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CENTRIFUGE MODELING OF FAULT PROPAGATION THROUGH ALLUVIAL SOILS

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Introduction. The behavior of alluvial deposits subjected to fault movements in the underlying bedrock is of major concern for critical structures located within fault zones. An understanding of fault propagation through soils would assist in design of such structures, but could also be utilized in geological interpretation of fault displacement history. On the premise that alluvial fault morphology contains shear patterns characteristic of modes and rates of fault displacements, a study was undertaken involving centrifugal and numerical models of reverse faulting. This paper describes the centrifuge model testing performed to backup simultaneous numerical studies (Geognosis Report, 1980), which will be described elsewhere.

A comprehensive model test series under earth gravity conditions (1g) involving reverse and normal faulting under different angles has recently been undertaken by Cole (1979). However, model tests performed under 1g-conditions are limited to rather thin soil layers because of their inability to simulate realistic gravity stress conditions. Furthermore, it is not possible to simulate faulting fast enough to include inertial effects with such models.

Centrifugal Model Testing of Soils

Because of the general dependence of the mechanical properties of soil on the ambient stress conditions, and the importance of gravity-induced stresses, scaling of geotechnical models can only be satisfied under special conditions. It is inconvenient or impossible to construct a model soil material, and a real soil is usually employed in model tests. In that case, the scaling conditions require that the soil model be subjected to a higher gravitational acceleration than the prototype. The ratio of the accelerations in model and prototype structures is inversely proportional to the ratio of their linear dimensions. To obtain the necessary accelerations, a centrifuge is required.

A number of centrifuges have been built and used for soil testing. There are three in the United Kingdom, two at Cambridge and one at Manchester, with radii up to 5 m and acceleration capabilities up to 200 g. In the Soviet Union, a recent paper (Polshin et al., 1973) refers to the employment of "several dozen" centrifuges for soil testing purposes. So far, only a few small centrifuges have been used for such tests in the United States, although the technique was apparently originated here (Bucky, 1931).

A few years ago, a small (9-foot diameter, maximum payload about 100 pounds at 150 g) centrifuge was obtained from NASA surplus for use in soil mechanics studies at Caltech. The rotating arm of this machine is illustrated in Figure 1. It has been employed in a number of investigations to date, including piles (Scott et al., 1977; Scott, 1979), ocean floor anchors (Tagaya et al., 1977), slipping on a fault (Liu et al., 1978), and offshore gravity structures (Prevost et al., 1981).

Model Scaling

If the ratio of linear prototype dimensions to those of the centrifuge model is h, then the ratio of area is h2 and volume h3. Forces in the prototype are h2 times those in the model, so that stresses are unchanged. Deformation in the prototype is h times larger than in the model, but strains are the same. Thus, the presence of the same material in both prototype and model results in identical stresses and strains at homologous points. For dynamic problems it is of interest that time in the prototype is h times the model time, but velocities are unchanged. Energy in the prototype is h3 times the energy in the model, but energy density is the same.

The friction angle of a soil being dimensionless, is the same in both model and prototype. Cohesion, which is a stress, is also the same. The relative contributions of the two quantities to a soil's response depends on the acceleration field. A particular soil's behavior at 1g (prototype) may be dominated by cohesion, whereas, at 100 g (centrifugal model), the response may be mostly due to friction.

Test Apparatus

The test apparatus shown in Figure 2 was designed to incorporate the field variables of angle of faulting, amount and rate of bedrock displacement and the depth of alluvial deposit. The depth of alluvium is constrained by the physical dimensions of the centrifuge bucket and the payload. It was considered necessary that the model width should at least equal the soil depth to reduce boundary effects. An 8-inch width and a 7-inch depth were chosen as the length of the model (19 inches) was maximized, again because of boundary effects.

Considering that at the chosen testing acceleration of 50g, 60 pounds of soil "weigh" 3,000 pounds, it was necessary to simulate reverse faulting by dropping the downthrown side instead of pushing the upthrown side up. Such a faulting mode allows use of the centrifugal acceleration field to propel the soil mass. A false bottom, representing the downthrown section of bedrock, is mounted on roller bearings which run down hardened steel ramps. Tests on a 45°-angle of "bedrock" rupture are reported here. However, the apparatus permits other fault angles to be used.

Whether or not similar faulting patterns develop in the soil for both modes of bedrock motion (upthrown upward, or downthrown downward) is an interesting question. For small rupture velocities both modes should theoretically be identical, due

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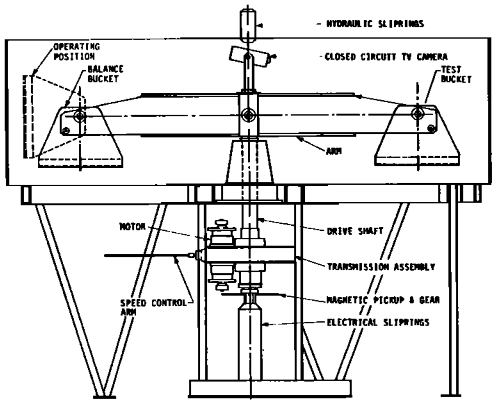


Fig. 1. Caltech centrifuge.

to the lack of appreciable inertial effects. However, for rapid faulting, inertial effects alter the state of stress at failure differently for the two modes, and therefore, may result in different faulting patterns. This question was investigated in a numerical analysis (Geognosis Report, 1980), which demonstrated little difference in the soil behavior for the two modes for rupture velocities of up to 2.5 meters per second.

Two failure rates, fast (total drop in tens of milliseconds) and slow (several seconds), representing dynamic and static motions, can be simulated with the test apparatus. A combination of a hydraulic ram, which was used to control the false bottom descent for slow displacement tests, and a toggle system, to hold the false bottom rigidly in place until release, are shown in Figure 2A. The toggle is pushed over center, by a small compressed air ram, allowing the false bottom to drop.

Both video and high-speed (400 frames a second) film cameras were mounted on the axis of the centrifuge where they were subjected to minimal acceleration effects. The front wall of the test box is made of 1-inch Lucite with 1/4-inch plate glass on the soil side to minimize friction and protect the softer plastic. The failure patterns were recorded using a mirror mounted at 45° as shown in Figure 2B. The rest of the box is made of 1/2-inch alluminum plates.

During preliminary tests it was found necessary to introduce a Teflon seal into the lip of the false bottom to prevent loss of material. To prevent similar loss at the other sliding contacts temporary tape seals were used. To dampen any spurious oscillations occurring upon impact after dropping, and to prevent further disturbance of the samples, 1/2-inch square Neoprene cushions were placed on the stops shown in Figure 2a.

Testing Procedure

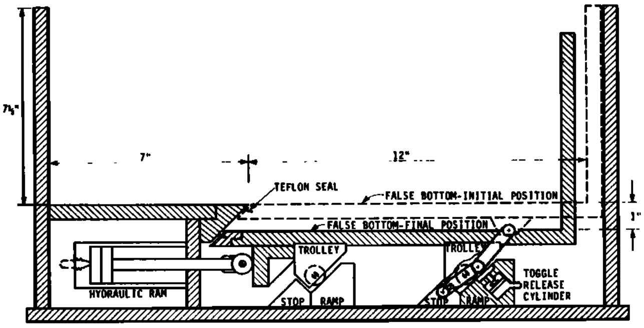
The object of the centrifuge tests was to investigate the effects of rate of displacement and material properties upon the rupture patterns resulting from bedrock offsets. Two rates of displacement were used with loose sand, dense sand, and remolded cohesive soil. To indicate the soil movement and aid analysis of the high speed film, colored marker layers were built into each test sample. A regular grid on the Lucite wall provided a reference.

The material response during faulting was recorded by miniature accelerometers and a strain gauge displacement meter, for the rapid and slow displacement cases, respectively. Their output was recorded by a Honeywell, inertialess light beam recorder. All but one of the tests were conducted at an acceleration of 50g at which the soil depth and the vertical component of the "bedrock" offset were equivalent to approximately 30. and 4. feet, respectively.

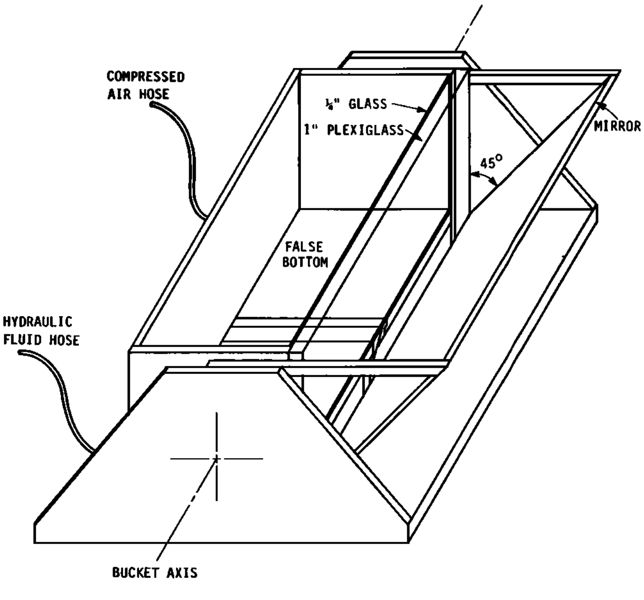
Results

Sample results from the tests indicating the general tendencies are shown in Figures 3 and 4. The dark bands show the final positions of the marker layers. Figure 3A shows the pattern resulting when loose Ottawa sand at a density of 88 pounds per cubic foot (pcf) was subjected to a rapid displacement (approximately 0.5g prototype peak acceleration). There is no surface discontinuity, and the yield zone appears to be spread out rather than confined to a narrow shear zone as in the next test.

When dense Ottawa sand (density = 107 pcf) was subjected to a slow failure, a marked rupture plane resulted in a distinct surface discontinuity



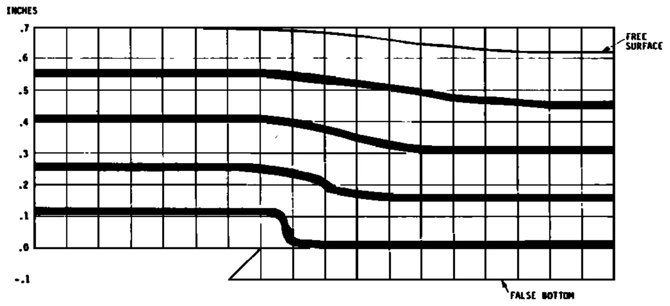
a) SCHEMATIC CROSS SECTION



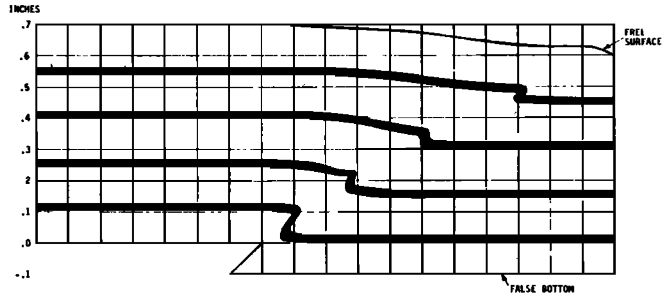
b) MODEL IN CENTRIFUGE BUCKET

NOT TO SCALE

Fig. 2. Centrifugal test apparatus.



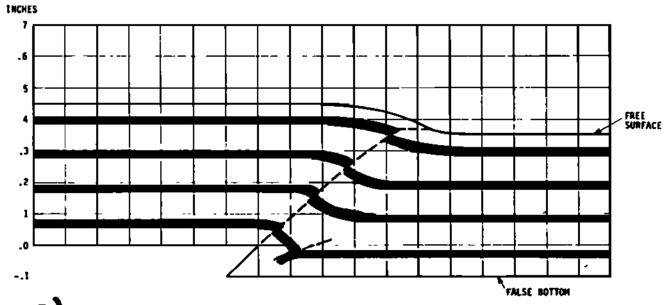
a) LOOSE SAND, FAST DISPLACEMENT (50g)



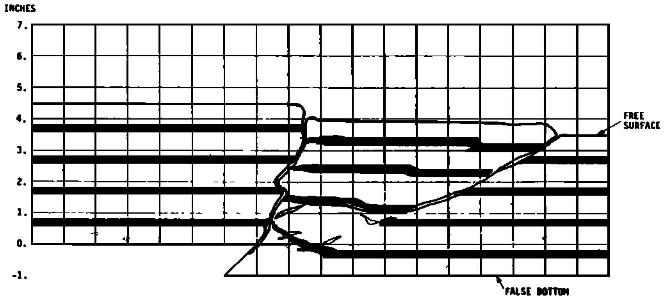
b) DENSE SAND, SLOW DISPLACEMENT (50g)

Fig. 3. Typical results with Ottawa 30 sand.

(Figure 3B). Generally, slow displacement produced more marked offsets and shallower shear angles than rapid displacement for a given density of sand. The dense sand tests also showed shallower shear angles than the tests performed with loose sand at the same displacement rate.



a) FAST DISPLACEMENT (50g)



b) FAST DISPLACEMENT (10g)

Fig. 4. Typical results with cohesive soil.

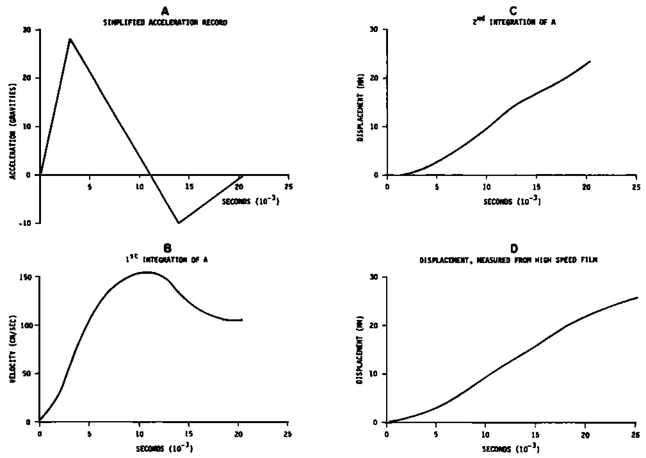


Fig. 5. Motion histories of vertical offset component.

The cohesive material (remolded fine sandy silt, ϕ = 32°, c = 1000 pounds per square foot) behaved in quite a different manner. Two typical failure patterns are shown in Figure 4 exhibiting more of a block failure mechanism with local bending in the shear zone. In Figure 4A a 45° failure plane reaches all the way to the surface and a secondary shear plane at a shallower angle attenuates rapidly. The most rapid failure achieved occurred in 120 x 10-3 seconds, and inertial effects must be considered minimal. That both slow (not shown here) and rapid failures exhibit similar failure patterns reinforces this conclusion. The relatively slow failure is due to the strength of the material preventing an "instantaneous" drop.

A simulated rapid bedrock rupture at 10g gravity scaling produced the result shown in Figure 4B. In this case, there are two fully developed failure planes, one very shallow and a second, possibly tensile, vertical plane. Because of the lower g-level, this test is representative of the behavior of a prototype soil cover only approximately 4 feet (4.5 inches x 10 inches) thick. At this scale, the lower stresses imposed by the 10g field cause cohesion to be relatively more important than friction in influencing the soil's behavior.

The adequacy of the recorded acceleration histories was checked by comparing their second integrations with the displacement histories obtained from high-speed movie frames. An idealized acceleration history record (the actual record contains random vibration noise) of the downthrown portion of a typical fast displacement test with dense sand is shown in Figure 5A. The peak acceleration of 28g at 50g centrifugal acceleration corresponds to approximately 0.5g for a prototype fault rupture. The first and second integrations representing velocities and displacements are shown in Figures 5B and 5C, respectively. The displacement history indirectly obtained through integration compares quite well with the measured displacements of Figure 5D.

Conclusions

The centrifuge model described provides a valuable insight into the propagation of shear planes through alluvial overburden. The model was utilized to varify numerical analyses on this subject which will be described in a more detailed paper elsewhere. The test results indicate that rate of fault displacement and soil property are significant factors in forming the failure pattern. Boundary effects in the tests do not appear to be significant.

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References

Bucky, P.B., Use of models for the study of mining problems, AIMME Technical Publications, American Institute of Mining, Metallurgical and Petroleum Engineers, No. 425, 1931.

Cole, D.A., Slip surfaces in cohesionless soil above dip-slip faults, Master Thesis, University of California, Los Angeles, 1979.

Liu, H.P., et al., Centrifuge modeling of earthquakes, Geophysical Research Letters, Vol. 5, No. 5, May, 1978.

Numerical investigation of overburden deformation due to thrust dislocation of the bedrock, Geognosis Report #GJ-1 for Dames & Moore, Los Angeles, 1980.

Polshin, D.E., et al., Centrifugal model testing of foundation soils of building structures, Proceedings, 8th Internation Conference of Soil Mechanics and Foundation Engineering, Vol. 1.3, pp. 203-208, 1973.

Prevost, J.H., et al., Offshore gravity structures centrifuge modeling, Journal of Geotechnical Engineering Div., ASCE, Vol. 107, Feb., 1981.

Scott, R.F., et. al., Dynamic pile tests by centrifuge modeling, Proceedings, 6th World Conference on Earthquake Engineering, Paper 4-50, New Delhi, January, 1977.

Scott, R.F., Cyclic and static model pile tests in a centrifuge, 11th Annual Offshore Technology Conference, Paper No. 3492, p. 1159-1168, 1979.

Tagaya, K., et al., Fundamental study on extraction of buried anchors, Proceedings, 12th Conference on Soil Mechanics and Foundation Engineering, Japanese Society of Soil Mechanics and Foundation Engineering, Tokyo, 1977.

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