with the right end displaced downward 1/4 inch and the container appropriately shortened. Two fault displacement tests were conducted, the first representing a loose soil condition of 93 pcf unit weight, and the second representing a dense soil condition of 102 pcf unit weight. These conditions were intended to bracket the range of probable soil conditions at the Hollywood site.

CENTRIFUGE TEST RESULTS

The prototype longitudinal bending moments and flexural stresses for the fault tests at $\gamma = 93$ pcf and 102 pcf are presented in Figures 3 and 4. The prototype transverse bending moments and flexural stresses are shown in Figure 5 for the 93 pcf fault test. These figures are oriented to match Plates 1 and 2 so that points to the right of the fault are displaced downward relative to those on the left side of the fault which remain fixed. The static pretest values represent the tunnel condition immediately prior to fault rupture, the dynamic values represent the maximum moments and stresses during fault rupture (unless indicated minimum) and the static post-test residual values represent the tunnel condition after all transients of fault rupture have died away.

In the longitudinal direction, the maximum bending moment of 8.6×10^5 kip-ft and maximum flexural stress of 27.1 ksi occur directly over the fault for $\gamma = 102$ pcf. It should be noted that throughout the tests the model aluminum tube remained linear in its response and hence one would not expect a stress of 27.1 ksi to actually develop in a reinforced concrete tunnel. Instead, one would expect such a tunnel to yield and fail at a stress of approximately 6 ksi over a distance of at least 30 feet either side of the fault as indicated by Figure 3.

In the transverse direction, the maximum bending moment of 59 kip-ft/ft and maximum flexural stress of 10.5 ksi occur 10 feet from the fault on the downthrown side for the 93 pcf fault test. The maximum transverse flexural stress is noted to be less than half the maximum longitudinal flexural stress.

Figures 6 and 7 show the dynamic characteristics of longitudinal bending moment directly over the fault for the 93 pcf test during fault rupture. Figure 7 is an enlarged version of a section of Figure 6 showing, in more detail, the dynamic response of the tunnel immediately after initiation of fault rupture. It is observed that fault displacement takes place in less than 0.1 seconds and the time between data points is approximately 6 milliseconds (2).

ONE-DIMENSIONAL STATIC FINITE ELEMENT ANALYSIS

A one-dimensional static finite element model of the tunnel was constructed using planar beam elements. As shown in Figure 8, the beam elements were supported by springs at the nodes and the nodal forces were computed from the overburden plus a nonlinear correction for soil-tunnel interaction. This correction was additive or subtractive depending on the relative movement between tunnel and soil and its magnitude accounted for the softening of soil with increasing strain (2). The finite element model was calibrated by adjusting its parameters to obtain the closest possible agreement with the static residual longitudinal bending moment curves of the centrifuge tests (Figure 3). Figure 9 shows how close a match could be achieved. This calibration quantified the amount of soil-tunnel interaction experienced during the centrifuge tests.

In spite of the plastic sleeve placed over the right end of the centrifuge tube, shortening of the faulting container developed an axial force in the tube directed to the right and a shear force directed downward at the capped left end of the aluminum model tube. Inclusion of the shear force at the left end was found necessary in the analysis to match the numerical to the experimental results as shown in Figure 9.

With the nodal springs and soil-tunnel interaction of the finite element model calibrated by the centrifuge test results, the boundary conditions were removed from the finite length numerical model to allow it to predict the longitudinal bending moments of the infinite length prototype tunnel. The predicted longitudinal bending moment profile is shown in Figure 10. The maximum moment for the infinite length model occurs directly over the fault for the dense (102 pcf) soil test and has a value of approximately 6.4×10^5 kip-ft. This compares very favorably with the maximum moment for the finite length model and centrifuge test results of Figure 9.

CONCLUSION

Despite the finite length of the centrifuge model and the boundary effects associated with the centrifuge fault displacement tests, the centrifuge does appear to capture the essential behavior of an infinite length prototype tunnel during a rapid earthquake faulting episode.

ACKNOWLEDGMENTS

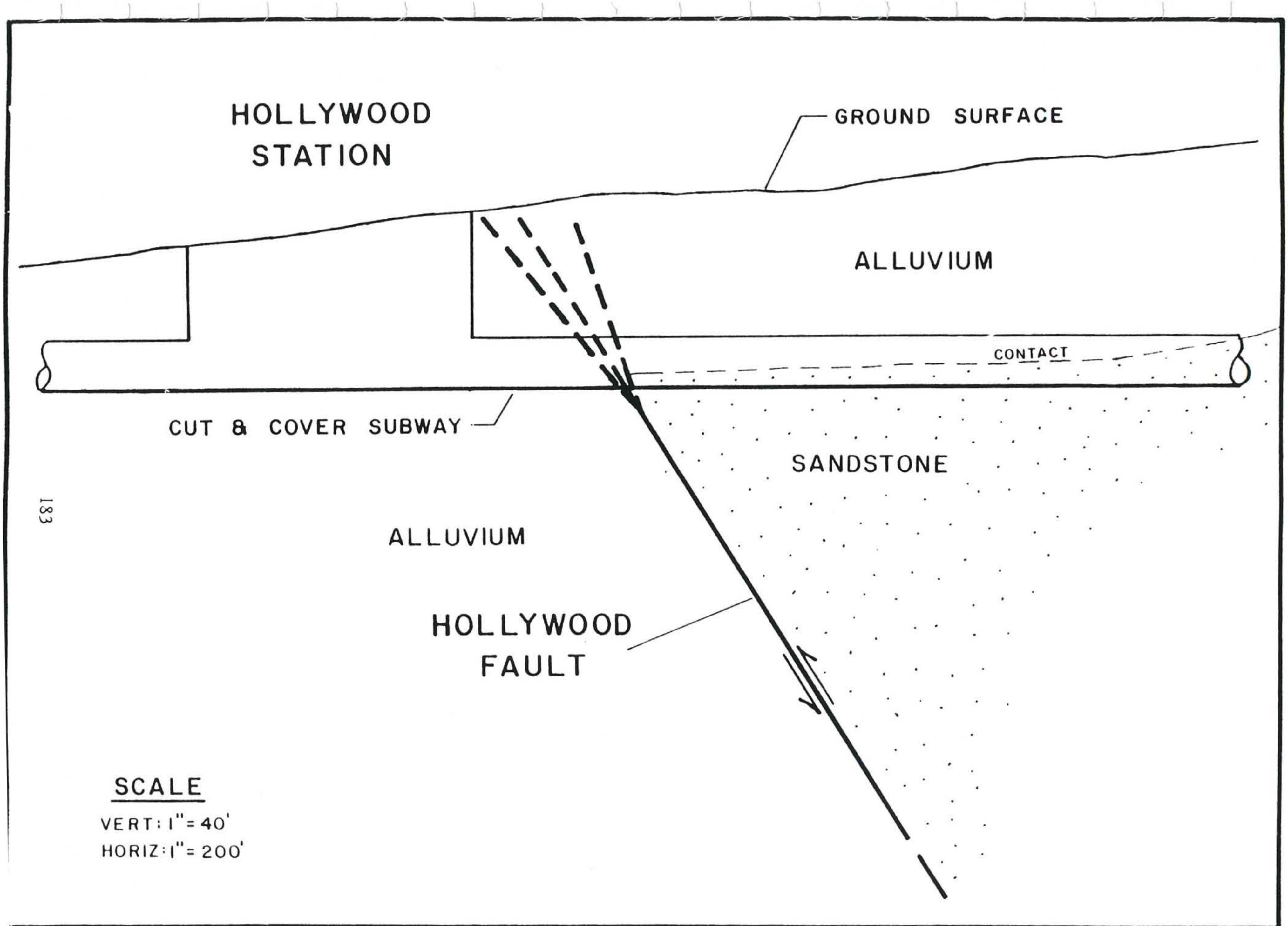
The centrifuge and finite element model studies were carried out under a subcontract between the California Institute of Technology and

Lindvall, Richter and Associates (who were directly contracted by the Southern California Rapid Transit District to study the earthquake response of the proposed Metro Rail system).

The centrifuge tests were performed with the invaluable assistance of J. R. Lee while the finite element studies were carried out by Professor J. F. Hall. The entire Caltech effort was supervised and guided by Professor R. F. Scott.

REFERENCES

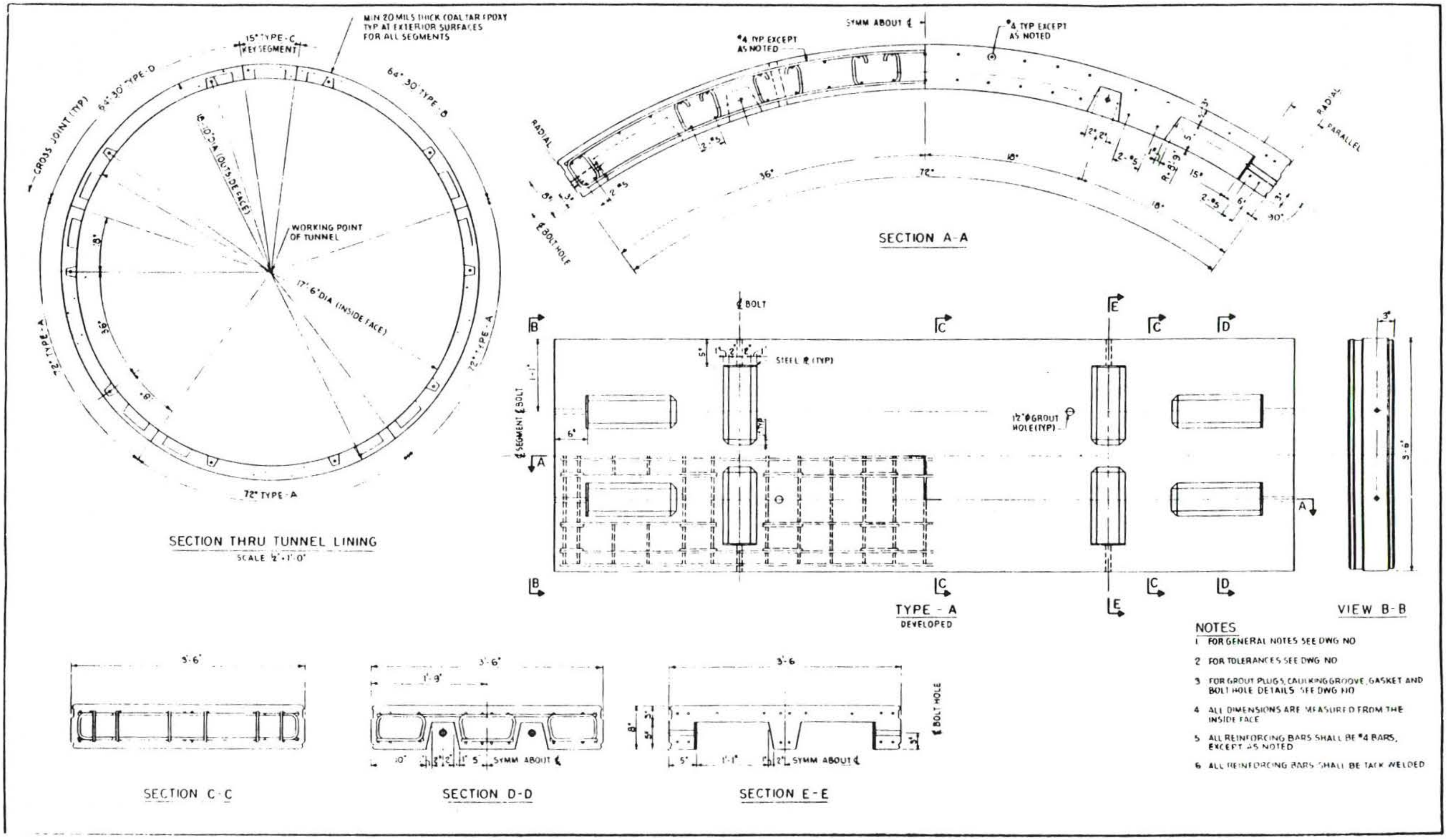
1. Roth, W. H., Scott, R. F. and Austin, I., "Centrifuge Modeling of Fault Propagation Through Alluvial Soils," Geophysical Research Letters, Vol. 8, No. 6, pp. 561-564, May 1981.
2. Lindvall, Richter and Associates, "Centrifuge and Numerical Studies to Evaluate Effect of Fault Displacement on Metro Rail Tunnel for Southern California Rapid Transit District," July 1984.



LINDVALL RICHTER & ASSOCIATES
EARTHQUAKE SCIENCES AND ENGINEERING GEOLOGY

SUBWAY PROFILE AT HOLLYWOOD FAULT CROSSING

FIGURE 1



NOTES

1 FOR GENERAL NOTES SEE DWG NO

2 FOR TOLERANCES SEE DWG NO

3 FOR GROUT PLUGS, CAULKING GROOVE, GASKET AND BOLT HOLE DETAILS SEE DWG NO

4 ALL DIMENSIONS ARE MEASURED FROM THE INSIDE FACE

5 ALL REINFORCING BARS SHALL BE #4 BARS, EXCEPT AS NOTED

6 ALL REINFORCING BARS SHALL BE TACK WELDED

Figure 2 Structural drawings of prototype tunnel

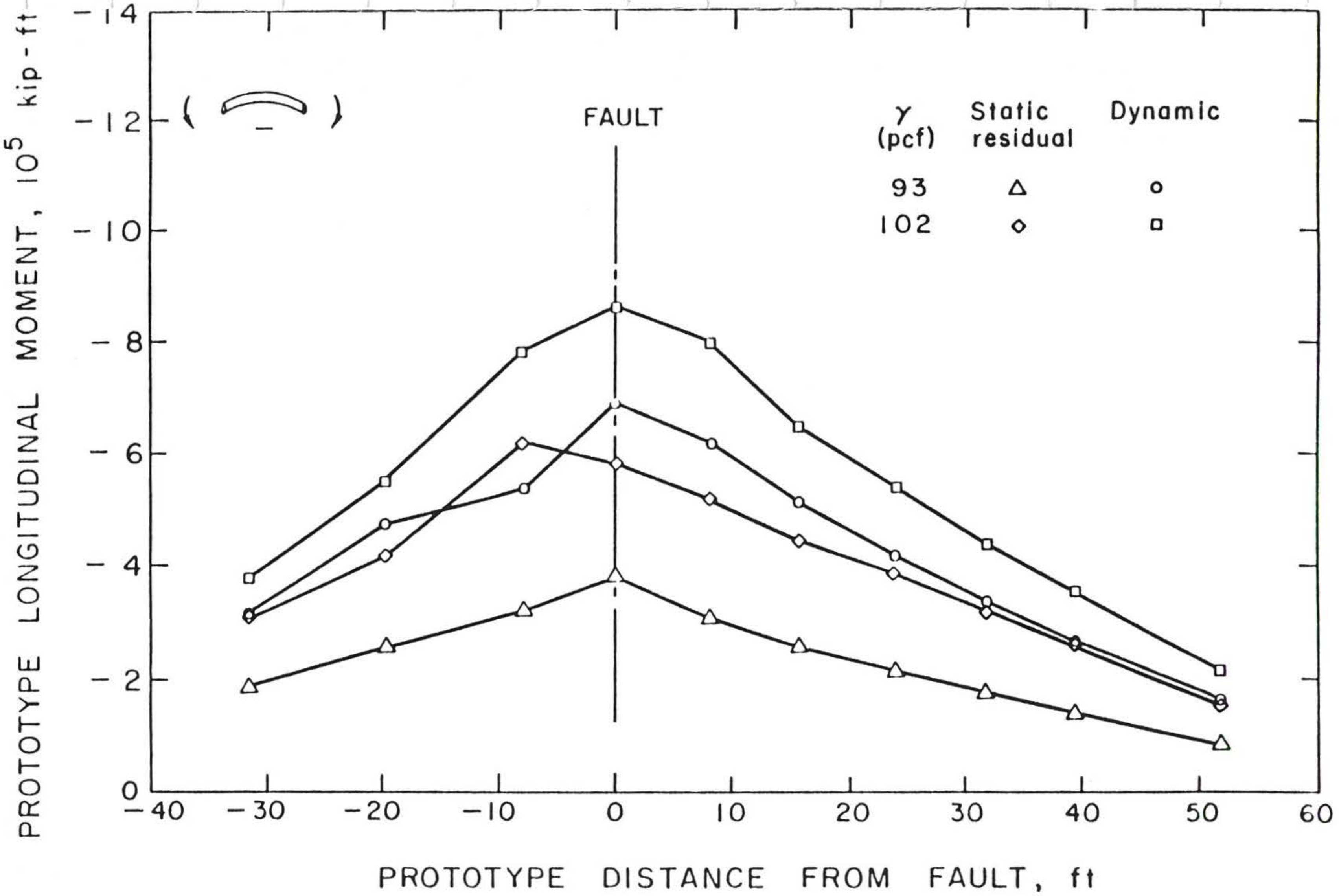


Figure 3 Prototype longitudinal moments due to faulting in loose soil (93 pcf) and dense soil (102 pcf).

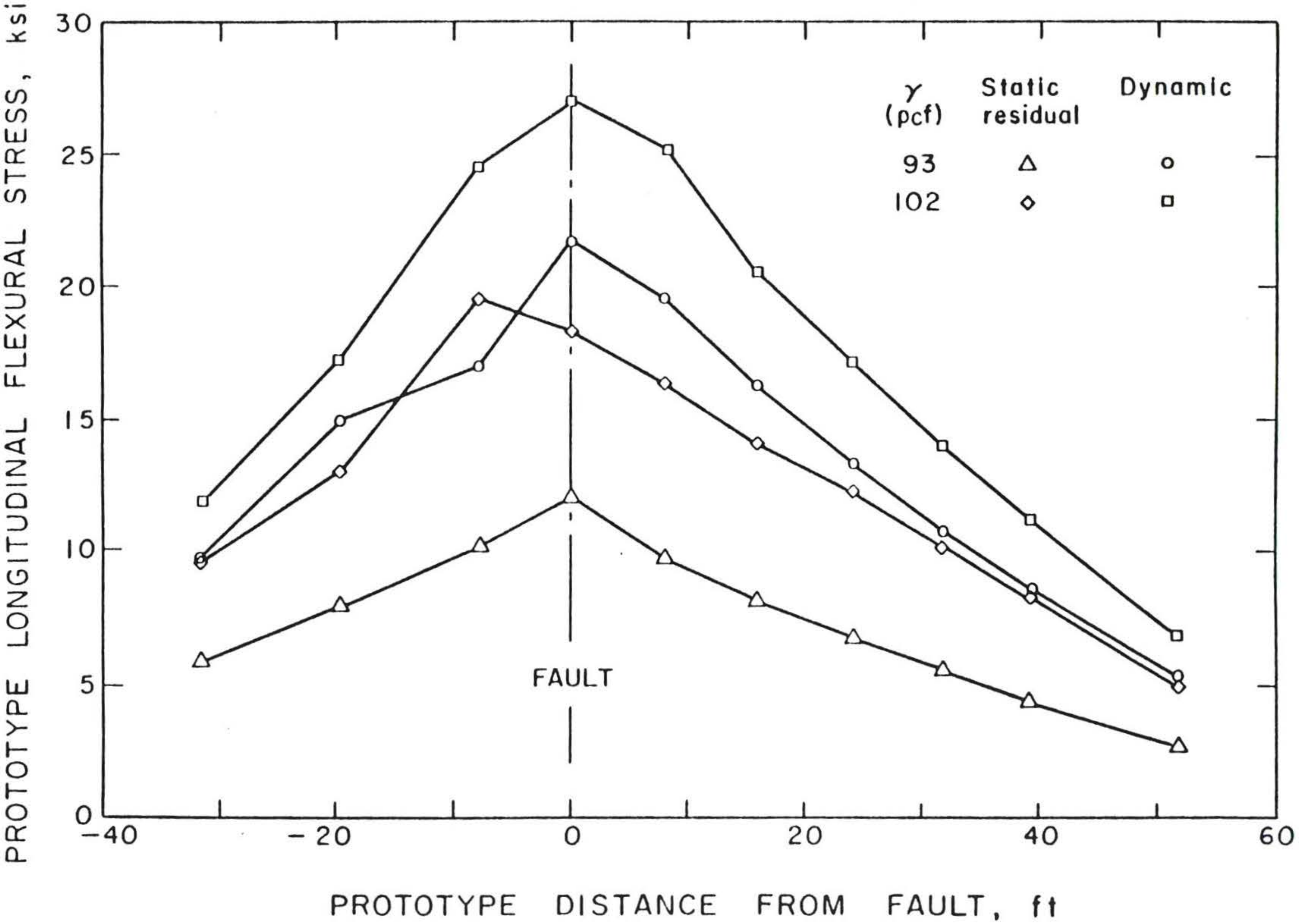


Figure 4 Prototype longitudinal stresses due to faulting in loose soil (93 pcf) and dense soil (102 pcf).

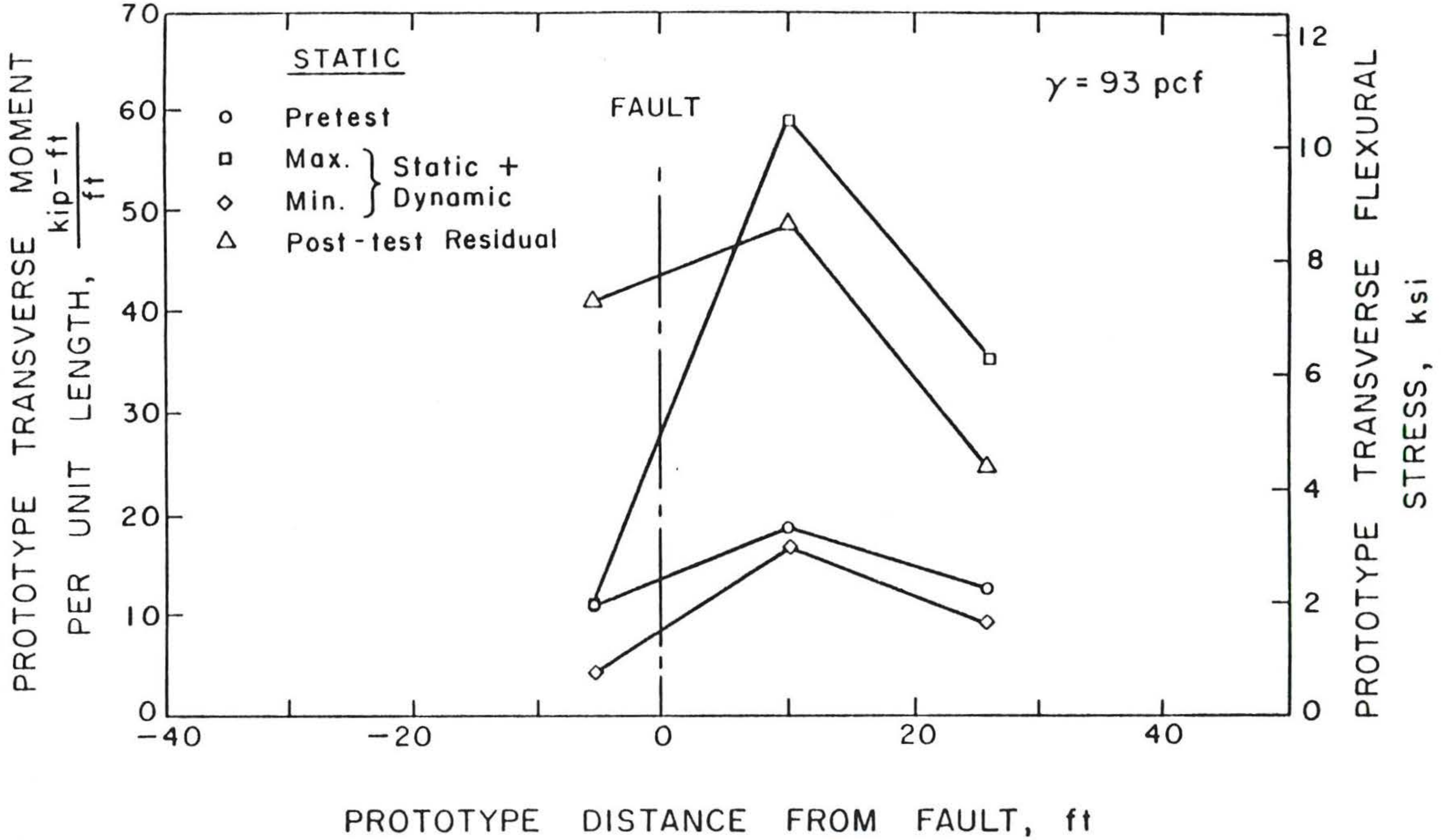


Figure 5 Prototype transverse moments and stresses due to faulting in loose soil (93 pcf).

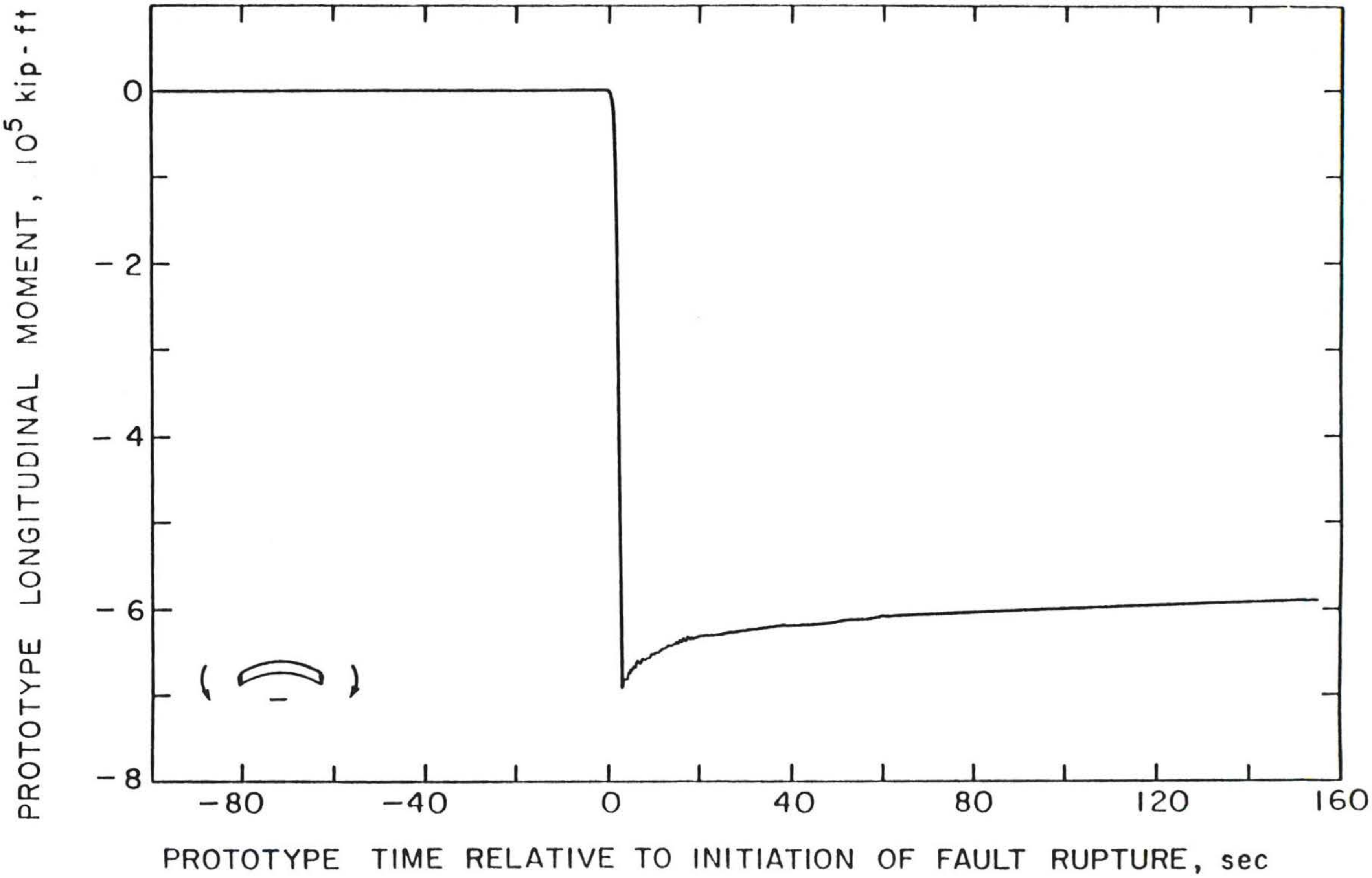


Figure 6 Prototype longitudinal moment directly over fault as a function of prototype time during faulting; loose soil (93 pcf) test.

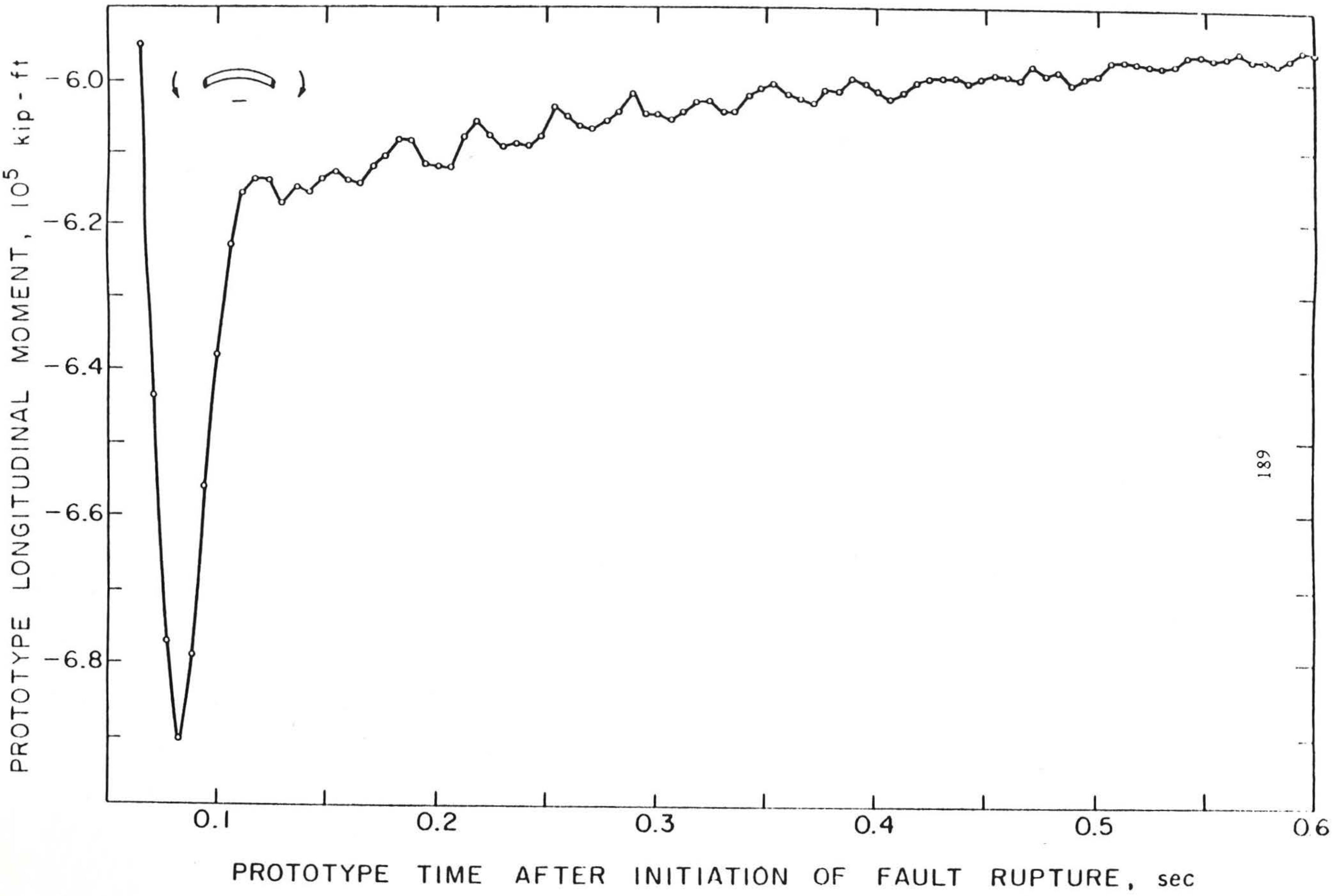


Figure 7 Prototype longitudinal moment directly over fault as a function of magnified prototype time during faulting; loose soil (93 pcf) test.

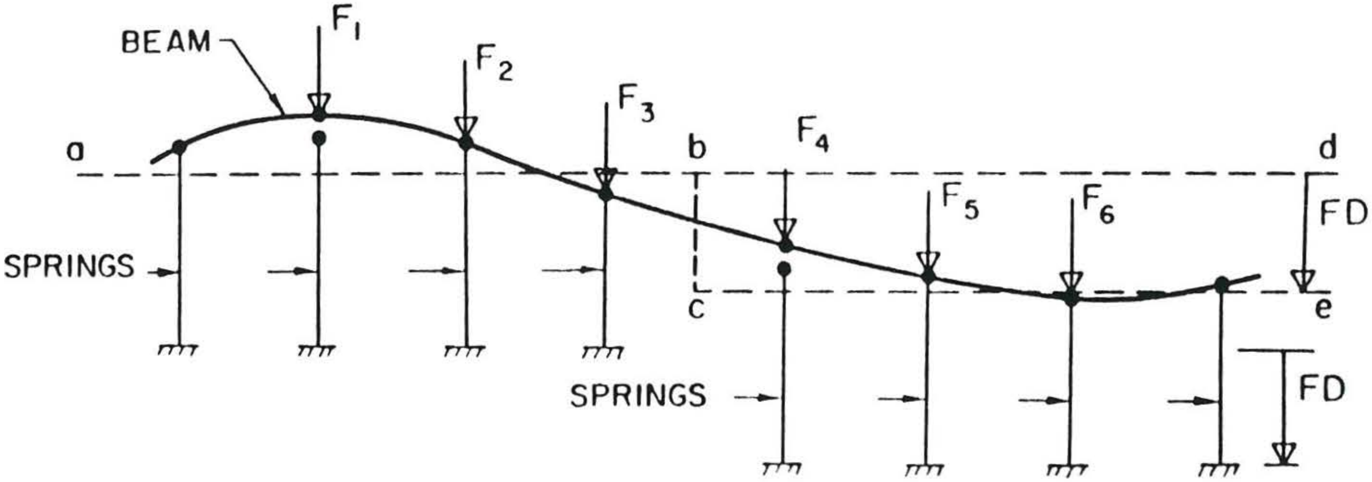


Figure 8 Finite element model. Line a-b-d is the initial location of the beam elements (horizontal) and line b-c is the fault line. During faulting, the soil and spring bases to the right of b-c move down a vertical distance FD (2 ft), representing the vertical component of fault displacement. In particular, the soil at level b-d moves down to c-e.

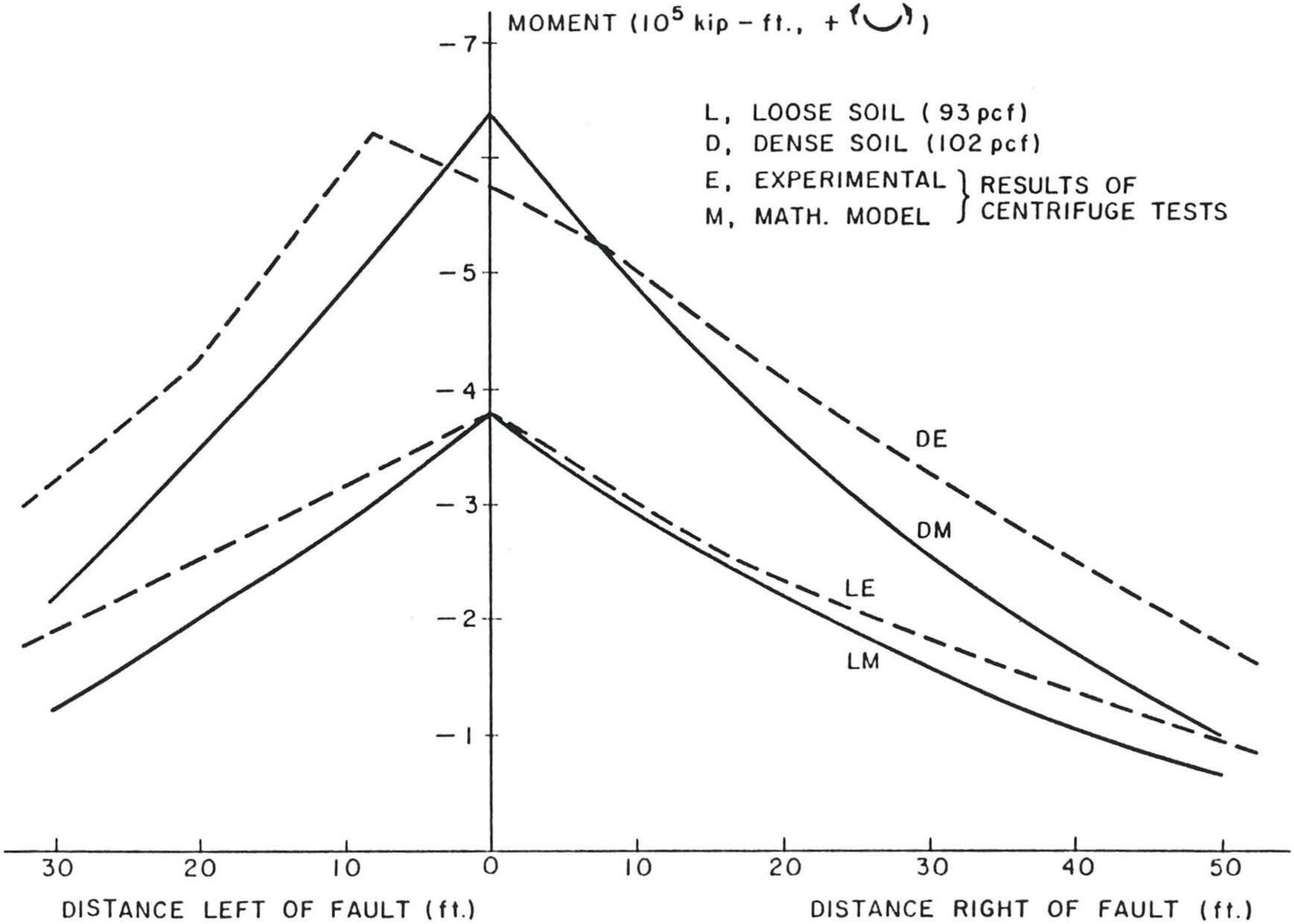


Figure 9 Comparison of prototype longitudinal moments from finite length numerical model and centrifuge fault displacement tests.

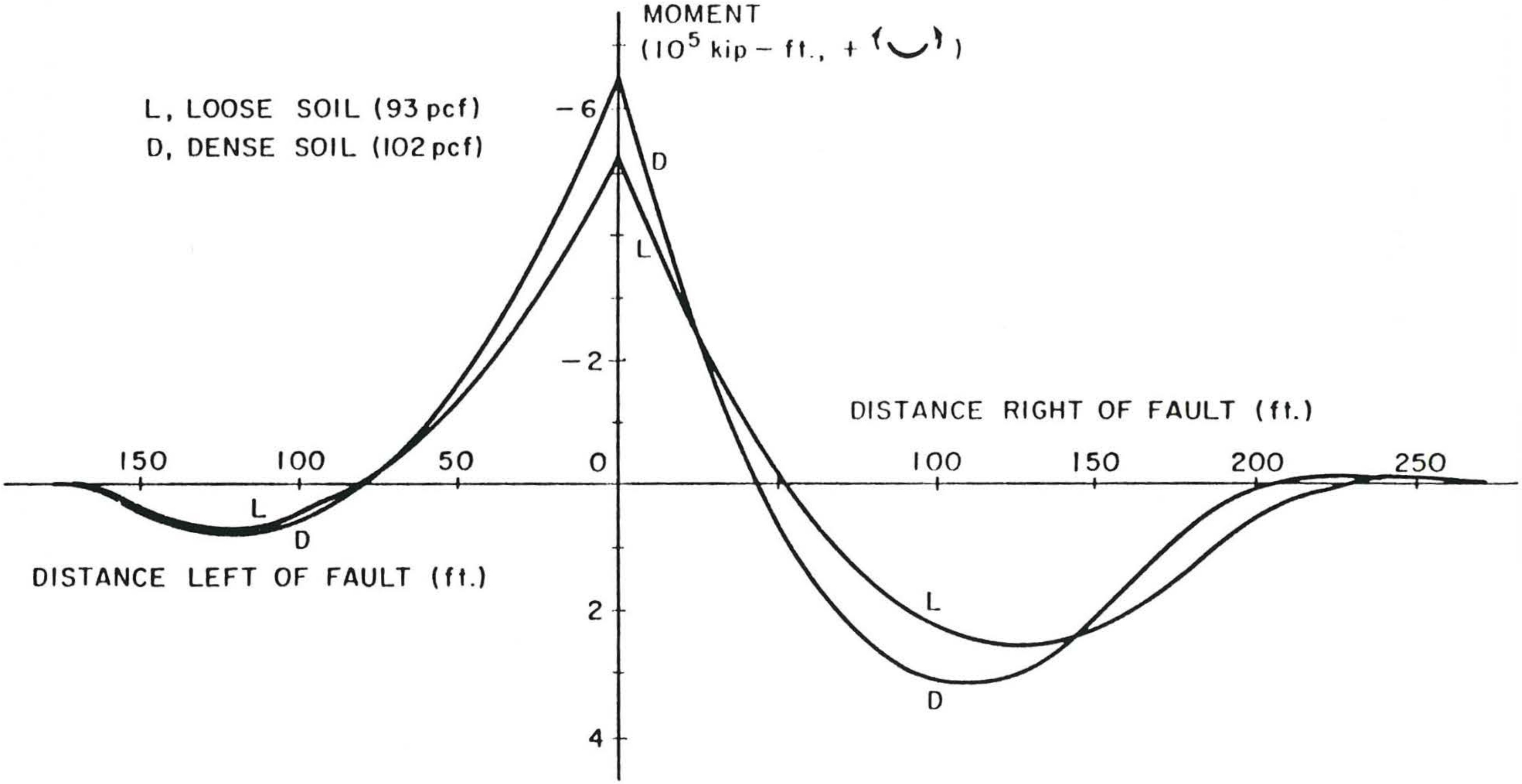


Figure 10 Prototype longitudinal moment profile predicted by infinite length numerical model.

Plate 1 Side view of fault actuation mechanism, front panel removed. False floor in level position.

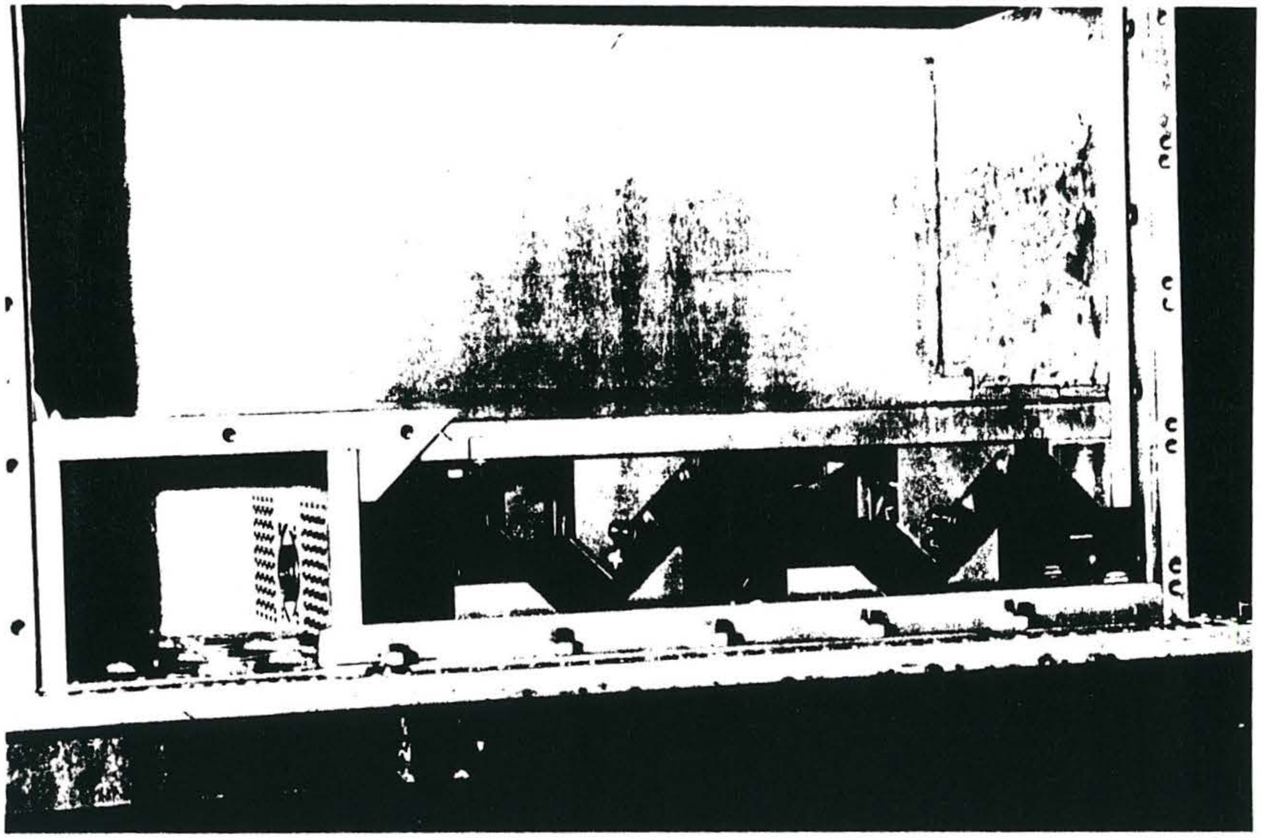


Plate 2 Side view of fault actuation mechanism, front panel removed. Fault displaced 0.25 inches.

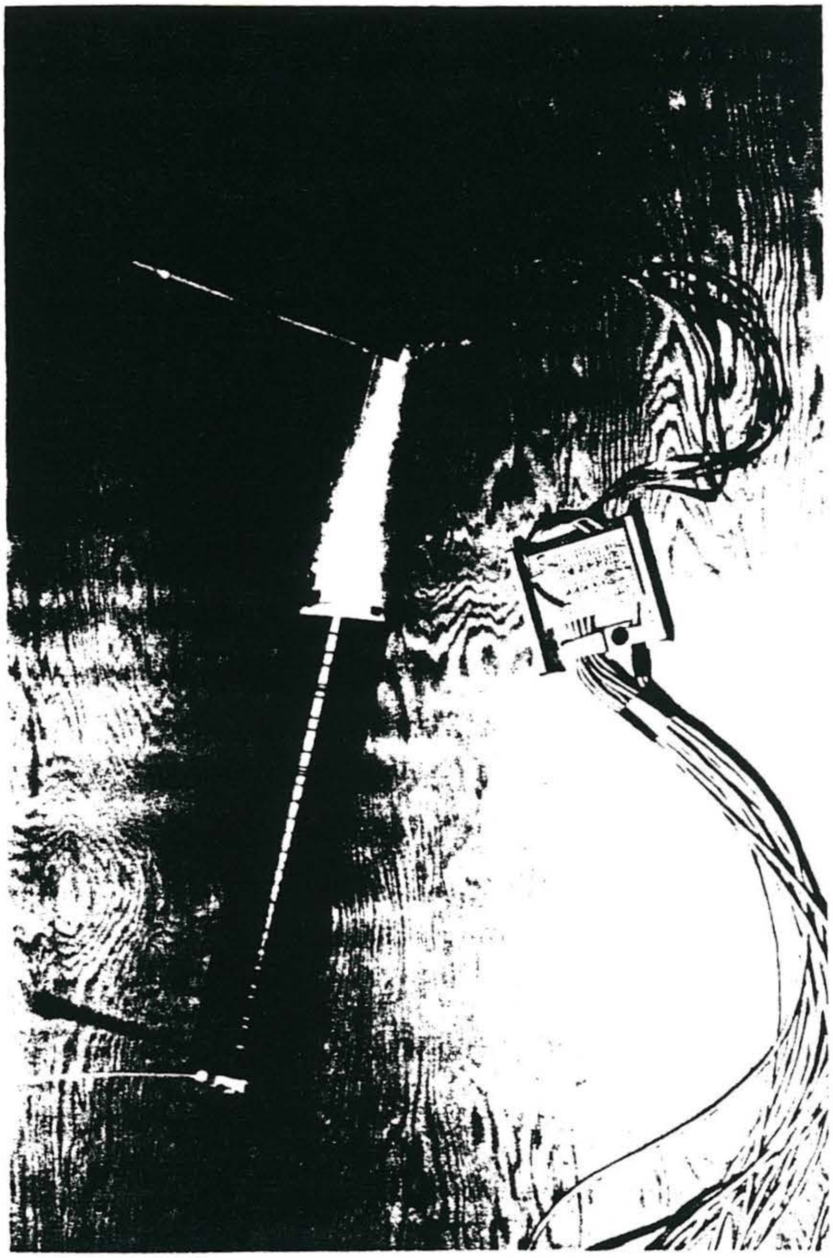


Plate 3 Aluminum model tunnel and strain gauge instrumentation.

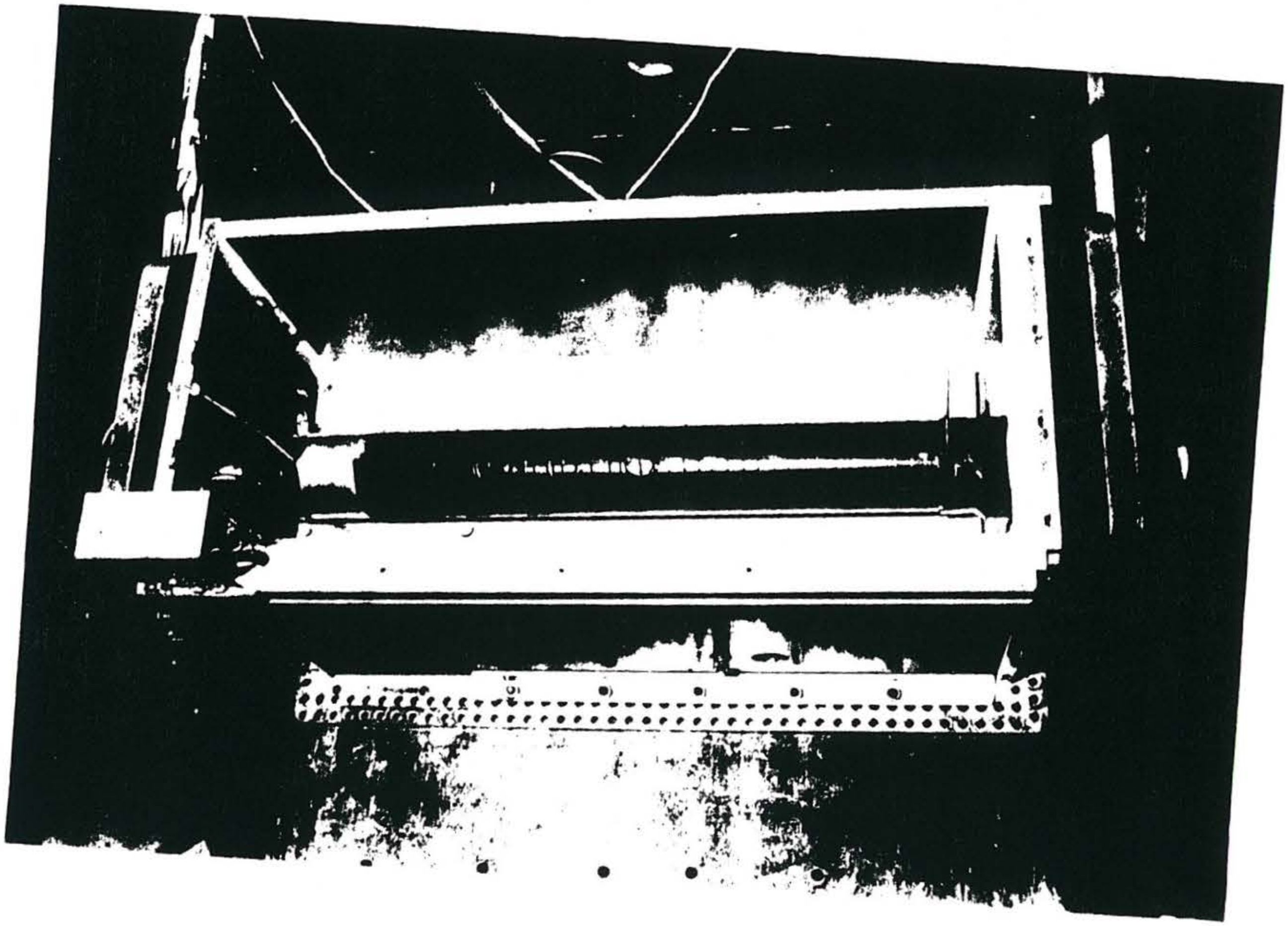


Plate 4 View from above of model tunnel installed in test container. Vertical displacement rods mounted at each end.

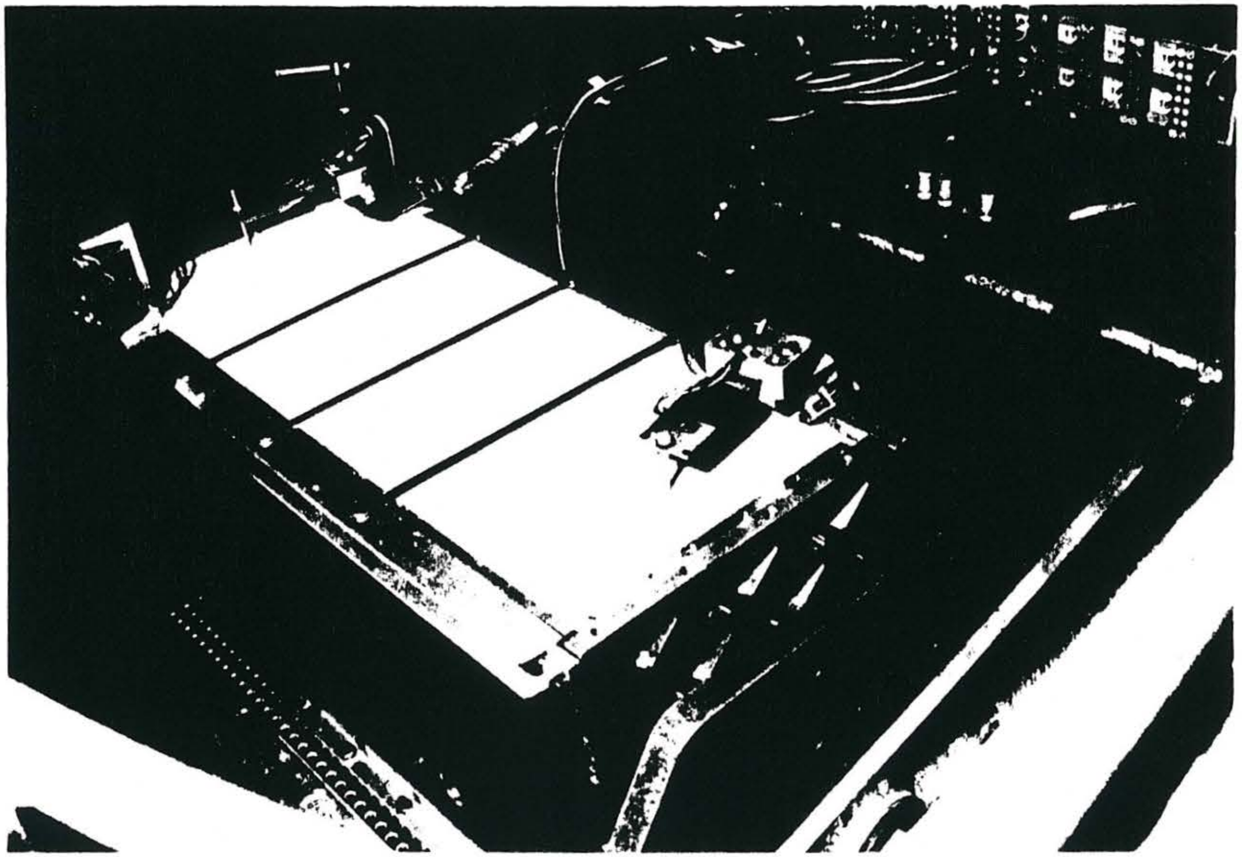


Plate 5 Test container after rapid faulting test. Vertical soil displacement visible with respect to side of container at right-hand end.