# GEOTECHNICAL CENTRIFUGE DEVELOPMENT CAN CORRECT A SOIL MECHANICS ERROR

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# Geotechnical centrifuge development can correct a soil mechanics error.

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## (1) Introduction.

This paper makes three points. First, geotechnical centrifuge model testing is as valuable as the observational method; both techniques are needed, in spite of Terzaghi's comment on "the utter futility of the attempts to discover a single-valued relation between the results of small-scale loading tests and the settlement of large foundations on stratified soils." Second, beam and drum centrifuges are now complementary to each other. Third, tests of models made of reconstituted soil paste have a fundamental value in correcting the "Mohr Coulomb" error.

## (2) The observational method and model tests.

In 1936 Terzaghi made a Presidential Address to the 1st (Harvard) International Conference of Soil Mechanics and Foundation (now Geotechnical) Engineering, (ISSMFE now ISSMGE). In it he said that (in) "the perpetual war of the civil engineer against the treacherous forces of nature concealed in the earth . . . scattered and world-wide efforts extending over a period of 25 years (have forged) new and efficient weapons and the prime purpose of our meeting consists in discussing the means of exploiting the advantages thus secured," and "the possibilities for successful mathematical treatment of problems involving soils are very limited. ... the accuracy of computed results never exceeds that of a crude estimate, and the principal function of theory consists in teaching us what and how to observe in the field. . . . successful work in soil mechanics and foundation engineering requires not only a thorough grounding in theory combined with an open eye for the possible sources of error, but also an amount of observation and measurement in the field far in excess of anything attempted by the preceding generations of engineers. Hence the centre of gravity of research has shifted from the study and the laboratory into the construction camp where it will remain." He was considering problems such as were then being encountered by engineers in the construction camps of the US Bureau of Reclamation and in the construction of the Panama Canal. There is a class of catastrophic event that he was not considering, where geotechnical engineers need to learn from model tests, and to avoid experiencing a succession of events in the field.

A copy of the first ISSMGE paper on centrifuges is appended to this paper. It is the paper by Pokrovsky in Vol. I, p 70, of the Proceedings of the 1st ISSMFE Conference. Terzaghi's strong reaction to this paper proved to be mistaken, in the light of developments that followed in the US and in the USSR (former Soviet Union). Pokrovsky had a second paper in Vol. II, pp 289-290, on "A method of determining the rate of deformation in a soil mass, by means of electricity" describing a plane electrical analogue in which electrodes feed sections of the system with current. In Vol. III, p 262. Terzaghi makes reference to Pokrovsky's papers, placing them in his discussion on "Instruction in Soil Mechanics", among "papers whose authors do not hesitate to generalise the conclusions derived from pure theory or from small scale tests on materials with very little if any resemblance to real soils." Terzaghi states; "One of the principal goals of instruction in soil mechanics should be to discourage this prevailing tendency to unwarranted generalisation." Six lines further on he speaks of "the utter futility of the attempts to discover any single-valued relation between the results of small-scale loading tests and of the settlement of large foundations on stratified soils." He proved to be wrong.

Pokrovsky's centrifuge paper opens with a statement that in 1936 the laboratory for Physics of the Military-Engineering Academy of the USSR studied problems with the aid Of a geotechnical centrifuge; 37 years later in 1973 the Western geotechnical engineers who were at the International Conference in Moscow included several of us who were engaged in centrifuge modelling. Before 1973 we supposed that there must have been some technical difficulty by which Pokrovsky's technique had turned out to be less useful than he had hoped in 1936. At the 1973 Conference our hosts invited all participants who were interested in the centrifuge modelling technique to a meeting for open discussion with Pokrovsky and other Soviet engineers, at the Hydro project, after the Conference. In the course of our visit to the Hydro Project facility we were told that Soviet engineers wanted the West to become more fully aware of their work. We saw the powerful Hydro project centrifuge and learned that Soviet dynamic model tests had included successful work on bomb craters. It seemed to me that it would be useful to speak about this in lectures in the USA.

Subsequently the US Defence Nuclear Agency sponsored crater model tests in the Boeing Company centrifuge in Seattle, which led to an order of magnitude reduction of crater size prediction at nuclear explosive levels. In his paper for the San Fransisco TC2 published volume, Schmidt (1988) wrote

"Results of recent geotechnical centrifuge experiments have dramatically reduced the size estimates for craters formed by near-surface large yield nuclear explosions and by planetary impact of large bodies. Since neither phenomenon can be tested at full scale, centrifuge simulation is the only alternative for obtaining an experimental data base. Estimates of crater size were reduced due to the identification of a strength-gravity transition size, above which cratering efficiency decreases with size. Existing field data were too sparse and were conducted in far too diverse media to observe this pattern. The geotechnical centrifuge has been a valuable experimental technique for investigating explosive and impact cratering behaviour. (The tests) establish the practicality of performing dynamic experiments on the centrifuge, as well as providing a theoretical basis for their interpretation."

Full details of the Boeing tests were confidential to their sponsor, but there was open discussion of the significance of Pokrovsky's work. The published literature showed that, after gaining centrifugal model test experience, Pokrovsky became a Soviet expert on the cratering effects of megaton bombs; that he was one of a small Soviet scientific elite who worked on the effect of bombs in close secrecy during and after World War II, (WW II); that he had the rank of Red Army General. Russians now tell us that we can not imagine the powerful role that was played by that elite and the life that they lived; for example, Stalin came to parties where Pokrovsky played the piano at home. In retrospect it clearly would have been valuable to the US if Terzaghi in 1936 had been less dismissive of Pokrovsky's "utterly futile" model technique. In the long Cold War between the US and the USSR the Soviet ability to estimate the damage that large weapons cause was no less important than their ability to make them. Nowadays, after the Gulf War, research is being undertaken on the damage to underground structures that is caused by small weapons that penetrate and explode in the ground beside a structure; the effect of such blasts is discussed by Lee, Goh, and Tan (1998).

Even in 1936 it should have been clear from Pokrovsky's Fig 2 that his model technique works. He makes no "conclusions derived from pure theory or from small scale tests on materials with very little if any resemblance to real soils". Pokrovsky shows no "tendency to unwarranted generalisation". Volume I of "Centrifuge 98" has 147 such papers to consider. Any comment that "their authors do not hesitate to generalise" would be not be warranted now, 62 years after the 1$^{st}$ ISSMFE Conference, and it was not warranted then. It is hard for participants here to appreciate the circumstances at the 1977 International Conference, when Soviet participants told me that they knew Pokrovsly's technique was not valid, and I was only interested in its military significance. In critical state soil mechanics, effectively stressed soil is treated as an elasto-plastic inviscid material with time effects primarily due to consolidation. I said I disagreed with Soviet academic analysis in terms of total stress and viscosity, but I got no more co-operation from Soviet engineers. So I turned to ISSMFE for the framework of a technical committee in which barriers of secrecy are lowered. In my view academics should openly discuss catastrophic events; threats of future conflicts when low yield nuclear weapons explode underground without venting contaminants into the atmosphere, r-nay be reduced if military scientists use centrifuge model techniques to estimate the impacts of such weapons, and defence engineers avoid order of magnitude errors in design of underground shelters.

The problems that are faced by geotechnical engineers are so complex that students should be taught how to exploit the advantages of any technique that can help to solve problems.

While Terzaghi was right to emphasise the importance of observations in the field however geotechnical centrifuge model tests help solve problems where "the observational method" cannot be used. Conditions which cannot be replicated for full-scale test purposes include: major tidal flood or river flood; earthquake; prolonged contaminant migration; storm loading on offshore structures. How Can Terzaghi's discussions on observation in the field be applied nowadays for example for a mobile independent leg jack up rig deployed offshore, Ng, Lee and Liaw (1998), in the extreme case of a typhoon storm loading? Significant aspects of such events can be observed at small scale, in reduced time, by the geotechnical centrifuge model technique. A violent model test has no publicly unacceptable environmental impact.

(3) Beam and drum centrifuges.

Pokrovsky shows in Fig. 1 how he built a 30g centrifuge from parts of a Ford truck. One half-shaft stands vertically upright above the differential. The centrifuge rotor replaces a back wheel. The rotor arms slope at 1/30. They act as tension members. In that sense this is not a "beam" centrifuge. The model containers swing up about hinges. They are shown end on. In his test a load bears on a plate, and pressures are measured below the ground surface. In Fig. 2 vertical pressure is plotted against depth with five lines showing pressure as follows;

in ground with self weight, and
(I) in an elastic half space under vertical load, and
(II) the sum of these two previous pressures, and
(III) pressures measured in Pokrovsky's centrifuge model test, which agree with
(IV) pressures observed in a full scale test.

Pokrovsky draws a pressure gauge in his Fig. 3. A short length of broken capillary tube was pressed in to a small tin full of pink petroleum jelly. The air filled space inside the tube was closed by pink jelly at each end. A rubber membrane covered the jelly. The tin was buried in the model. The model was subjected to high acceleration. The burette was opened. Fluid flowed down along the axis and out to a vessel which applied the required bearing load. After a test the tin was removed and the capillary tube was examined. The pressure increment had compressed the air. Jelly had moved into the ends of the tube leaving a pink stain. Pokrovsky determined the maximum pressure, at that depth, from the minimum length of the air bubble. Both in the full scale test and in the model test he measured pressures up to 50 percent higher than he had calculated theoretically. He had proved that his technique worked, and it was applied to a series of problems where there were no reliable theoretical calculations.

Malushitsky (1975) described the application of Pokrovsky's technique to problems of mine waste embankments. It gave him a capability for analogue modelling of a problem which might have been solved numerically if computation had been available to him. His centrifuge could achieve 320g but typical tests were at below 200g; the inside dimensions of his model were length 1400mm, width 500mm, height 750mm, corresponding at 320g to a prototype volume of 17.2 million cubic metres. He built up models in successive layers of reconstituted waste material which he consolidated in flight for long periods. He tested his models by rapid increase of acceleration until there was a slope failure. Academics in the USSR at that time analysed soil as a viscous material under total stress. The scale of time was expected to be the model scale to some power between 0 and 2; Malushitsky found a value of this factor that was appropriate to his class of problem by the technique of "modelling the model". The simple Instrumentation and the variability between successive models meant that his work took many years and he tested 255 models in total. He writes that they resulted in elimination of landslips at the waste heaps of an open-cast sulphur mine, reduction in re-excavation in internal dumps In an open cast coal mine, and safe tipping of new dry waste on old hydraulic lagoon disposal areas, with savings to industry of about three quarters of a million roubles per year.

The cost of such a facility includes both a beam centrifuge and a Strong chamber to enclose it safely, with several model containers for successive tests. Each model is made as a different batch of soil and several weeks may be needed for consolidation of a large model. If models are consolidated on the laboratory floor with a downward hydraulic gradient in order not to tie up the centrifuge, more containers are needed. Models have load and unload cycles each time a centrifuge starts and stops, for example to adjust some instrument. To improve the quality of experimental work, some beam centrifuges now have a facility to manipulate tools in the model container while it is in flight, Derkx, Merliot, Garnier, and Cottineau (1998). Such manipulators are costly because they operate in the high acceleration field of the model test.

Drum centrifuges were developed in Cambridge to reduce the cost of centrifuge tests, and to improve the accuracy and reduce the labour and the time needed for any one test series. In order to assist the safe introduction of drum centrifuges to other laboratories, I sought a long term commitment from some established manufacturer. Their risk was significant, as financial problems have affected many geotechnical centrifuge developments. They needed protection of their initial investment, and Cambridge University has a policy on intellectual property development . Some inventive ideas in this field were granted European and US Patents, Schofield (1997), and after negotiation, I and Cambridge University granted an established centrifuge manufacturer in the UK, Thomas Broadbent & Sons Ltd. an exclusive licence to incorporate our intellectual property in a series of novel drum centrifuges. The first of these came into in operation in Australia, Stewart, Boyle, and Randolph (1998); the next three now operate in Japan. An additional cost saving comes from the fact that the centrifuge channel both causes the acceleration that is applied to the model layer and contains the soil safely; there is no need to build a reinforced concrete chamber. It is safe to stand by the machine.

In a drum Centrifuge a channel full of soil is prepared as a single model. Both the volume and the surface area of a model can be large. For example a 2.2m diameter channel, 0.8m high with 0.2m depth, in flight at 320g, corresponds to a test site about 2000m long, 256m wide and 64m deep, with a prototype volume of 32.8 million cubic metres. On one model of a uniformly stratified layer of soil there is room for many tests. If for example it was decided to plan a series of up to 50 tests, about 20 litres of soil would be closely affected by each test, which is a prototype volume of 655360 cubic metres. A similar beam centrifuge test might be conducted on a model of 80 litres volume at 80g, a prototype volume of 40960 cubic metres, which is sixteen times less. So for series of tests the walls of the model container are relatively closer to the model test site in the beam centrifuge than in the drum.

The machine is designed for continuous safe operation. Time is taken for model preparation in the drum channel and for setting up the test procedure, but with the whole process fully automated the machine can run for many weeks in continuous flight. Tools or systems are available to work over the model and to be manipulated while in flight. A safety shield can be lowered while the channel continues in flight to allow safe access to the central work support. When it is brought to rest and the tools or other systems have been safely changed, the work support can be bought back to channel speed, and the tools or other systems can be brought back to work over any chosen site on the channel. Stewart, Boyle, and Randolph (1998) describe both an automated testing system and also a modern data acquisition system. Data acquisition systems provided to the US Army Centrifuge, Waterways Experimental Station, Vicksburg, Miss., and to Toyo Construction Technical Research Institute, Hyogo, Japan, are rugged and compact. They acquire digital data at 5000 samples per second in memory in a logger unit close to the model in the high g field, to be uploaded to a PC running a program at the control desk. The manipulators used in drum centrifuges can be inexpensive; they operate in the low g field at the centre of the drum. Where drum and beam centrifuges are in operation side by side in centrifuge centres in the UK, Japan, and Australia, they are complementary to each other; if both centrifuges are used on a single project then test equipment can be transferred from one machine to the other. Developments will be rapid. I anticipate that future parametric study of the problem on which Terzaghi made comments, “foundations on stratified soils”, will obtain a body of data from one test series in one drum operation that will have scientific accuracy unattainable from tests at full scale in the field. The development of Pokrovsky’s test which was dismissed in 1936, plus the observational method applied in the field, will permit soil mechanics to become a branch of applied mechanics.

In the case of the independent leg jack up rig, the three legs apply cyclic loads Of Up to ten thousand tonnes to spud cans bearing on a sea bed. When jack-up spud fixity was modelled in the Cambridge 1 Om diameter beam and 2m diameter drum Centrifuges, Dean et al (1993) studied the bearing capacity of conical footings on sand in relation to the behaviour Of spudcan footings of jackups, as part of theoretical and experimental studies undertaken Over a period of several years. The work is reported in Cambridge M.Phil and Ph.D theses, contract reports, and in publications. Tsukamoto (1990) tested foundation fixity of a model jackup with three independent legs, deployed at successive locations on a model "sea bed" round the wall of the 2m drum. Comparing this work on bearing capacity with that of Terzaghi (1943), a Significant difference is that now foundation fixity is described by a yield locus rather than by "bearing capacity factors". The model test data are equivalent to observations in hundreds of storms offshore. Each year the offshore industry deploys independent leg jackup units for ever longer periods in ever deeper water, and engineers need ever better guidance to select rigs that are appropriate for successive projects. Drum centrifuges also will be useful for problems such as the behaviour of drag anchors in layered calcareous soils, O'Neill and Randolph (1998), and of mooring lines in soft clay, Law and Ko (1998). The offshore industry already has confidence in geotechnical centrifuge modelling in general, Murff (1997).

(4) Earth pressure theories and models made of reconstituted soil paste.

In his Presidential Address, Terzaghi (1936) explains that he learned to mistrust theory

"some eighteen years ago . . (i.e. in 1918 at the end of WW I, when) . I went through all the volumes of the leading English, German, and French engineering periodicals which had been published since 1850 and through all the textbooks which I could secure, abstracting all the articles and chapters relating to the subject of my investigations. . . . At the time when the theories originated, their authors were still keenly aware of the bold approximations involved, and nobody thought of accepting them at their face value. As the years passed by, these theories were incorporated into the stock of knowledge to be imparted to students during the years of their college training, whereupon they assumed the character of a gospel. Once a theory appears on the question sheet of a college examination, it turns into something to be feared and believed, and many of the engineers who were benefited by a college education applied the theories without even suspecting the narrow limits of their validity. If the structures designed on the basis of these sacred theories stood up, their behaviour was considered normal and not worth mentioning. If they failed it was an act of God, which should be concealed from the eyes of mortals, who might believe the designer was poorly grounded in theory."

Terzaghi did not comment on bearing failure, but he does comment on slope failure and lateral pressure; his feeling that his paper to the Boston Society of Civil Engineers on May 20, 1936, was very significant is evident from the fact that he has reprinted it in full in the Proceedings; it is the only paper included in this manner. He had made full scale tests on retaining walls in 1929 that he reported in Engineering News-Record in 1934. His writing about the tests, and about slope failure, draws attention to the small movements that can be observed at visible surfaces. He conjectures about the way that forces, that are measured in trench supports, relate to strains in the ground beside the trench. The title of his Boston Civil's paper is "A fundamental fallacy in earth pressure computations"; his first conclusion is

" The fundamental assumptions of Rankine's earth pressure theory are incompatible with the known relation between stress and strain in soils, including sand. Therefore the use of this theory should be discontinued".

His complaint is that

"the factor "strain" does not enter the theory".

Terzaghi did not act on his dictat that "the use of (Rankine's) theory should be discontinued". His text book Terzaghi (I 943) proposed "bearing capacity factors" that he based on Prandtl (1920) and, in spite of his rejection of "classical theories", Rankine's theory continues to find a place in the current edition of his textbook Terzaghi, Peck and Mesri (1996). But there is a simple reason for the problem with "theory"; there is an **error** in the Mohr Coulomb equation.

Coulomb's Essai (1773) had the title "Sur une application des règles de Maximis & Minimis à quelques Problèmes de Statique, relatifs à l'Architecture " (On an application of the rules of maximum and minimum to some statical problems, relevant to architecture). It considered the large set of problems for which there is a solution by statics. Sokolovsky (1960) and others considered plane problems of limiting plane equilibrium, as defined by the two equations,

$$\delta\sigma_x/\delta x+\delta\tau_{xy}/\delta y=0,\ \delta\tau_{xy}/\delta x+\delta\sigma_y/\delta y=0,$$

in a zone filled with material for which the limiting stress criterion has a general form

$$F(\sigma_x,\tau_{xy},\sigma_y)=0.$$

This system of three equations in the three unknowns $(\sigma_x,\tau_{xy},\sigma_y)$ is of the hyperbolic type, with two real characteristic directions. There are solutions for given stress boundary conditions. For a criterion of the Mohr Coulomb type there are two real characteristic directions along each of which a certain function of the magnitude and direction of stress maintains a constant value. If the stresses are defined at each point along a particular length of boundary, then there is a triangular domain of dependence within which the stress at some place in the domain is fixed by values of these functions that are propagated to that place from two points on the length of boundary along the two characteristics that reach that place.

This is a mathematical matter, which is not affected by Terzaghi's discussion in his Boston Civil's paper. If the equations written above apply to the earth pressure problem then there are solutions by statics which satisfy the mathematics. The only good reason for their use to be discontinued is that the equations do not apply to the problem. The equilibrium equations are beyond question. It is in the limiting stress criterion F=O that the factor "strain" can be introduced into the solution of earth pressure problem. The Mohr Coulomb parameters called cohesion and friction are seen below to be functions of strain, not "true" soil properties.

Schofield (1993) and (1998) explains that Terzaghi and his research student Hvorslev were wrong in their interpretation of the behaviour of overconslolidated reconstituted clay; peak strength is due to interlocking, not to molecular attraction of "cohesive" soil particles. The most basic and fundamental test of soil is the liquid limit test, in which reconstituted saturated soil exhibits strength that increases as effective stress increases; apparent cohesion is equal to suction times critical state friction; as suction increases the plastic compression of the soil fits the plastic compression of cam clay, Schofield and Wroth (1968). Failure on the dry side of critical states is in one of two ground behaviour regimes; faulted soil dilates on slip planes, causing water to be sucked into the "slick" soil paste on the failure plane; near low effective stress, soil begins to crack. If there is piping or channeling in a zone across which there is a high hydraulic gradient, then rapid transmission of pore pressure into the body of soil, as it begins to develop cracks or pipes or channels, will transform what was initially a stiff lightly stressed continuous soil body into the clastic debris flow typical of the diverse phenomena grouped together as liquefaction events. Centrifuge model tests of soil structure interaction show deterioration of stiffness in cyclic increase of pore pressure and fall of effective stress; a dynamic "groundwater mound" causes flow siding, Phillips and Byrne (1998).

In models made of reconstituted soil paste, zones for which the stress path brings the soil into states on the dry side of critical states exhibit discontinuous behaviour mechanisms. If peak strength in progressive failure on a slip surface is correctly to model strength at homologous points in a prototype then the interlocking and effective stress must be correct everywhere in the body of soil through which the fault propagates. On the wet side of critical states, plastic yielding and compression in the presence of shear strain in a body of reconstituted soil will cause innumerable elementary volumes of soil to be tested with a different "true triaxial test" each at the same time. In this sense the geotechnical centrifuge is an ideal test apparatus for reconstituted soil, both on the wet and the dry side of critical states. The critical state view that the apparent cohesion is due to friction and interlocking not clay bonds, agrees with Coulomb and Rankine. In Schofield (1998) I explain my attribution of the "Mohr Coulomb" error to Terzaghi. The geotechnical centrifuge model test solves the problem of applying critical state soil mechanics to a wide range of boundary value problems. It offers the possibility of future development of a better understanding of ageing and creep in reconstituted soil, and of the role of chemicals in development of adhesive-cohesive bonds, and of a future period when centrifuge models solve problems of fracture mechanics in undisturbed ground. However, even in the present Volume I there begins to be comparison of models made of undisturbed and reconstituted soil, Gurung, Kusakabe, and Kano (1998).

(5) Conclusion.

The work of TC2 differs from the work of other research committees in that the fundamental question we ask goes back to the first "law" of soil mechanics, as stated by Coulomb (1773); "reconstituted soil has no adhesion". Coulomb and Rankine dismissed cohesion from design calculations. Critical state soil mechanics originally claimed that the design problem "is not so difficult if we consider the *ultimate* fully remoulded condition that might occur if the process of uniform distortion were carried on until the soil flowed as a frictional fluid". In centrifuge tests I recognise three regimes of large strain behaviour (fissure, fault, fold) in many soil mechanics problems where soil is seriously disturbed by geotechnical processes. The factor "strain", that Terzaghi wanted to see introduced into the theories, is present as significant plastic strain in mechanisms seen in our tests. In the section where Terzaghi criticised Pokrovsky for the utter futility of his tests he states that "There is no complete theory of the settlement of foundations or of the lateral pressure of earth and there never will be". It applies equally to us and to those who observe small strain behaviour in the field and in site investigations, and use numerical analysis with non-linear elastic constitutive models to predict very small strain soil structure interaction. One day we will achieve a solution that is respectable in applied mechanics, with calculations validated by good model tests and good field data; never is too long a time.

When BGS (British Geotechnical Society) was asked to support our fledgeling TC2 committee it agreed to a modest commitment; the BGS would underwrite the publication of the first TC2 publication; they had made a substantial profit by publishing the proceedings of the European Conference in Brighton and made it clear to the TC2 Chairman and Secretary (Schofield and Craig) that BGS did not expect to make a loss on our TC2 publication. We did not expect TC2 committee members to find funds for travel, and took our message to small conferences in the cities of our committee members; Tokyo, Manchester, Davies, Manchester. We held our first meeting of TC2 immediately after the San Fransisco Conference; BGS lost money on our publication. The workshops and conferences and the subsequent publications of TC2 now make it the most successful of all technical committees. TC2 now has the capability, and I think it has the duty, to address fundamental matters that affect the work of all geotechnical engineers. Terzaghi's Harvard Conference introduced the "Mohr Coulomb" error. TC2 could bring evidence on this matter before our colleagues in Istanbul in 2001,

(6) References.

Dean et al (1993), Wroth Memorial Symposium.
Derkx, Merliot, Garnier, and Cottineau (1998), see Vol I, pp 97-102.
Law and Ko (1998), see Vol. I, pp 805810.
Malushitsky (1975), The *centrifugal modeling of waste-heap embankments.* Russian edition, Kiev, English translation edited by A. N. Schofield, Cambridge University Press (1981).
Murff (1997), OTC keynote address.
Ng, Lee and Liaw (1998), see Vol. I, pp 397-402.
O'Neill and Randolph (1998), see Vol. I, pp 793-798.
Schmidt (1988), Centrifuges in soil mechanics; Craig, James and Schofield eds
Schofield (1993), From cam clay to centrifuge models, JSSMFE Vol. 41, No. 5 Ser. No. 424 pp83- 87, No. 6 Ser. No. 425 pp84-90, No. 7, Ser. No. 426 pp71-78.
Schofield (1998), Mohr Coulomb Error Correction, Ground Engineering August issue, pp30-32
Schofield (1998), The Mohr Coulomb Error, see Cambridge University home page.
Schofield and Wroth (1968), *Critical State Soil Mechanics.* McGraw-Hill, London.
Schofield (1997 and 1998) Granted patents.
Stewart, Boyle, and Randolph (1998), see Vol. I, pp 35-40.
Terzaghi (1943), Theoretical Soil Mechanics, John Wiley, New York.
Terzaghi, Peck and Mesri (1996) most recent edition of this work.
Tsukamoto (1990), Cambridge PhD thesis.

Proceedings of the 1st International Conference on Soil Mechanics and Foundation Engineering, June 22 to 26, 1936
Volume 1 E-5 page 70 Graduate School of Engineering Harvard University, Cambridge, Mass.

No. E-5

# STUDIES OF SOIL PRESSURES AND SOIL DEFORMATIONS BY MEANS OF A CENTRIFUGE

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The study of soil problems by means of modeling with the aid of a centrifuge is used in various institutions of the USSR. (The laboratory for Soil Physios of the All-Union Foundation Research Institute, the laboratory for Physios of the Military-Engineering Academy, the laboratory for Soil Mechanics of the Researoh Institute for Water-Supply and Hydro-Geology, and the Research Laboratory of Moskva-Volgostroi).

The centrifuge gives the possibility to create 8 complete mechanical similarity and exactly ceproduoes the loadings called forth by the weight of the given system.

This principle has been put forward in the USSR by Professor N. N. Davidenkov snd Professor G. J. Pokrwsky, independently of the American investigator, P. Bucky.

Centrifuges with effeotive radii from 0.8 to 1.5m have been made for experiments and the following problems have been studied by means of these centrifuges: (Fig. 1)

1. Stability of slopes in earth banks and cuts.

2. Distribution of pressure under foundations.

The results are shown in Fig. 2. The curve II is a theoretioal one; the ourve III shows the results of model experiments and the curve IV of field experiments.

The experiments have been oarried out on sand. The pressures were measured by means of aerostatioal dynamometers, which consist of a small vessel filled with coloured viscous liquid, and closed by a rubber membrane. The height to whioh the liquid rises at the end of the test in the capillary tube immersed in the liquid, indicates the pressure exerted on the apparatus during the test. (Fig. 3)

3. A similar apparatus has been used for determination of pressure on oulvert pipes buried in earth. By a special dwioe not only the normal, but the tangential pressures as well could be measured. Fig. 4 shows the results. (The normal stresses are shown by the dotted line and the tangential stresses by the full line.)

4. Settlement of foundations. In Fig. 5 the results of model and field experiments are compared. The curve I shows the relation between time and settlement. The curve II-the relation between load and settlement.

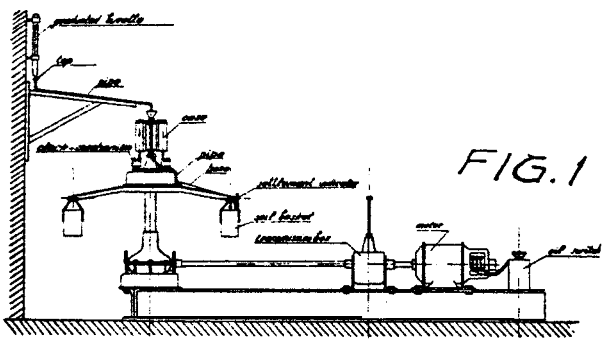

FIG. 1

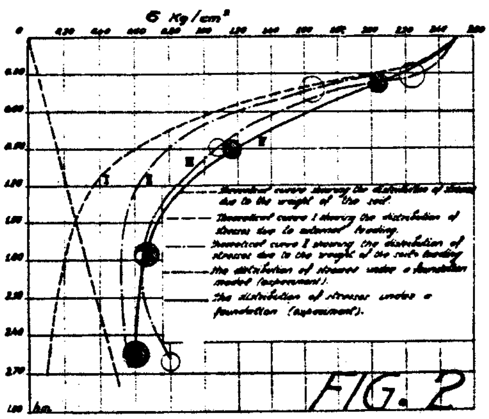


FIG. 2

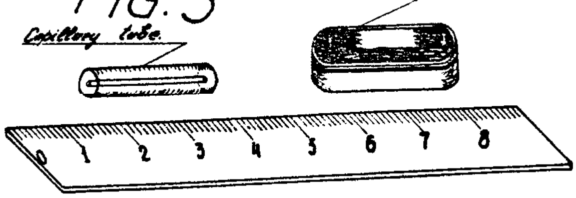


FIG. 3

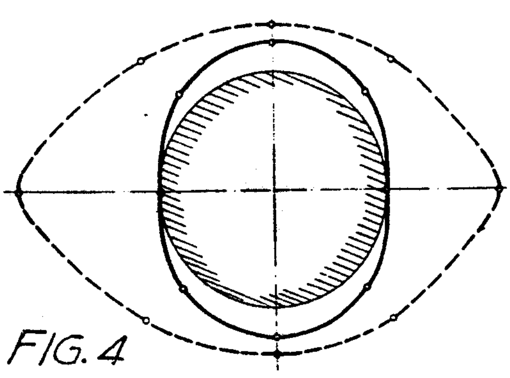

FIG. 4

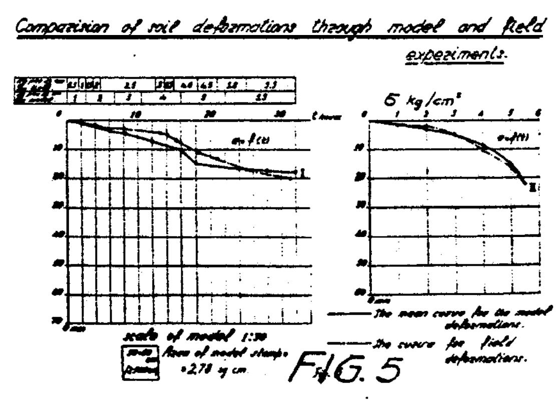


FIG. 5