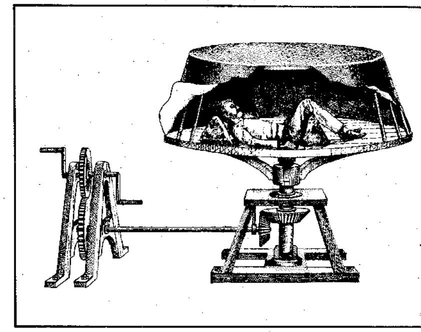
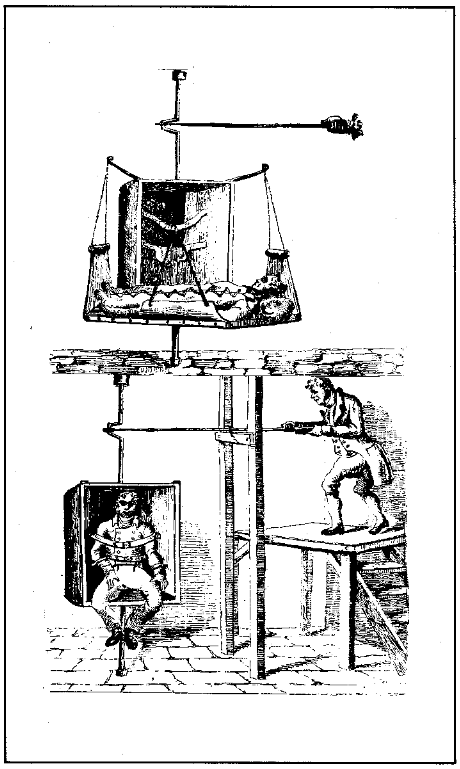
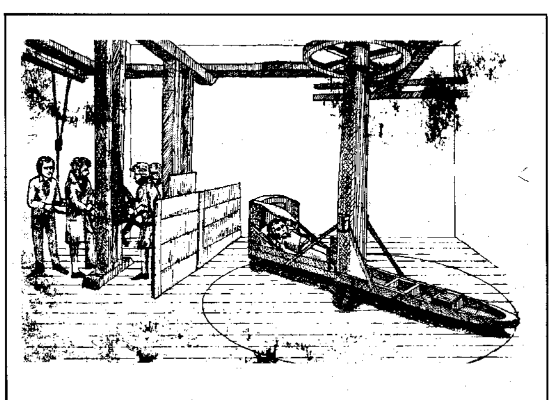
Centrifuges in the Earth Sciences:

A Revolutionary Idea *

by RONALD F. SCOTT







A NUMBER of materials, primarily geological in nature, such as soils and rocks, but also including other granular substances, have physical properties which depend on the stresses induced in them by the density of the overburden in the earth's gravitational field. It is frequently necessary to build structures on or in these materials, or to dig holes in or through them. These structures or cavities must be designed to have adequate factors of safety under the imposed loads.

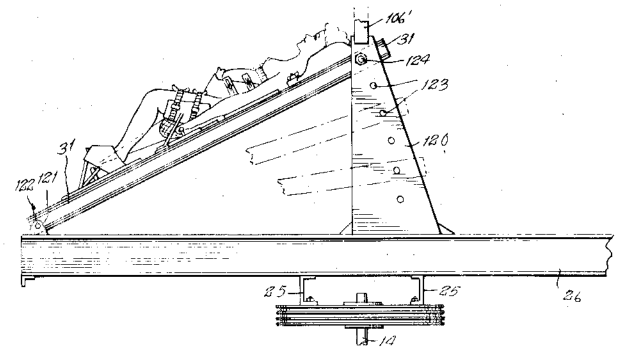
While there are various analytical or computer methods available for use in problems involving soils or rocks, the heterogeneity or anisotropy of the natural material is such that field tests of prototype structures are very desirable. In many cases models are constructed and tested. However, field tests are hard to perform (how do you impose loads of hundreds to thousands of tons on a full-scale structure?), and model tests on soils at earth's gravity are not scaled correctly, because the stresses and forces in the model are much smaller than in the prototype. As a consequence, the model material behavior is not correct.

When the model scaling relations are established for soils or rocks, it turns out they can be satisfied if a particular scale model is subjected to a high enough acceleration to impose stresses in the model the same as those in the prototype at similar points. Thus a 1/100 scale model should be subjected to 100 times gravity (100g). The only practical way of doing this is to test the model structure in a centrifuge.

*The reader is invited to follow his bent in picking other titles to this discussion. Phrases such as "Soil Testing: Let's Give It a Whirl," "Circular Thinking (Arguments in Geotechnology)," and "Around the Lab in 80 Milliseconds" come readily to the right kind of mind.

This method of testing has assumed considerable importance in Europe and the Soviet Union in recent years, but has not been employed extensively as yet in the USA.

Recently I received a grant from the National Science Foundation to organize and hold a workshop conference in December 1975 on the centrifugal approach to testing to apprise U.S. research workers and engineers of the potential of the method. In my introduction to that workshop, I traced a brief history of the development of certain kinds of centrifuges. An abbreviated version follows:



The 1965 Blonsky Spin-It — an ingenious, and patented, idea for medical use of the centrifuge.

I did a minimal amount of research on centrifuges to find out where they came from and how they got started. The most significant thing I learned was that they were *not* invented by Leonardo. The original idea appears to have developed about the middle of the 18th century, probably in France, in the form of carnival amusements — carrousels, or merry-go-rounds. ("Carrousel" comes from an Italian word meaning a demonstration or parade of horses in a circle.) Probably the reason there were no substantial developments until the 1750's was a lack of machines to power them. Muscle power alone couldn't turn the centrifuge fast enough to give an interesting enough sensation to a rider to induce him to pay for it.* The introduction of steam power in the 18th century gave the impetus to the centrifuge concept in the area of entertainment.

Shortly thereafter the medical profession picked up the idea, particularly for the treatment of the mentally ill. This approach gave rise to a series of centrifuges, some illustrated on the opposite page. The pictures come from various pieces of medical literature beginning roughly in the 1790's. At this time Erasmus Darwin, the grandfather of Charles, first made some comments about using centrifuges in the treatment of mental patients. The idea caught on and there are a number of references in medical books of the 19th century to apparatus designed to spin mentally ill people in the hope of effecting cures. It is not very clear whether it was the spin or the threat of it that was efficacious; a certain amount of progress was reported.

One thing that interested me was that Darwin apparently started the medical merry-go-round (which continues) because of a conversation he had with a famous civil engineer of his day, James Brindley. Brindley had made the observation that some farm workers would lie across a rotating millstone (they got stoned) to induce sleep. I suppose it was a variation in their daily round. An antic high. In point of fact, as the aviation people learned, the farm hands were experiencing negative g's and were actually losing consciousness.

Interest in centrifuges in the medical business continues. The example above is from a 1965 U.S. patent obtained by a New York mining engineer and his wife. They devised this equipment for facilitating birth by centrifugal force. The prospective mother, waiting for life's cycle to be repeated, is placed on the revolving platform and whirled around under the direction of an obstetrician. It's not quite clear where he would stand* and what he would do. Perhaps he jogs, keeping abreast of the patient, and of course counting the laps. Alternatively, he remains stationary, inspecting the mother's condition briefly by synchronized stroboscopic flash as she zips by. There is always closed-circuit television of course.

George E. and Charlotte B. Blonsky called their machine the Spin-It. Smooth rotation is assured by the use of water ballast, and the baby is received in a padded net. Girl children inevitably become spinsters. Boys are well rounded. In this day of automation, of course, there is one final touch: The baby's arrival switches off the motor and rings a bell. I could see a problem develop were the occasion one of multiple births (circlets). One more instance of spiraling population increase.

In the 20th century the effect of acceleration on the human body became of importance to the aviation and, later, space fields. Many large centrifuges have been built and operated in a number of countries to study the response of human and animal subjects to acceleration loads.

*After this talk I learned that in India a man-powered device like a Ferris wheel carrying a number of riders has appeared at village festivals for centuries. It is driven by a number of men who run up a plank to the horizontal axle, mount a spoke of the wheel and walk out to the end of it. There they drop off and repeat the process.

*"Obstetrician" means "one who stands before."

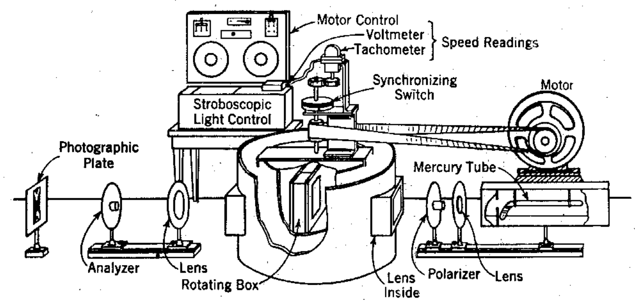
If the scaling relations developed for soils and geological materials apply to biological organisms, then the movements of, say, a human being of normal size in a 2 g field simulate those of a similar organism of twice the linear dimensions in a normal 1g environment. During our meeting in December, one of the engineers from Ames Research Center said that a number of generations of rats had been bred there in a continuous 4 g centrifugal condition. On being asked what were the obvious physiological manifestations when later generations were brought to 1g, he said, "They are good jumpers." It seems to me that this would have a useful application in Calaveras County, or, at a more ambitious level, to steeplechase racing.

Apart from medicine, centrifuges have, of course, proliferated in a variety of fields. They are used in sedimentation studies, biological work, and in industry for separation in chemical applications, and in metal and concrete casting. I will proceed, however, to the application of interest to us.

The idea of using a centrifuge in the testing of engineering models seems to have originated with the Frenchman Edouard Phillipps. In 1869 a short paper by him appeared in the *Comptes Rendus* of the French Academy of Sciences, suggesting that a model of a recent and controversial British bridge, the Britannia, be tested in a centrifuge at somewhere around 50 g in order to determine the effect of gravity on the deformations and stresses in the bridge. Gravitational loads are, of course, the most important factor in bridge design. At the time, the Britannia was the second and largest example of a wrought iron tubular bridge. It was originally proposed to support it by suspension chains, but the designers decided to omit them on the basis of model tests performed on a variety of tubular beams. There was a considerable amount of discussion at the time on the wisdom of this decision and regarding the strength and flexibility of the structure. Phillipps's remarks had apparently been stimulated by a discussion in the minutes of the British Institution of Civil Engineers. It is not clear why it occurred to him to do a centrifuge test. Perhaps a friend had been centrifuged.

It would have been very difficult with the technology of the 1870's to have conducted such a study in a centrifuge. However, with their ingenuity in mechanical gadgets, I think they would have obtained some useful information out of it on, for example, displacements, if, in fact, Phillipps's idea had been implemented.

By the 1920's the whole business of model studies had been placed on a firm foundation with the similarity and dimensional analyses of E. Buckingham and P. W. Bridgman. There seem to be no other references to the technique until the late 1920's or 1930's.



A diagram of the centrifuge built by P.B. Bucky in 1930 for use in testing mining models.

In 1930 an American investigator, P. B. Bucky, at Columbia University, built a small centrifuge and used it for testing some mining models. He examined the stability of tunnels and cavities, using the apparatus pictured above.

About a year or two later, investigators in Russia, apparently independently, took up the same idea, as happens so commonly. Davidenkov proposed the use of a centrifuge in soil studies, and the notion was developed by Pokrovsky and Fedorov. Their area of interest was primarily soil mechanics, and in succeeding years Pokrovsky built more centrifuges and performed many tests in them. They are quite well reported in the European literature in the 1930's. The papers do not seem to have received much attention by Western engineers; it could well be argued that they did not receive the recognition they deserved. Subsequently, the business of centrifugal testing of geotechnical models proceeded in the USSR to an extent which was not followed in Europe or the United States except by Bucky, who pushed on with his mining studies. Following his lead, some work was done by the Bureau of Mines in this country up to the 1950's, but then apparently the centrifuge method was dropped.

In the early 1960's H. Ramberg in Sweden started work on the behavior of geological models in centrifuges, to study the processes of instability in various earth crustal structures. Recently he has examined plate tectonic processes. At about the same time in South Africa, E. Hoek took up the centrifuge idea and began rock mechanics and mining investigations there.

In the 1950's at Cambridge University, England, A. N. Schofield edited a translation of a Russian plasticity book by Sokolovsky. In the book there is a reference to

Pokrovsky's work with centrifuges, which is described by Sokolovsky as "well-known." It certainly was not very well known anywhere else but in the Soviet Union. This remark sparked Schofield's interest, and he followed up by first building at Cambridge a small centrifuge for soil studies. The results were interesting, and he and his colleagues went on to tests on larger specially designed and built centrifugal machines.

The centrifuge is a uniquely useful tool for testing materials such as soil and rock, whose mechanical properties depend on the pressures to which they are subjected. However, the full-scale problems of interest involve structures such as earth dams with dimensions of hundreds of feet. If they are to be brought to manageable size, scaling factors of the order of 100 to 500 are required. At these scales, the larger models are a few feet in size and weigh up to two or three tons. As we have seen, a linear scaling ratio of 100 requires that the model be subjected to 100 g. Consequently, for large tests a centrifuge is required that will bear a payload of a few tons at accelerations of up to a few hundred g. The axial force in the centrifuge arm is then several hundred tons. In a centrifuge rotating at a constant speed, the acceleration at a point in a specimen depends on the radius. This means that different parts of the model are subjected to different accelerations, which violates the similarity conditions and is therefore undesirable. A large radius (a few meters) minimizes the effect.

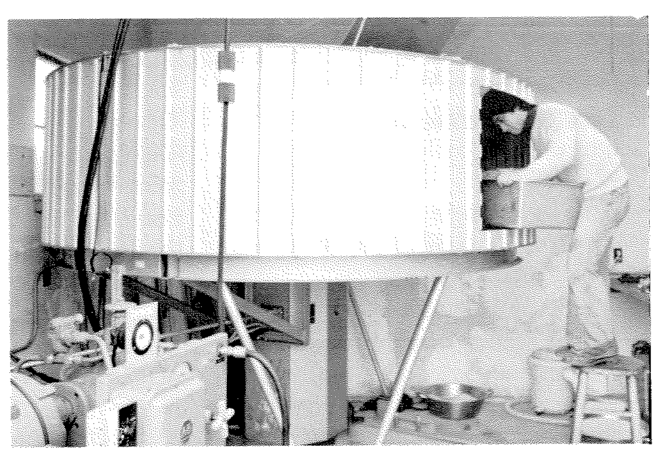
The result of all these considerations is that centrifuges designed for geotechnical testing are large and potentially dangerous. Careful checking procedures to ensure adequate balancing and structural integrity are required. In practice, the large machines are usually constructed in concrete-lined circular pits. At present in England there are large machines at the University of Manchester, University of Manchester Institute of Science and Technology, and at Cambridge University, as well as a few smaller machines. A recent Russian paper mentions "several dozen" centrifuges in the Soviet Union, where they seem to be employed in relatively routine testing applications.

Interest in the centrifuge as a geotechnical testing device seems to be stirring again in the United States. If we get back into the technology that Bucky pioneered here in 1930, one could say that we have come full circle.

I spent the year 1972-73 at Cambridge, and while I didn't work on the centrifuge they were using, I was interested in what was going on there. It seemed it might be a useful tool for dynamics studies in the earthquake engineering area. I found I could get a small NASA centrifuge and proposed successfully to the National Science Foundation that I initiate some dynamic soil studies in it. It has been remarked that this is a good example of spin-off from the space program. We've been using this centrifuge for the last year or so.

My own involvement with gravity in soil experiments came a little earlier. I had been concerned in the early 1960's with the question of how soil would behave under lunar gravity (about one-sixth of earth's). Apart from a purely scientific interest, there was a great curiosity at the time in certain circles as to how far various lunar vehicles and astronauts would sink into the lunar surface. With the surface sampler on the Surveyor unmanned spacecraft, I was concerned with obtaining the mechanical properties of the lunar surface material to answer such questions. The interpretation of the tests that were carried out depended on a knowledge of soil behavior at lunar gravity.

There were two ways of going about obtaining experimental results: One was to mount full-scale apparatus including soil in an airplane equipped to fly arcs at one-sixth gravity. A graduate student, Dr. T.-D. Lu, and I did this. The other was to perform model tests at earth gravity. This method required the apparatus to be one-sixth the scale of the full-size lunar surface equipment. In this instance, the earth acted as our centrifuge. I also suggested at that time that some tests be carried out at accelerations greater than that of earth's gravity, so that interpolations and extrapolations could be made with greater confidence. However, it would have been quite complicated to operate appropriately scaled experimental equipment in a centrifuge at the time, and I did not pursue the thought further. □



Caltech's recently acquired centrifuge is nine feet in diameter and is capable of spinning two 100-pound models at 100 g. The test material in this case is sand.