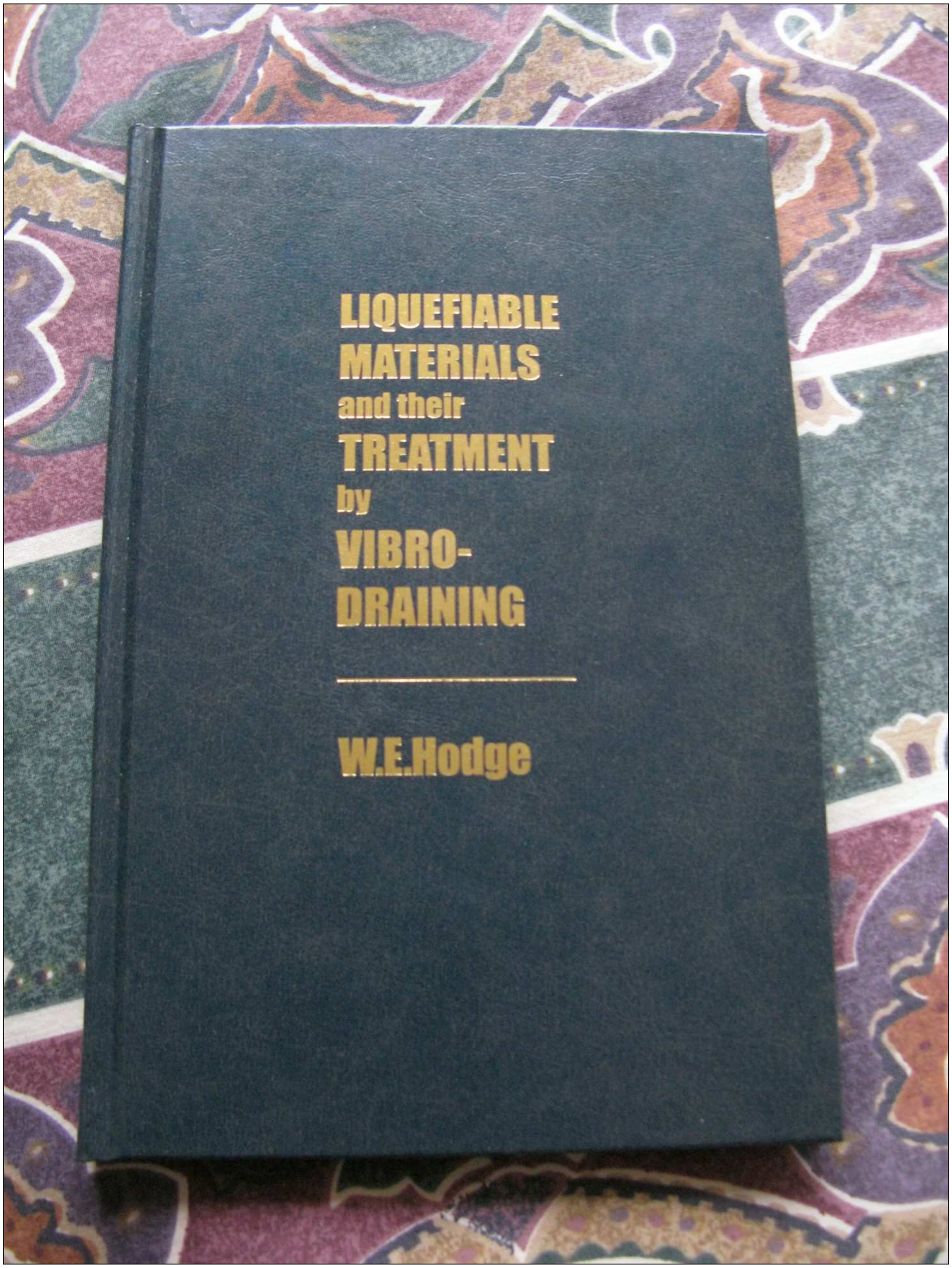
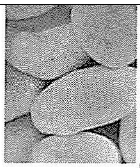
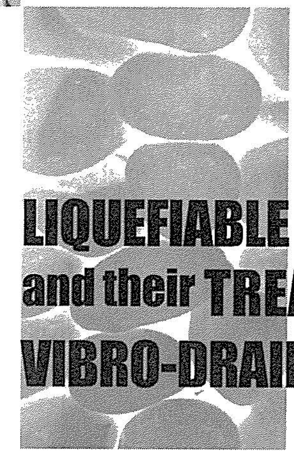


LIQUEFIABLE MATERIALS and their TREATMENT by VIBRO-DRAINING

W.E.Hodge





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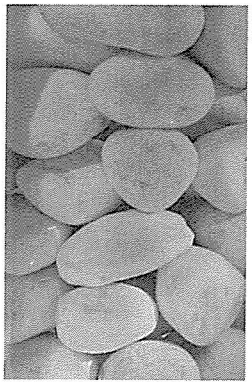

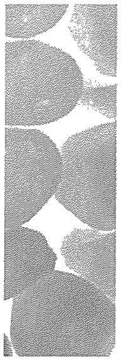

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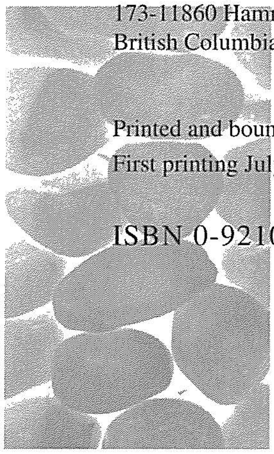
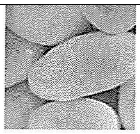
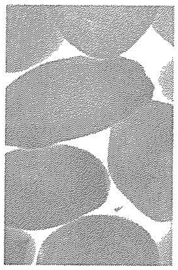
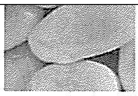




Dedication

Willie and Nancy Hodge





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Eamonn Dillon of University College Cork was responsible for me becoming a geotechnical engineer. Many times I have blamed him for this, but most of the time I have been grateful to him. All of the time his enthusiasm for applied science has been boundless and infectious.

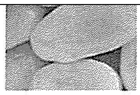
Don Bazett designed the first dam I worked on, an earthfill placed mainly through flowing water. Since then he has been my mentor, offering a willing ear and sound advice whenever I was floundering, technically or otherwise.

Yogi Vaid of the University of British Columbia came to my aid with eleven selected articles on laboratory testing so that I might catch up on the state of that art. Afterwards he read an early version of my thoughts on his subject and his encouraging comments gave me a much needed moral boost at that critical stage of this investigation.

David Woeller of ConeTec read an early draft of this work and I used his perceptive comments to amplify the text and to introduce new charts. Because of him a long article became a short book.

Kazuko Suzuki supplied the equipment and consumables needed to perform the simple tests which helped confirm the hypothesised pore pressure model. Sometimes I think she would have made a better engineer than me, but I am glad she does what she does instead.

Walter van Woudenberg and James Cramer of Nilex have the business sense I lack, and now with their help, I have some reason to believe that the vibro-draining equipment will someday become another of the tools to chose from in the contractor's yard.



Preface

As a child I was impressed by friction. I was more annoyed by it than interested in it. It always acted in the wrong direction, that is, working against the way I was trying to go. But after I entered engineering I had a change of mind. Friction, I learned, is what holds the mountains up. So friction really had a good side to it after all - it was just that my perspective had been too focused, and my perception too limited. Later, as a junior engineer I inherited the belief that seepage was nothing if not bad. And there was plenty of evidence to sustain that notion. Seepage seemed to be the most effective way of producing a failure. It was a long time before I realized I was looking at seepage the same way I had been looking at friction - things going the wrong way for my liking. From that stage on it was obvious that what was to be done with seepage was to make it work for you. Seepage forces are not bad, just powerful.

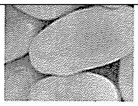
While working on the ground treatment device discussed here (the Phoenix® Machine) it became necessary to understand liquefaction and densification as well as I could. It has taken about fifteen years of intermittent thinking and field trials to get to this point, and this is far enough for my purposes. Since a lot of what I learned along the way relates directly to the basic principles of Soil Mechanics I wanted to document my position in print. So, following the time honoured route, I responded to a request for papers and wrote an article which was promptly rejected for being too long. This little book, or monograph, is my solution to that particular rebuff. But, there was another reason for writing, and this is a little difficult to explain.

Preface

In the late sixties, laboratory testing being carried out at Harvard and at Berkeley to investigate liquefaction of sands lead to a divergence of opinion. It is unfortunate that when this healthy competition for the minds of engineers was in its critical stage, Arthur Casagrande was already in his terminal illness. When the Harvard school subsequently shut its doors to engineering the countervailing opinion to the popular Berkeley hypothesis, and the rational opposition essential to stimulate responsible progress, was lost. In the years that followed the meaning of the word *liquefaction* became obscure. This would not have been too serious if such an esoteric engineering definition had not found its way into the media lexicon. Now, the casual or inappropriate use of this word can generate such public fear in a society obsessed by safety that *"liquefaction"* has become a profitable revenue base for engineers. As a consequence, in my opinion, a huge amount of public and private money has been wasted on treating ground that did not need to be treated, "just to be on the safe side". It seems to me, because of this and similar overkill, engineers are in danger of losing much of that subliminal social respect they once enjoyed, and which had been hard won by generations of sincere problem solvers.

In developing a new approach to an old problem I believe it is necessary to make a conscious effort to keep off the beaten track. If you do not separate yourself from the security blanket of standard solutions and popular technical assumptions, logic, applied to existing premises, will lead, if no mistakes are made, to the same old conclusion. I used a few techniques to try to avoid this happening. In general, I resisted looking for help in the literature until after I had made up my own mind. It is too easy to be seduced by other engineers' opinions, especially those who are established authorities. Another rule was to avoid as much as possible thinking in terms of stress, total or effective. Working in terms of stress is a temptation to resort to the convenience of existing mathematical formulations when the problem seems intractable, thus temporarily avoiding the need to visualize the phenomenon in real physical terms. Using the term stress in relation to saturated cohesionless materials is in any event misleading since nowhere within the system is such a condition known to exist, neither as an inter-granular stress between particles, nor as an intra-granular stress within the individual grains. Pressure is a better word. Also, I concentrated more on strain than pressure. Strain is physically more fundamental than stress or pressure. There can be no stress effect without first having a strain cause. So strain, or better yet, displacement, is more helpful in visualizing what might be happening in a soil under changing load. And finally, I concentrated most of all on the pore water. Water, being frictionless, can move about efficiently, keeping most of its energy for other purposes, bad or good.

Once upon a time, when geotechnical engineering was young, little was known, and it was full of free thinking. Today innovation seems to be hamstrung by bureaucratic codes, owner/utility apathy, design complacency, academic lethargy, and much too often, legal entropy. Yet, there is much we still do not know for sure, and still plenty of room for speculation. The positions put forward in this book were initially personal intuitions. But, intuition in engineering, as in horse racing, must take third place to performance in the field. Geotechnical reasoning comes second, and is necessary in any event to give some theoretical framework for understanding. A good bet is all three in a close race. These days everyone knows that nothing in science is permanent, and no theory can remain sacred for long. Consequently, in the spirit of Karl Popper, I have tried to state my notions as clearly as I can so that they are as vulnerable as possible to refutation. The best that can be hoped for is that what is said here might be a useful step along the way of others.



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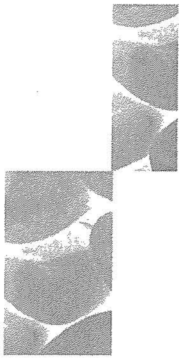

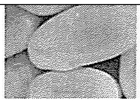

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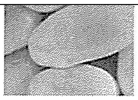

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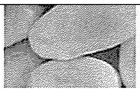


Introduction

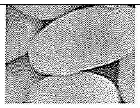
The Vibro-Drain is similar to conventional Vibroflots inasmuch as it is a long cylindrical device with a vibrator at the bottom which is inserted in the ground. Where it differs is that in addition to a vibrator, it incorporates a filter/drain module which actively pumps water out of the soil. The vibration and the removal of water are carried on simultaneously and it is believed that the combined action of these two activities is advantageous.

CPT probing from two sites which were treated by vibro-draining are presented. One site involved a dredged sandfill which had been deposited inside an offshore structure called the Molikpaq Platform. The other site involved an interlayered silt/sand/clay sized mine tailings impounded behind a retaining dyke at Myra Falls on Vancouver Island. Improvements in behaviour of the very fine tailings were encouraging, but difficult to explain. In an attempt to gain an understanding of what actually happened to improve the tailings, the mechanics of discrete particle (non-cohesive) interaction during deformation was examined at a fundamental level. This effort yielded a working hypothesis which is formulated here.

The hypothesis concerns itself with how soil structures are developed, and how those formations subsequently respond to external forces which make them change. It also offers an explanation for pore water pressure generation, and suggests a method of calculating its maximum value for various particle sizes. To avoid misunderstandings arising out of simple semantic differences in the use of words, a glossary is given to make clear the sense in which certain terms are used in the hypothesis.

To see if the hypothesis had any viability, it was checked against laboratory records of load-deformation behaviour in sands. The ideas seemed compatible with published laboratory data, and in addition, some insights into elemental testing were suggested. Having thereby gained a degree of confidence in the hypothesis, it was then applied to earthquake liquefaction to see if it would help discriminate between material types and conditions which were inherently vulnerable and those which were naturally safe. In this case it helped clarify the phenomenon and suggested new ways of approaching this problem.

At that stage, with the hypothesis available, two things were possible. First, the Myra Falls data could be revisited with some confidence, and this resulted in a more satisfactory explanation of the field data, thereby allowing a conclusion to be reached regarding the value of that particular ground improvement effort. Then, armed with a knowledge of what range of materials could actually liquefy, it became possible to take a rational approach to the optimization of future versions of the Vibro-Drain so as to treat only those materials which would benefit from treatment.



Vibro-Drain Approach to Ground Improvement

The general mechanical detail of the equipment used at Molikpaq and Myra Falls is shown in Campanella et al (1990), and Figure 1 is a schematic of the hardware and its mode of deployment. Photo 1 shows a similar configuration being deployed at Blackdome mine. The two active elements are a vibrator and a drain; the vibrator and the filter/drain modules are both 1.5 m (5 ft) long and 190 mm (7½ inch) diameter. The vibrator, located at the bottom of the string, consists of an eccentric weight which rotates about the vertical axis. The drain, attached immediately above the vibrator, consists of an outer filter screen which houses a water discharge system. Extension rods carry the energy down to the pump and the vibrator, and also carry the water discharged from the filter/drain module out to the surface. The motor which drives the vibrator is about 7 kw (10 hp) and the capacity of the drainage system is about 6 l/s (100 gpm). The Vibro-Drain equipment is used in a manner similar to conventional Vibroflots, where the stinger is first inserted in the ground to the full depth requiring treatment, and then gradually withdrawn in a predetermined manner, to compact the surrounding soil. Also, in similar fashion to the operation of the Vibroflot technique, the array spacing on which the stinger is inserted and activated, and the average rate of withdrawal, are functions of the soil type and the degree of improvement required.

The idea of pumping water out of the ground at the same time it is being compacted by vibration evolved from research into the placement of underwater sandfills, as reported in Hodge (1988). There it was argued that pumping water out of a submerged fill while it was being placed, served both to increase the steepness of the outside slopes, and to improve the density of the resulting sandfill. In this case (vibro-draining) it was believed that managing the water around the stinger had two benefits:

- Supernatant water generated beside the vibrator, because of the void ratio reduction accompanying compaction, is removed, thereby allowing the vibrations to aggressively impact the soil particles rather than expending energy within a slurry.
- The low potential created around the filter/drain module causes groundwater seepage to be initiated towards the stinger, and this flow through the zone being treated favours translation of soil particles towards the source of the compaction energy.

The interaction between soil grains and water, whenever water flows through a soil, can be quantified in terms of Seepage Force, as defined by Taylor (1948). Seepage forces can be considered a measure of the amount of energy expended by the water on viscous drag as it moves past particles, or conversely, as being a measure of the work done on the soil skeleton by the flowing water. It is believed that the main mechanical advantage the vibro-draining approach may have is tied to its ability to generate such seepage forces by causing water to flow towards the stinger. Because of its central importance to this particular ground treatment approach, two related quantitative aspects of water flow within the mass being treated will be brought out by means of two simple, but instructive, generalizations:

1) The magnitude of the Seepage Force ("SF") per unit volume is:
SF per unit volume of soil = $\gamma w . i$
where:

γw is the unit weight of water, and
i is the hydraulic gradient at the point of interest.

2) The rate of flow ("Q") into the filter/drain module can be approximated by the steady state flow equation:

$Q = k . i . A$

where:

k is some hydraulic conductivity typifying the local mass, and

A is some characteristic area normal to the flow, and which depends on the drain geometry.

Now, since SF is directly proportional to i, and i is dependent only on the hydraulic head difference, and the distance between a point of interest in the ground and the pump intake, then the seepage force benefits are theoretically independent of soil type. On the other hand, since the rate of seepage flow (Q) is proportional to k (as well as i), the quantity of water flowing through the system in any given period is directly dependent on the soil type. Consequently, for the fixed value of i generated by the Vibro-Drain at a particular depth, seepage force benefits will be of equal value whether the ground being treated is a fine silt or a coarse sand, whereas the quantity of water being discharged would be orders of magnitude lower in the silt than in the sand.

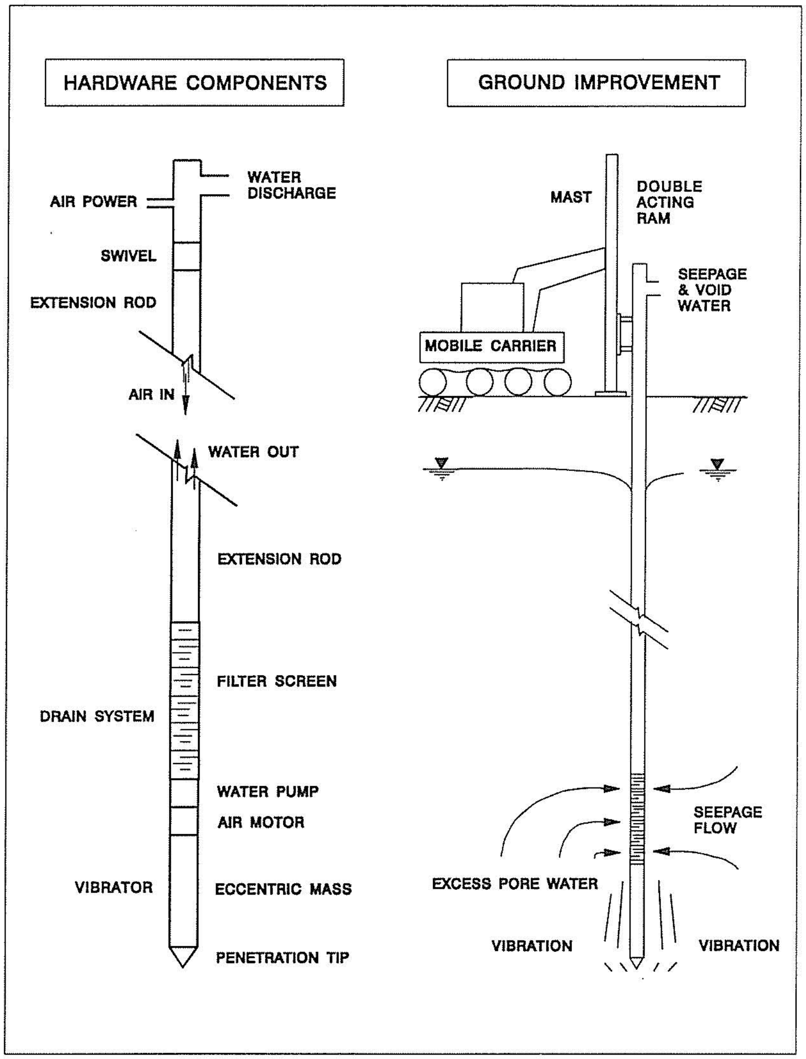


Figure 1. Schematic of Vibro-Drain Equipment