HARVARD

SOIL MECHANICS SERIES

No. V-1

FROM THEORY TO THEORY IN SOIL MECHANICS

HARVARD UNIVERSITY
DIVISION OF ENGINEERING AND APPLIED PHYSICS
PIERCE HALL
CAMBRIDGE, MASSACHUSETTS

A Note of Interest for Soil Scientists Remembering **Professor Arthur Casagrande**

The following manual preserved in PDF form was donated from the library of Earl Peterson, one of the truly great Geotechnical Drillers of his time. He drilled for the once mighty Guild Drilling from the early 1950s until his retirement in the 1990s. The manual is written in satirical form and comes to us courtesy of Harvard University.

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SOILS MECHANICS

The 1960's

To Professor Arthur Casagrande

With respect and admiration.

This book was written by the board of specialists attending the First International Conference of Failures in Soil Mechanics:

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PREFACE

We have all awaited patiently this happy day when Soil Mechanics can finally be honored with the title of Soil Scientists.

At last we can forever convince those non-mathematiccally minded engineers who don't realize that precise and accurate solutions for soil problems have become imperative. This way sophisticated solutions, expressed by differential equations, shall eliminate calculated risk and the false sense of security, adding confidence, multiplying the reliability of results, dividing expenses, and minimizing the engineer's headaches.

One must believe strongly in this theoretical approach to understand the beauty of the accuracy. This is invariably substantiated by precise laboratory tests. This uncanny agreement of tests with expected results is one of the miracles of modern technology.

The publication of this comprehensive compendium will eliminate the necessity for equivocal empirical rules. The need for such a textbook has been repeatedly borne out in courtroom testimony of experts when faced by those who have never published a book. We modestly give all credit for this masterpiece to our professor in honor of his 30 years of devoted teaching at Harvard with full confidence that he will not be burdened with additions to any chapters during the next 30 years.

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Chapter 1

Soil Exploration

It consists in an introduction of the engineer to the soil. Generally done after finishing the construction.

The best procedure is by air photos. It is cheap, easy, quiet, and clean. (12 Ref. "Professional Detachment)

In special cases borings can be made; one inch (1") diameter samplers furnish excellent undisturbed samples of any soil, suitable for all imaginable soil tests. In this case half a boring is plenty because soils are homogeneous and isotropic earth, nevertheless the hole must be performed exactly at the integral logarithmic geometric center of the area.

Chapter 2

Soil Identification

In this chapter the soil becomes an intimate friend of the engineer.

Obviously the high class of the engineer does not permit himself to put his hands into the dirt; any chemical laboratory with an electronic computer will identify the soils for him. The reader may refer directly to the chapter on soil properties.

Chapter 3

Soil Testing

In the old days the engineer had to abuse the soil. Tests like liquid limit, plastic limit, permeability, consolidation, shear strength are now of academic interest only. Today the best test is the grain size analysis which can be conducted very quickly by optical turbidity meters, which furnishes all information one needs for his soil studies. Larger laboratories may use X-rays and nuclear tests which are also infallible and sophisticated methods of soil testing.

The plasticity chart can still be used by the classicist if a rigorously mathematical curve would replace the so-called A line.

In case of uncertainty or heterogeneous soils, it is imperative that sufficient tests (preferably quadraxial tests at $60) be performed so that a reliable harmonic mean of the results can be derived. Anomalous details are easily eliminated in this way.

Great expectations are cherished for the new giant quadraxial machine being developed by the Federal Bureau of Soil Investigation. The dimensions are large enough to allow a technician within the pressure chamber to take direct stress and strain measurements. This great advance will eliminate all errors in soil testing and the technicians. Until such time as P.L. 11,239 makes the use of this machine mandatory, we will have to rely on the two old standbys: the A. C. (Axial Compression) and L. C. (Lateral Compression) and other members of that test family.

Chapter 4

Properties of Soils

Exhaustive quadraxial T, U, V and Z tests have finally led us beyond the "uncertainty principle" temporarily borrowed from Quantum Mechanics. It has been recently demonstrated that soils are merely spheres arranged in face centered tridecahedral rhomboidal latices. This makes it possible to compute all soil properties theoretically and tabulate them in easy to use charts and simple partial differential equations easily handled with the IBM 709. To avoid confusion between the symbol for void ratio and base of the natural logarithm and in the interest of international cooperation, the Japanese symbol is used:間隙比

A quick reference to the soil types in alphabetical order has been included here for the benefits of neophytes to soil science to save them the inconvenience of leaving their desks. In general, it will be found that the laboratory technician can quickly classify the soils in accordance with the code as explained in the ASTM Handbook of American and Unamerican Soils.

1. Adobe - The strength of this material is attested by bricks in a small building in the Texas town of Alamo, which have withstood the onslaught of Mexicans and other unfavorable elements over a hundred years.

2. Bentonite - An uncommon element found only in Leo Casagrande's pond. Discovered and named after B. Franklin, it usually occurs in such thin layers that it can be ignored.

Calicho - A swear word sometimes used by contractors. Named for the wife of a friendly Indian, Cochise.

4. Clay - Recent progress in physiobiochemicalelectronmicroscopy have made this nomenclature obsolete.

5. Diatomaceous earth - (Kieselgurps) This very important foundation material must be analyzed carefully. One inch frozen samples every ten square feet should be considered a minimum. Correlation of the angle of repose of the angle of symmetry of the formanifera in electron photographs provide all necessary information.

6. Hardpan - Elevation at which refusal is found.

7. Kaolin - Of historic interest only. Once used for dishes before the discovery of plastics.

8. Loess - (Pronounced lice or loose in reference to its licentious character) This material is found in great quantities in Communist China. Any description would be unpatriotic.

9. Marl - Careful analysis of the pronunciation of this word will give your geographic location in the United States.

10. Peat - A euphemism used in reference to an organic fata morgana. When encountered it must be quickly covered with clean granular material. Tradition allows its "removal" to be classed as excavation among pay items. Any job inspector will confirm its unreality.

11. Quicksand - Unknown outside the MGM studio where Tarzan movies are made. Grainsize analysis will dispell any worries of spontaneous liquifaction.

12. Rock - Any hard, strong durable material such as shale, limestone, or gypsum.

13. Sand - A treacherous material whose ultimate bearing capacity has never even been measured. A careful grain size analysis will generally confirm the need for piles. Peace of mind concerning foundations on this material can be purchased from the Shakorsink Corporation.

14. Till - Not worth a dam.

Chapter 5

Theoretical Rheology of Soil

Thanks to a brilliant stroke of genius the thorniest problem of soil mechanics has been solved and at the same time all dissension among soil scientists will come to an end. All the formulas for sheer strength have been combined and the harmonic mean of the sum has been taken as the most probable value. The harmonic mean was chosen in favor of the simple average after an overwhelming two-thirds majority vote at the last soils conference. The scientists were overwhelmed by the unassailable consideration of the stochiastic implementation of the leptokurtic anomaly.

Inspired by this great leap forward we modestly take credit for a further step toward the understanding of the elastic property of soil by introducing the sexidecahedral diagram which is twice as simple as the octahedral diagram since it has twice as many principal **planes**. The resemblance of this diagram to a well-known polyp, the sea anemone, has suggested the name anemone coordinates or A. C. for short.

More exhausting and comprehensive tests using inertia balanced, electronically controlled tilt tables have confirmed that the bhrinanti[1] is exactly the angle of repose. The only question seems to be whether this is measured from the horizontal or the vertical. This detail should be cleared up by the latest research grant of the National Space Administration.

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[1] Angle of internal friction or Reibungswinkle. In keeping with the new status of Soil Science we feel it fitting to replace modern Greek and Latin word roots with the original Sanskrit.

Chapter 6

Elastic States in Soil

Earth pressure - All earth materials may be divided into two classes, sands and clays. A clay is any material which sticks together as a lump when wet, and a sand is any material in which you can see the individual grains. These materials have different properties and will be treated separately.

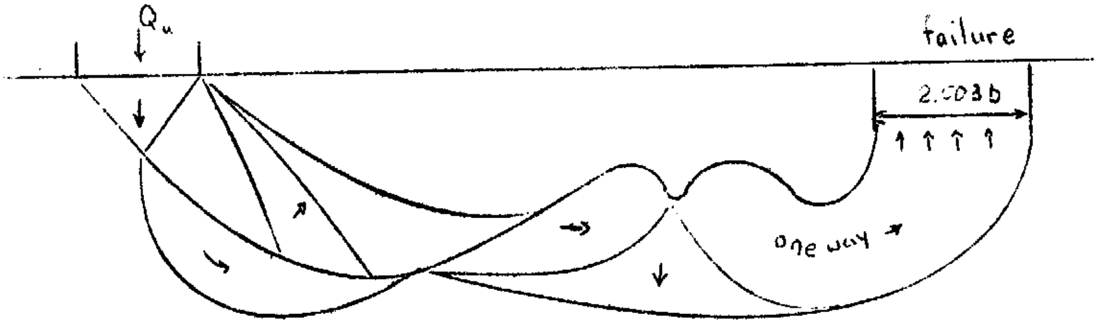
Sands - Sands are obviously poor materials to use behind retaining walls because they have no cohesion. To convince yourself of this, try excavating a vertical slope of sand. Also sands tend to redistribute their loads behind a retaining wall, and one never knows where to expect maximum stress. One should never rely upon arching in soils to reduce earth pressures because of the inherent dangers of transmitting loads over a great and unknown area.

Clays - One may demonstrate the superiority of clays behind retaining walls by excavating a self-standing vertical slope in clays. In any case a retaining wall will not be necessary if the clay stands without failure after excavation.

Active Earth and Passive Pressures - We are not interested in active pressures because they are only developed during failure. Also one never knows exactly what earth pressure to expect, so design for passive pressure is advised. In other words, be active; use passive earth pressure and then "rest."

Design Tips - Freezing of the material behind retaining walls is to be encouraged, for the frozen water helps make the grains stick together, and substantially reduces earth pressure. To convince oneself of the value of freezing, note how many failures occur in the Spring after the ice support has been withdrawn. Crib walls are an eyesore; if used at all they should be painted silver for esthetic reasons.

Bearing Capacity - Unfortunately at present we are unable to realize the most accurate method of bearing capacity analysis - analyzing the individual stresses on each grain of soil. However, recent developments in computers give some hope for the future. Until such a method is possible we must be content with the most elaborate systems of analysis that we now have. Xenophrastenes (550 B. C.) has developed the most satisfactory method:



Once again we must warn against use of sand beneath footings. The superiority of clay may be shown by the greater difficulty of cutting this material with a knife. A peaty clay is most recommended because of the reinforcing properties of the wood fibres. A mixture of sand and clay in equal proportions is also of great strength, because it combines the strength properties of both materials.

Chapter VII

Wilduntergrundwasserstromung

(Ground Water Flow and Seepage)

Despite efforts by mathematicians and physicists to put the theory of ground water flow on a rigorous rational mathematical basis, there exist still to this day small enclaves of the old non-rigorous school. Admittedly it is hard to reconcile the fact that the latter seem to get better solutions which agree with experimental and in-the-field testing. However, just remember the high price that they have to pay for these results; namely complete loss of rigor and mathematical elegance. I think that Dr. Strabismus of Utrecht summed up the dilemma when he said: "Nature is nothing if it cannot be understood mathematically." Some feel that this is a restatement of Newton's axiom "enim natura simplex est." To the support of the non-rigorous school of course we can recall the cri de coeur of that great Roman foundation engineer, Victruvius: "Amor meus, pondus meum; illo ferar, grocumque ferar."

As can be surmised from the very name of the subject, ground water flow, literally deals with the flow of water through the ground. This may seem to be very straightforward, but in fact this statement holds the whole dilemma of rigor or non-rigor. For the pragmaticists claim that several recent tests have shown that not all "ground," i.e., "soils," can be considered as being uniform and isotropic in all directions. These disclosures were of course not as damaging as might have been thought to the theoretical school because after all they only deal with soils of their own definition and choosing. So the controversy rests here. In the meantime, the real world is having some trouble as to how to deal with seepage.

Due to lack of space in this chapter, we shall do no more than to outline the basis of the mathematical approach which the reader will no doubt be able to extend at his leisure, and we shall briefly outline the pragmaticist approach.

For compressible soil and fluid

$$\frac{\partial(\Delta M)}{\partial t} = \left[\theta\frac{\partial\rho}{\partial t}\Delta z + \rho\frac{\partial\theta}{\partial t} + \rho\theta\frac{\partial\Delta z}{\partial t}\right]\Delta x\Delta y$$

After several assumptions becomes

$$-\frac{\partial(\rho V_x)}{\partial x} - \frac{\partial(\rho V_y)}{\partial y} - \frac{\partial(\rho V_x)}{\partial z} = \theta\rho\left(\beta + \frac{\alpha}{\theta}\right)\frac{\partial p}{\partial t}$$

Which after more assumptions gives

$$k\rho\left(\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2}\right) + k\rho_0^2\beta g\left[\left(\frac{\partial h}{\partial x}\right)^2 + \left(\frac{\partial h}{\partial y}\right)^2 + \left(\frac{\partial h}{\partial z}\right)^2 - \frac{\partial h}{\partial z}\right] = 0$$

Ignoring second order terms and making a few more assumptions we finally get

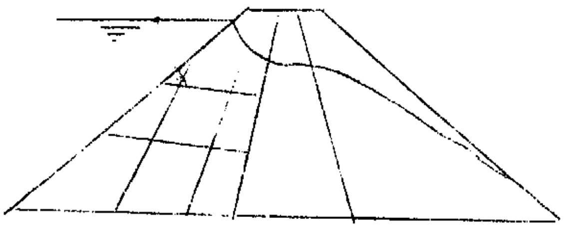
$$\nabla^2 h = 0 \qquad \text{(a)}$$

Equation (a) can be very easily handled on any conveniently located IBM 7090 computer. As can be seen from the above outline, even the rigorous school has to make one or two assumptions.

To master the "art" of ground water flow, one first has to master the art of the "flow net." The flow net is a strange imaginary mesh which springs up around and in any stratum carrying the flow of water. This art while not requiring the talent of a Michaelangelo or an El Greco has a lot in common with the Cubists or the Surrealists or perhaps even Picasso in his "blue period." Flow nets also pose many metaphysical problems such as "when is a square not a square?" This may make a fine subject for a medieval disputation in Latin but is difficult to reconcile to twentieth century philosophers who cannot be certain that the square even exists in the first place. Many times also during the formative years of flow net art, the Platonic concept of the "golden rectangle" was used. The early "flow-neteers" recognizing the innate superiority of the golden rectangle over the more mundane and prosaic square claimed for the rectangle the honor of completing the flow net.

Having mastered the art of the flow net one need only quote the hypotheses of two Frenchmen, accept them as universal objective truths, and one is ready to tackle any problem of the flow of water and for that matter practically any other known fluid (beer, coffee, tea, gin, etc.) through any soil. The two French gentlemen mentioned are of course none other than Messieurs D'arcy and Dupuit.

At this stage a few examples of flow nets will intricate the scope of this method for solving quite diverse problems.



Before sudden drawdown

After sudden drawdown

The true essence of the flow net cannot be brought out in black and white. For nature really goes to town on these mythological creatures - : for instance, equipotential lines are always red, flow lines are yellow, and discharge surfaces are green. To obtain practical corroborations of these facts, one only has to look at the downstream face of an earth dam to verify that discharge surfaces are green. Verification of the color of the flow and equipotential lines is more difficult but it is felt to be a safe assumption in the face of evidence to the contrary.

In conclusion we would like to issue a warning to all ground-water hydrologists to solve as few problems as possible by the non-rigorous method but to wait, if at all possible, until the mathematicians have finished their analysis and have come up with an elegant solution.

When in doubt
Don't scream and shout
Grout
Throughout.

\- Hydrophobese

Chapter 8

Foundations

From Latin fundo, fundas, fundavi, fundatum, fundare - means poetically to establish the bottom of.

The foundations may be accomplished by caissons (improperly called piers), mats, and piles. There is another type of building foundation called flotation that can be employed if the water table is artesian.

Piles

Since piles are the most important type of foundation, more emphasis is given to them here. "Piles do not settle, ever."

They are most appropriate where easily driven in sensitive clays and rock flour. This is especially true in compact sand where they are necessary to provide bearing capacity.

Driving techniques: The most efficient manner of driving a pile is achieved by using small ram weight falling from great height.

Bearing capacity: It is precisely and only determined by dynamic formulae. We advise the use of the following simple and complete formula:

$$R_s = \frac{2.0053\ W_R H}{0.375 + \sqrt[3]{\frac{W_p}{W_R}}} + \iint_{-L}^{+L} (a-b)\frac{n-1}{n}\frac{\ell H}{AE}\, d\ell\, dh + 0.251(T-U)^m + 201F \pm 10I$$

Where

S = penetration for 100 blows

L = length

a, b, n = factors to take in account elastic properties of piles, pile cap, pile driver, etc.

T, U, M = factor to consider elastic and plastic properties of soil and water.

F = function of the age and temper of the foreman.

I = factor allowing for the financial status of the Inspector.

In case of difficulty divide the results of the pile formula by two to reduce pressure bulb diameter, and drive more piles.

Note: If an engineer mentions negative skin friction just multiply him by minus one.

Finally: "In case of doubt use pile from north to south." Or as said once by Confucius: "In case of confusion use them in profusion."

Chapter IX

Tunnels - Anchored Bulkheads and Cofferdams

Tunnels

After the advent of the A-bomb all the theories and rules of thumb in rock mechanics applied to tunnels and cavities are just bare nonsense. Nowadays the question is: How many megatons should an atomic bomb have to reduce the mountain to road grade? In this case the task is transferred to the "fire" department.

Anchored Bulkheads

They are not a soil problem but a concern of the metallurgists because they are used a lot in steel plants.

Cofferdams

Since Dr. Tuna proved the wavy equations, showing the influence of the logarithm of the length of the fish caudal fin on the amplitude of sea waves, the cofferdam problem became a handbook application.

So use:

$H = 2.035r$ and $b = 1.695H$ and fill the inside of cells with tetrapods.

If safety is to be improved, use a drydock.

ϕ = ANGLE OF EXTERNAL FRICTION $53^{\circ}61'21.35''$

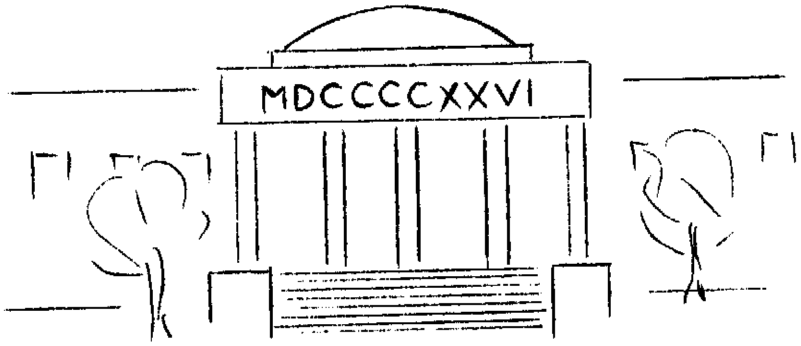
Chapter X

Settlements

Thanks to the discoveries of modern soil science, this is no longer a problem, and this chapter is included for historical interest.

As everyone knows, no settlement can be tolerated in a proper design of modern buildings. Our leading universities have demonstrated this in the design of their additions in recent decades. Notwithstanding occasional propaganda about "floating foundations," obviously subject to tidal action, the only security can be through the use of sufficient piles.

Careful perusal of objective research by Franky, Giled, Ramond, and Prepax have confirmed the infallibility of piles. The precise amount of settlement can be computed from the dynamic piles formulas (see Chapter VIII and ENR, May 1963). To dissipate any uncertainty a single pile may be driven and tested to maximum load. The settlement of this pile will be representative of the settlement for the entire foundation. Ex.: MTA building.



In the case of large ore piles where settlement is of paramount importance, great success has been achieved through the shrewd application of the well-known geologic principle of isostasy. In this case, sheet piles are driven in the ground until the tonnage of iron below the ground exactly balances the weight of the ore pile. This is not to be confused with the dangerous method of floating foundations.

The prevalent use of spread footings, other than on bedrock, is to be deplored. Any risk of settlement is not compatible with the present science of structural engineering. Any cases in which piles did not prevent settlement entirely can easily be explained by the obvious answer that not enough piles were used.

Chapter XI

Practical Theories

The subject can be treated in a completely general, if slightly idealized, manner by the use of inverted Laplace transforms over the integro-differential equations for the thermoviscoelastoplastic behavior of little round salted peanuts coated with peppermint sauce by the method of steepest descent. However, look out for that last bump, its a rough one. Another slight difficulty lies in the fact that the fudge factor hasn't yet been determined -- although why a fudge factor should be required to treat peppermint sauce escapes us.

An approximation can be introduced into the boundary conditions, greatly simplifying computations, if all soils are divided into those having a liquid limit above 10,000 and those having one below. This boundary is not especially critical since a variation of plus or minus 1.3 has been found to make little difference in the end result. However, if the liquid limit is above 10,000, it is wise to check up on the client since he may be the type who dabbles in mail order promotions of Florida real estate.

If the liquid limit is below 10,000 a floating pile foundation is often feasible. This is an elegant solution to the foundation problem, but care must be taken to remove all of the pressure bulbs. A backfill of a light fluffy material such as expanded trap-rock can then be placed. An alternative method is to insert baloons filled with helium into the holes. Hydrogen should be avoided if the pile foreman smokes cigars. A lightweight pile of papier-mache reinforced with hairpins can then be driven with a Vulvan No. 1 hammer or the equivalent. The driving should be done gently to avoid excessive skin friction. If skin friction develops, it can be removed by applying a mixture of snake oil, Tennessee mountain red eye, and Tiger Balm. This also helps get the corrosion over with in a hurry.

A little care is needed in tying down this type of foundation. The last one I saw was built in Lower Slobbovia, but before the first story had been built it disappeared in the direction of Upper Slobbovia at an altitude of about 8,000 meters -- they don't use feet in Slobbovia, and besides it was a cloudy day and hard to judge distances. The consultant on that job received a prize for his fine write-up in the Operating Engineer's Review (AFL-CIO-FDR-JFK).

In case you don't have any piles (you could be worse off, you know) a raft foundation can be used. One made of balsa wood is especially effective in soils over the 10,000 liquid limit.

It has been found empirically that sand drains in this type soil aren't very effective if less than 3 feet in diameter placed on 3 foot centers. If the sand drain method is used, a sheet pile cutoff can then be made to bedrock, the excavation carried to bedrock and a pre-pack of crushed granular fill installed to slab level. When the pre-pack is carefully grouted, it is often found that an economical floating foundation can be designed. Sometimes very little reinforcing is needed in the slab.

In our experience, the best approach to foundation design is to remain flexible -- the young engineer should not plan on being around any one site too long, in fact, time is often saved by keeping all your belongings in the back of your car, and the motor running.

Conclusive Conclusions

In this scientific age the engineer need no longer fear catastrophic failures, since these are acts of God and the responsibility of the consultant.