AN ACOUSTIC METHOD FOR IDENTIFYING SAND FABRIC AND LIQUEFACTION POTENTIAL

GENE VINCENT ROE

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AN ACOUSTIC METHOD
FOR IDENTIFYING SAND FABRIC
AND LIQUEFACTION POTENTIAL

BY

Gene V. Roe
B.S. Worcester Polytechnic Institute, 1972
M.S. University of Connecticut, 1974

DISSERTATION

Submitted to the University of New Hampshire
in Partial Fulfillment of
the Requirements for the Degree of

Doctor of Philosophy
in
Engineering

May, 1981
This dissertation has been examined and approved.

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Date May 7, 1981
ACKNOWLEDGEMENTS

This is an attempt to recognize all those persons who have in one way or another over the past five years, contributed to this effort. If I have left anyone out, it will not have been intentional, and please accept my apology.

First of all I would like to thank all those people who directly worked on the project. This includes Jo-Jo, Dick, Ed, Kenny, Jim Irish, Ken Baldwin, Joe Maiolino, Jane and Muriel. Special thanks to Bob and Walt; without their help this project could never have been a success.

For their support and encouragement I would like to thank Harry and Bob, Barbaros, Steven, C.J. and particularly Pedro DeAlba and The Coach.

A special thank you to Yvette, Alice and Warren for their super effort in the preparation of this dissertation.

The project was funded in part by the Office of Sea Grant, National Oceanic Administration, U.S. Department of Commerce, through a grant to the University of New Hampshire; additional support was provided by the Leslie and Iola Hubbard Fund of the University of New Hampshire. This support is gratefully acknowledged.

And finally to my father, the wisest man I've every known, to my mother who gave me the strength to go on, and to my wife, who is the only one who really knows what this was like, mere words cannot express my gratitude.
### TABLE OF CONTENTS

ACKNOWLEDGEMENTS ................................................. iii

LIST OF TABLES .................................................. vi

LIST OF FIGURES .................................................... vii

ABSTRACT .............................................................. ix

CHAPTER

I. INTRODUCTION .................................................... 1

  Background ......................................................... 1

  Acoustic Method .................................................. 3

  Test Program ....................................................... 3

  Future Testing ..................................................... 4

II. LITERATURE REVIEW ........................................... 6

  Acoustic Rigidity ................................................. 8

  Sand Fabric and Resistance to Liquefaction ............... 10

  Wave Propagation Velocity and Elastic Moduli .......... 11

III. PRELIMINARY INVESTIGATION ................................. 14

  Description of Test Material .................................. 14

  Description of the Methods of Sample Preparation ........ 16

  Description of the Testing Equipment ....................... 22

  Description of the Test Procedure ........................ 25

  Results of Tests ................................................. 36

  Discussion ......................................................... 40

IV. TEST SERIES I .................................................... 41

  Description and Results of Tests Performed to
  Determine the Acoustic Response of the Test
  Apparatus ......................................................... 41
# LIST OF TABLES

<table>
<thead>
<tr>
<th>TABLE</th>
<th>Title</th>
<th>PAGE NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Peak Power Values</td>
<td>53</td>
</tr>
<tr>
<td>II</td>
<td>The Effect of Changes in Effective Stress on the Dry Compressional Wave Velocity</td>
<td>70</td>
</tr>
<tr>
<td>III</td>
<td>$V_p$ Dry and Saturated, $V_p/V_s$ and Poisson's Ratio</td>
<td>113</td>
</tr>
<tr>
<td>FIGURE</td>
<td>DESCRIPTION</td>
<td>PAGE</td>
</tr>
<tr>
<td>---------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>III-1</td>
<td>Gradation of Test Sand</td>
<td>15</td>
</tr>
<tr>
<td>III-2</td>
<td>Dry Pluviation Sample Preparation Method</td>
<td>17</td>
</tr>
<tr>
<td>III-3</td>
<td>Flask and Stoppers</td>
<td>18</td>
</tr>
<tr>
<td>III-4</td>
<td>Moist Tamping Tool</td>
<td>21</td>
</tr>
<tr>
<td>III-5</td>
<td>Test Equipment Schematic</td>
<td>23</td>
</tr>
<tr>
<td>III-6</td>
<td>Acoustic Sensors</td>
<td>24</td>
</tr>
<tr>
<td>III-7</td>
<td>Signal Generator and Digital Oscilloscope</td>
<td>26</td>
</tr>
<tr>
<td>III-8</td>
<td>Tektronix Model #535 Oscilloscope</td>
<td>27</td>
</tr>
<tr>
<td>III-9</td>
<td>Initial Height Measurement Using Gauge Block</td>
<td>30</td>
</tr>
<tr>
<td>III-10</td>
<td>Triaxial Chamber Flow Control Board</td>
<td>31</td>
</tr>
<tr>
<td>III-11</td>
<td>Sample in Triaxial Chamber</td>
<td>32</td>
</tr>
<tr>
<td>III-12</td>
<td>B-Value Measurement Device</td>
<td>34</td>
</tr>
<tr>
<td>III-13</td>
<td>Typical Transmitted and Received Pulse Replicas</td>
<td>37</td>
</tr>
<tr>
<td>III-14</td>
<td>Shape of Received Signal Envelope</td>
<td>39</td>
</tr>
<tr>
<td>IV-1</td>
<td>Water Column Standard Frame</td>
<td>44</td>
</tr>
<tr>
<td>IV-2</td>
<td>System Response Replica</td>
<td>46</td>
</tr>
<tr>
<td>IV-3</td>
<td>Typical Water Column Trace</td>
<td>48</td>
</tr>
<tr>
<td>IV-4</td>
<td>Computer Plot of Data File</td>
<td>50</td>
</tr>
<tr>
<td>IV-5</td>
<td>Peak Power Computer Plot</td>
<td>51</td>
</tr>
<tr>
<td>IV-6</td>
<td>Maximum Value of Density Function vs. Relative Density</td>
<td>52</td>
</tr>
<tr>
<td>V-1</td>
<td>HFV/P Sample Preparation Method</td>
<td>59</td>
</tr>
<tr>
<td>V-2</td>
<td>Vibro Engraver Tool</td>
<td>60</td>
</tr>
</tbody>
</table>
V-3  Schematic of Acoustic Transducer Locations  62
V-4  Typical Time-of-Flight Measurement  67
V-5  Dry Compressional Wave Velocity vs. Relative Density  72
V-6  Saturated Compressional Wave Velocity vs. Relative Density  74
VI-1  CKC Cyclic Loader  80
VI-2  Cyclic Triaxial Test Equipment  82
VI-3  Strip Chart Recorder  83
VI-4  Typical Cyclic Triaxial Test Records  85
VI-5  Saturated Compressional Wave Velocity vs. Relative Density  88
VI-6  Compressional Wave Transmission Loss vs. Relative Density  90
VI-7  Cyclic Stress Ratio vs. Number of Cycles to Liquefaction  92
VII-1  Schematic of Shear Wave Bender Element  97
VII-2  KB-GR Transducer Components  99
VII-3  Schematic of KB-GR Transducer  100
VII-4  KB-GR Piezoelectric Crystals  101
VII-5  Dry Shear Wave Velocity vs. Relative Density  109
VII-6  Saturated Shear Wave Velocity vs. Relative Density  111
VII-7  Saturated Compressional Wave Velocity vs. Relative Density  115
VII-8  Shear Modulus vs. Relative Density  117
ABSTRACT

AN ACOUSTIC METHOD FOR IDENTIFYING SAND FABRIC
AND LIQUEFACTION POTENTIAL

by

GENE V. ROE

University of New Hampshire, May, 1981

The testing program described in this dissertation was performed to develop an acoustic method for identifying the fabric of saturated medium to fine sand samples, and their related resistance to liquefaction. Three methods of preparation, that produced repeatably different preferred long grain axis orientations, were used to prepare laboratory samples (6.8" high by 2.7" in diameter) of a uniform, angular sand.

Acoustic signatures were obtained, for both dry and saturated samples, using compressional and shear wave transducers. The latter were developed specifically for the test program and included a 4 bender bimorph array as the shear wave crystal. The samples were then tested to liquefaction under undrained, stress controlled, cyclic triaxial conditions.

Results of the investigation revealed that the compressional wave velocity and attenuation of the saturated triaxial sand samples were reliable indicators of sample fabric, albeit they were very sensitive to the level of saturation. In turn, these acoustic parameters were found to be directly related to the liquefaction resistance of the same laboratory samples. The effect of stress history...
on the liquefaction resistance of a test sample was also predicted by the above acoustic parameters.

The results of tests employing the newly developed acoustic transducers confirmed the initial compressional wave results as well as providing information on the shear wave velocity of the test sand fabrics. This more complete acoustic signature permitted the computation of the Shear Modulus, $V_p/V_s$, and Poisson's Ratio for the laboratory samples. Each of these parameters was found to be a sensitive indicator of the method of sample preparation, and the resulting acoustic rigidity. Shear wave velocity was observed to decrease with increasing moisture content and decreasing effective stress. The effect of overconsolidation was seen as an increase in the shear wave velocity.
CHAPTER I

INTRODUCTION

Background

The potential for liquefaction of saturated sands subjected to dynamic loads has been studied with increasing detail since the pioneering work of Seed and Lee (1966) in the mid 1960's. One need only recall the catastrophic failure of foundation soils due to earthquake-induced liquefaction at both Niigata, Japan and Anchorage Alaska in 1964 to understand the importance of this effort.

At the present time the geotechnical engineer essentially has two methods available to him for assessing the liquefaction potential of a given sand deposit. He may attempt to remove and preserve intact, so-called "undisturbed samples" of the soil for laboratory evaluation of the resistance parameters, or he can use an empirical method which correlates the Standard Penetration Resistance of the deposit with its liquefaction potential. A glossary of terms is provided in Appendix I.

The reliability of the first method has to be questioned for at least two related reasons. The first is that a number of investigators (Mori, 1976) have shown that the fabric, or interparticle orientation of a sand is very sensitive to sample disturbance. The latter exists to some degree in all so-called undisturbed sampling procedures. Secondly, it has been shown in the laboratory that the susceptibility of sands to liquefaction is directly dependant on the
fabric of the sample being tested. By creating samples with repeatable, known differences in sand grain long axis orientation, and then subjecting them to cyclic triaxial testing, the number of cycles required to cause liquefaction at a given stress level varied by as much as 100% for samples of the same sand and density (Mulilis, 1975).

The second method, which predicts liquefaction resistance from the results of the Standard Penetration Test, has been shown to be quite reliable in a number of study cases (Seed (1976)). However, should the sand deposit in question be located offshore, the geotechnical engineer finds that neither one of the currently available techniques for assessing liquefaction potential is at all well adapted to the rigors of a marine environment.

In the ocean, of course, the potential for liquefaction of a foundation soil is everpresent due to the cyclic nature of the wave-induced loads on the structure. In fact, it was predicted from laboratory tests, that even a medium-dense marine sand deposit could liquefy when subjected to the massive loads of a 100-year North Sea design storm (Lee (1975)).

As a result, in order to resolve the present dilemma one of two approaches can be taken. Either a method for directly determining the in situ liquefaction resistance of a marine sand deposit could be developed; or the natural, truly undistrubed fabric of the sand deposit could be determined, from in situ tests, such that truly representative samples could then be reconstructed in the laboratory to an interparticle arrangement equivalent to that found in nature. These laboratory samples could then be tested to determine the deposit's liquefaction characteristics. It is important to note that the
laboratory-reconstructed fabric need not be identical to that found in situ, only that it possess the same dynamic strength properties.

**Acoustic Method**

The use of acoustics was selected for the basis of a technique, which could, at least in theory, quantify the in situ fabric, if not the resistance to liquefaction, of a marine sand deposit. Since a wealth of information already exists in the geophysical community on the relationship of sediment properties to acoustic wave transmissions, it was felt that an acoustic signature could be developed which was sensitive to the fabric arrangement of sands, and that ultimately this acoustic parameter, or parameters, could be related to liquefaction resistance.

Since such dynamic strength parameters as Shear Modulus and Poisson's Ratio for a soil sample can be calculated directly from a knowledge of the density, compressional wave velocity and shear wave velocity, a simple, reliable acoustic test procedure was developed that permits determination of these parameters in standard triaxial, laboratory sand samples.

**Test Program**

The test method itself is a direct transmission, pulse technique which employs low-strain (probably less than $10^{-6}$ Horn (1980)) acoustic transducers mounted in the top and bottom caps of a standard triaxial sand sample. The transducers used initially in the testing program were capable of operating in only the compression mode. Eventually a second set were designed and built, as part of the test program, that were capable of operating in both the compression and shear modes.
Three laboratory reconstruction techniques known to produce different, but repeatable fabric arrangements were used to mold the test samples. The techniques selected had been previously shown to produce significant differences in resistance to liquefaction.

Thus, any differences in the observed acoustic behavior of the test samples would provide a basis for a fabric-sensitive acoustic signature that could be related to liquefaction resistance.

Results of the test program have indicated that both the compressional and shear wave velocity are affected by the fabric arrangement of sand in a test specimen. That is, two samples of the same sand, prepared by different techniques to the same density, do exhibit different acoustic behavior. Both the velocity and attenuation of the received acoustic signal were found to be related to sample fabric. Cyclic triaxial testing confirmed that there were also significant differences in the resistance to liquefaction of samples of the same sand and density, but different fabric.

Finally, acoustic transducers have been developed which are capable of operating in both the compressional and shear wave modes. These devices have been shown to perform simply and reliably under a number of controlled saturation and stress conditions.

**Future Testing**

The major result of this laboratory test program has been the development of an acoustic technique that is sensitive to the fabric arrangement of a sand. A data base, albeit limited, has been established that provides a means of quantifying and relating by non-destructive methods, the fabric of sand and its resistance to liquefaction.
Future work in this area will include the further collection of laboratory baseline data to better define the relationships of fabric, resistance to liquefaction and acoustic signature. Once this has been accomplished the ultimate goal of developing a field technique capable of accurately determining the fabric and/or liquefaction resistance of in situ marine sand deposits can then be brought into a more clear focus.
CHAPTER II

LITERATURE REVIEW

The propagation of sound waves in marine sediments has been studied extensively by a number of investigators. Some examples of the many excellent papers are those by Gassman (1951), Hamilton (1979), Laughton (1954), Nafe and Drake (1957), Shirley (1975), Shumway (1960), Urick (1974) and Stoll (1974), as well as the reference texts edited by Hampton (1974) and Hill (1963).

Most of this work has been concerned with defining the effect of a number of variables such as porosity, pressure, temperature, presence of air bubbles, and frequency on the compressional wave speed and attenuation of acoustic transmissions. Hamilton (1979) and Shumway (1960) have shown that compressional wave velocity varies in marine sediments with changes in temperature and pressure in nearly the same manner as it does in sea water alone. On a related topic Bell and Shirley (1980) recently reported that variations in compressional wave speed caused by changes in temperature were found to vary as would water alone. They also found the shear wave velocity to be independent of temperature. Richart, Hall and Woods (1970) have shown that the presence of 0.1 percent air bubbles in the sample should reduce the compressional wave velocity by a factor of 4. Hamilton (1971) has developed a relationship between the static bulk modulus (reciprocal of compressibility; see Appendix I) of individual mineral grains and the dynamic frame bulk modulus, as well as an
empirical relationship between this modulus, which he equates to acoustic rigidity, and the porosity of the sample. This work has led to, among other things, the more accurate interpretation of marine geophysical surveys.

It is only recently that the need for similar studies using shear waves has been recognized as being critical to the development of a complete understanding of the behavior of marine sediments. Hamilton (1979), in a recent paper, notes the lack of available shear wave data in comparison to the abundant supply of compressional wave information. Bell and Shirley (1980) also cite the need for more shear wave velocity and attenuation studies.

Geotechnical engineers have also made wave propagation studies. Hardin and Richart (1963), utilized the resonant column method to study elastic wave velocities and attenuation in a variety of soil types, and under a number of different test conditions. They found that both the compressive and shear wave velocities varied with approximately the 1/4 power of confining pressure for dry, saturated, and drained sands with little effect of pre-loading. Hardin and Drnevich (1972) utilized the resonant column test to develop a set of empirical graphs and equations that have been used extensively to predict the shear modulus and damping characteristics of a soil deposit subjected to dynamic loadings.

An extensive literature also exists on the factors which effect the liquefaction resistance of a saturated sand deposit. These include, as identified by Seed (1976), the density or relative density, grain structure or fabric, length of time since deposition, prior stress history, and the value of lateral earth pressure coefficient.
In the following section, some of the variables which have been shown to affect either the so-called acoustic rigidity (defined below), fabric, or the liquefaction resistance of marine sediments are referenced. It is interesting to note that those factors which have been identified by the geophysical community as leading to an increase in the acoustic rigidity of a sediment, are also those identified by the geotechnical engineer as tending to increase the resistance to liquefaction of a sand deposit.

**Acoustic Rigidity**

A term commonly used by the geophysical community to identify the dynamic stiffness of a particular spatial interrelationship of individual soil grains is rigidity. This rather loosely defined, all-encompassing term is used by a number of researchers as the basic descriptor of soil structure. Obviously the rigidity, from an acoustic point of view, and the fabric with its associated resistance to liquefaction, from an engineering point of view, must be inherently related, since they are in the final analysis derived from the same intergranular stress contact mechanism.

Of those variables identified by Shumway (1960), rigidity was noted as contributing the most to the propagation velocity of marine sediments. Biot (1962) and Stoll (1977), in the development of their viscoelastic models, include a number of moduli which characterize the various components of sample rigidity. In general, however, acoustic rigidity has been viewed by the geophysical community as a variable which cannot be accurately controlled or practically determined.
Nonetheless, a number of studies, both quantitative and qualitative have been made in the area of soil structure, which must undoubtedly be related to acoustic rigidity. Collins and McGown (1974) studied the form and function of microfabric variations in natural soils. Using an electron microscope they found little evidence of unique relationships between microfabric features and depositional environment in what they termed undisturbed samples. Taira and Lienert (1979) compared the reliability of various methods of determining the orientation of sedimentary grains. These included magnetic, photometric, and microscopic techniques. They found excellent correlations between the results of all three methods.

Nacci and Taylor (1968), Shirley and Anderson (1975), Franklin and Mattson (1972), and Martin (1965) have all studied the influence of structure on compressional wave velocities in clay soils. In general, they found significant variations in velocity that were dependent on the direction of transmission in oriented clays. Nacci, Wang, and Gallagher (1974) stated that it was reasonable to assume that there is a correlation between strength and acoustic properties.

Biot (1962), Stoll (1979), and Hamilton (1972) have each developed theoretical models which predict the attenuation of sound in marine sediments. They all found energy losses to be dependent on two distinct phenomena. The first mechanism, by which acoustic energy is lost, results from the inelasticity of the skeletal frame. The second, is derived from the motion of the pore water relative to the frame. The majority of the effort in this area has been focused on the frequency dependence of attenuation, with little regard for the method of sample preparation or resulting fabric. As a result,
very little, if any, quantitative information exists on the relationship of fabric, acoustic rigidity and attenuation.

Hamilton (1972) states that dynamic rigidity is a measure of the resistance to shearing forces which tend to move grains. He reasoned that if attenuation is due to energy lost by friction between grains, then rigidity and attenuation should vary because of the same factors. Some of the factors that he cited were grain size, shape, porosity, presence of moisture, and the level of effective stress.

**Sand Fabric and Resistance to Liquefaction**

Inderbitzen (1975), Hvorslev (1949), Richards (1966), and Rosfelder and Marshall (1967) have all studied the causes of disturbance during the sampling process. Inderbitzen (1975) felt that it was impossible to obtain samples offshore without major disturbance. Mori (1976) showed that sand fabrics were extremely sensitive to sample disturbance. Unfortunately, from the literature, it appears that the geophysical community is unaware of the importance of this sampling disturbance.

In fabric studies made by Mulilis (1975), laboratory triaxial samples of the same sand were reconstructed by different methods. This resulted in samples with known and reproducible fabric differences. By comparing these samples at the same density, the number of cycles required to cause liquefaction at a given stress level was found to vary by as much as 100%, depending on the sample fabric.

Mitchell, Chatoian and Carpenter (1976) analyzed these same fabrics with the method of thin rock sections. Using a statistical approach, they found that the predominant long axis orientation of
sand grains varied significantly, but repeatedly with the method of sample preparation.

Sutton et al. (1957) found that compressional wave velocities were highest in those sediments which were slowly deposited, and in those that were older in geologic age. Lee and Focht (1975) showed that "pre-shaking" a soil mass at stress levels considerably below that required to produce failure resulted in fabrics with significantly increased resistance to liquefaction.

Horn (1980) recently reported that the transmission of shear wave energy in a sediment is dependent on the number and types of sedimentary intergranular contacts. He also found by continuously monitoring a sample during a liquefaction event, that the shear waves temporarily disappeared.

Currently, on land, results of Standard Penetration Tests have provided the most reliable tool, to date, for assessing the "liquefaction resistance" of prospective foundation sites (Seed, 1976). The Standard Penetration Test, however, as with most other terrestrial soil exploration techniques, is not easily adapted to the marine environment. It should be noted, however, that an empirical technique does exist for correlating the results of the SPT to the cone penetrometer, which is used more easily offshore.

Wave Propagation Velocity and Elastic Moduli

In general, the shear strength of a soil mass is classically known to depend on the level of intergranular, or effective stress. As a consequence, the related dynamic strength moduli for that soil must be similarly dependent. These same moduli, however, can also be
determined from a knowledge of the propagation velocity of transmitted acoustic energy. Thus, any variations in the level of effective stress, or other factors which affect the shear strength, can be expected to produce a corresponding change in the propagation velocity of that soil.

Hardin and Richart (1963) found that the shear wave velocity of elastic waves in sands varied approximately with 1/4 power of confining pressure. They also reported a decrease in shear wave velocity as the moisture content of the sample increased from the dry condition. In addition, their results indicated that only approximately 40% of the pore fluid was moving with the frame, as opposed to the normal assumption that the entire mass of water was involved.

Seed and Idriss (1970) found that the basic parameters affecting the dynamic shear modulus (Modulus of Rigidity) were mean effective stress, void ratio and shear strain amplitude. Their empirically derived relationship has been used to predict the behavior of soil masses subjected to dynamic loads, such as in the case of machine foundations and nuclear power plants.

Ultrasonic testing was carried out by Stephenson (1978) to determine the dynamic soil moduli of a processed silty clay. He found that the test method was capable of determining soil parameters appropriate for dynamic analysis.

After an extensive literature review, this author has not been able to find any published results on the correlation of dynamic shear modulus and resistance to liquefaction. The test method described herein may eventually provide some information on this potentially valuable relationship.
In summary, a number of very important studies have been reviewed in the areas of sediment acoustics, sand fabrics and resistance to liquefaction. To date, however, the use of acoustics to identify, and relate the fabric of a saturated sand to its resistance to liquefaction has not been reported.

As a result, the testing program, to be described in the following chapters, is a first time attempt at integrating the apriori knowledge of each of these study areas into one integrated test method. It is believed that both the geotechnical and geophysical community should benefit from this investigation.
CHAPTER III

PRELIMINARY INVESTIGATION

At the beginning of the project a number of preliminary tests were performed. These included tests on the sand to determine the necessary index properties, calibration of the preparation techniques to obtain the required sample densities, and a general feasibility study of the proposed acoustic method. The latter included an investigation of the acoustic transducers, along with the required electronic signal generation and processing equipment.

Description of Test Material

The sand used in this feasibility study was obtained from a local aggregate supplier. The results of the sieve analysis are seen in Figure III-1. The $D_{50}$ size (see Appendix I) of the natural deposit was 0.31 mm.

As seen in Figure III-1, only that portion of material passing the #40 sieve (0.417 mm) and retained on the #50 sieve (0.297 mm) was used in reconstituting the samples. The purpose of this procedure was first of all to remove, as a variable in the test procedure, the effect of variations in grain size of the sample. Secondly, sorting the test sand, hereafter referred to as Dover 40-50, resulted in a material that was very similar in size to the sand used in many previous liquefaction studies, Monterrey No. 0. And finally, it had been shown previously by Lee and Fitchen (1969) that medium to fine
FIG. III-1 GRADATION OF TEST SAND
sands, such as the Dover 40-50, would be highly susceptible to liquefaction.

The minimum and maximum dry density (see Appendix I) of the sorted material were found to be 87.7 and 102.8 lbs. per cubic foot, respectively. The sand was a predominantly angular, quartz material with a specific gravity of 2.67.

Description of the Methods of Sample Preparation

For the preliminary investigation two methods of sample preparation shown by Mulilus (1975) to result in as large as 100% difference in liquefaction resistance, at the same density, were used. The fabrics produced by these methods were also studied by Mitchell, Chatoian, and Carpenter (1976). Using the method of thin rock sections they found significantly different, but repeatable differences in the predominant long axis orientation or the two sand fabrics.

The first of these preparation methods was termed pluvial compaction through air, or dry pluviation. Its fabric was found to possess a relatively random oriented distribution of contact planes (Mitchell, Chatoian and Carpenter, 1976). The procedure, as seen in Figure III-2, consists of raining the air-dry sand from a 1000 ml. flask, with holed stopper, held inverted over the test mold. The flask and stopper can be seen in Figure III-3.

Three factors have been shown to affect the density produced in this manner.

1. The size of the nozzle opening: for relative densities from 45 to 65 percent the nozzle opening
FIG. III-2  DRY PLUVIATION SAMPLE PREPARATION METHOD
FIG. III-3 FLASK AND STOPPERS
used was approximately 0.19 inches, and for relative densities from 65 to 80 percent the stopper opening was decreased to 0.12 inches.

2. The speed of rotation: While the sand is being rained into the sample mold the flask is being constantly moved in a circular motion. The faster the rate of rotation the higher the resulting density. With practice it was possible to reproduce the desired density to within approximately ±2%.

3. The height of drop: This variable was reported by Mulilis (1975) to have the least effect on the resulting density. To standardize the procedure, a constant drop of approximately 7" was maintained by constantly adjusting the vertical position of the flask as the depth of sand in the mold increased.

At the end of the pouring process the top surface of the sample was leveled using a small vacuum device that deposited the removed material back into the flask. This procedure resulted in a sample that was approximately 6.9 inches high and 2.8 inches in diameter.

The second preparation method used was termed moist tamping. The fabric study, referred to earlier, found that the moist tamped fabric exhibited a much less random orientation of the contact planes, when compared to that produced by the dry pluviation technique. In fact, a preferred orientation of the contact planes that ranged from 0 to 40° with the horizontal was reported for the moist tamped procedure (Mitchell, Chatoian and Carpenter, 1976). In this method the desired
weight of moist sand is placed in the test mold in layers, each layer being tamped into place with a specially designed tool, as seen in Figure III-4.

Since the tamping of each successive layer tends to further compact the layers below it, an undercompaction technique, as put forth by Ladd (1978), was used to achieve a sample of uniform density. In this procedure the relative density (see Appendix I) of the first layer was purposely reduced by 5 percent to account for the effect of future compactive effort on the layers placed above it. This undercompaction value was then reduced in a straight line ratio for the next layer, assuming a seven layer system. This process was continued such that the final layer was placed with an undercompaction value of zero.

The procedure itself consisted of first filling a beaker with carbon dioxide, adding the desired weight of air dry soil, and then adding enough water so as to produce a moisture content of 8 percent. The sand, carbon dioxide, and water were then thoroughly mixed, poured into the test mold, and the surface roughly leveled.

The material is then compacted using the tamping tool, moving around the surface of the sand in a circular motion. Tamping proceeds until the desired height, and consequently relative density, of the layer is achieved. This height is pre-set using the locking collar on the tool's shaft. The tamping foot was 1.4" in diameter, or approximately 1/2 the diameter of the test mold.

The compacted surface of each layer, except the last one, was then scarified to a depth of approximately 1/4" and the remaining portion of the mold refilled with carbon dioxide, prior to adding the
FIG. III-4 MOIST TAMING TOOL
next layer. The desired weight of material for the next layer was then weighed out, moistened, mixed and added to the mold. The locking collar was repositioned for the next height of drop and the sample tamped into place. In this manner, a sample approximately 6.9 inches in height and 2.8 inches in diameter was prepared.

A third method of sample preparation was used in Test Series II. A description of that procedure will be reserved until Chapter V, where the purpose for this technique will be more clearly understood.

Description of the Testing Equipment

The basic components of the test apparatus used in all of the tests performed in this investigation included a slightly modified version of the standard triaxial cell, acoustic transducers incorporated into the base and top cap of the specimen, a signal source and an oscilloscope. Figure III-5 is a schematic representation of the test apparatus. For the preliminary tests an R-283E, piezoelectric acoustic transducer, manufactured by Massa Products Corporation, was used. The technical specifications of these compressional wave transducers are included in Appendix II.

Two identical pairs of transducers were actually employed in the "pitch-catch" configuration of transmitter and receiver. One pair was used with the soil sample, while the second pair was used in a water standard column for comparison and calibration purposes. The pair used with the soil were permanently potted into the lucite specimen caps with a rigid setting epoxy resin as seen in Figure III-6.
FIG. III-6 ACOUSTIC SENSORS
The signal source used throughout the entire testing program was an Exact Model 506 Sweep/Function generator, as seen in Figure III-7. The special feature of this component was its ability to burst a signal, at the desired frequency, of a pre-determined number of sine wave cycles.

The oscilloscope used in the preliminary investigation was a dual trace Tektronix Model #535, as seen in Figure III-8. It was equipped with a Polaroid camera attachment for photographing and recording signal traces. A black and white positive/negative type film was used in the camera so that enlargements of the original photographs could be made. The enlarged photos were eventually hand-digitized, from which data files were created for future signal analysis and processing on the UNH computer.

Description of the Test Procedure

The very first test procedure used in the preliminary investigation was rather crude in its design, but it did achieve its intended purpose. The R-283E transducers were placed in a container with their long axis horizontal and their radiating surfaces facing each other. The container was approximately 12" wide, by 18" long, by 10" deep. The transducers were embedded in the test sand, which had been randomly poured into the container, to a depth of approximately 6", and then saturated by adding water such that the top of the sand was approximately 2" below the surface of the water.

One of the transducers was connected to the signal generator and the other to the oscilloscope. A sine wave of approximately 225 KHZ was then transmitted into the soil/water mixture from one of the
FIG. III-7 SIGNAL GENERATOR AND DIGITAL OSCILLOSCOPE
FIG. III-8 TEKTRONIX MODEL #535 OSCILLOSCOPE
transducers. Although accurate acoustic measurements could not be made, a very stable signal was being received at the other transducer. Based on this result it was decided to investigate the use of the R-283E transducers under more controlled conditions.

Before the actual acoustic testing could proceed the standard index property tests were performed on the test sand. These included a sieve analysis, maximum and minimum dry density, and specific gravity. In addition, as noted in the discussion of the material, only that portion passing the number 40 screen and retained on the number 50 was used in the preparation of test samples.

A series of tests had to also be performed to calibrate the dry pluviation sample preparation technique. Nozzle openings and rates of rotation were varied until the desired density could be achieved within a reasonable range of variation.

Once the above information had been obtained a preliminary series of acoustic tests were undertaken. Triaxial samples first had to be constructed by one of the two previously discussed preparation techniques. The relative density was allowed to range in this series of tests from 40% to 70%.

After a sample had been constructed to the desired height, the top cap was placed on the sample such that the face of the R-283E was in contact with the upper surface of the sand. An encapsulating rubber membrane (thickness - 0.012 inches), which had been affixed to the base of the triaxial cell, and held by vacuum against the inside of the sample mold during the sample construction, was rolled up around the top cap and sealed against the side of the lucite ring with two or three o-rings.
A vacuum was then applied to the sample such that the mold, which was actually 2 split halves, could be removed. Next the dimensions of the sample were obtained, so that the relative density could be determined.

To accomplish this a gauge reading was first recorded, and compared with an initial reading taken on 7.000" gauge block, as seen in Figure III-9. A comparison of the two readings theoretically permits determination of the height of the sample to 0.001". The diameter of the sample was obtained with a circumferential measuring tape (Pi-Tape) by averaging these measurements along the height of the sample. The sample diameter was also measured to the nearest 0.001".

The weight of the sand in the sample was found as the difference in the weight of the flask before and after constructing the sample. Once the volume and weight were known the dry density, and relative density of the sample could be calculated. It was felt that the density determined in this manner was accurate to the nearest 0.1 pound per cubic foot.

The next step in the test procedure was to assemble the triaxial chamber. Extreme care was taken here to minimize the vibrations to which the sample was subjected. Once the cell had been assembled and filled with deaired water (to a constant height for all tests) confinement of the sample was changed from internal vacuum, to an external pressure on the cell water. The control board, seen in Figure III-10 was used throughout the test program to control flows in and out of the triaxial chamber and sample, seen in Figure III-11.
FIG. III-9 INITIAL HEIGHT MEASUREMENT USING GAUGE BLOCK
FIG. III-10 TRIAXIAL CHAMBER FLOW CONTROL BOARD
FIG. III-11 SAMPLE IN TRIAXIAL CHAMBER
Carbon dioxide was then percolated through the sample for approximately 15 minutes, shut off for 5 minutes and then started again for 10 minutes. The reason for trying to have carbon dioxide in the void space in the sample rather than air, whenever possible, is that the carbon dioxide is some 10 times more easily compressed into solution with water than is air. Thus, later on in the procedure, when the final saturation process is undertaken any remaining gas in the voids will be carbon dioxide, and therefore more easily forced into solution.

Next, deaired water was allowed to flow into the sample. It was found later in the test program that this part of the procedure is very critical to obtaining a high degree of saturation in the sample. The process must be carried out at a very slow rate of flow, and for a significant period of time, particularly at the higher densities. It was felt that a minimum of 8 hours was required in many cases in order to be sure that all of the gas in the sample had been replaced with water.

Once a sufficient amount of deaired water had been flushed through the sample, the next major step in the saturation procedure was to apply an internal, or back pressure (see Appendix I) to the pore water of the sample. The purpose of this was to force any remaining gas in the sample into solution in the pore water as discussed above, thereby causing all of the sample voids to be completely filled with water.

To apply this back pressure the sample was first connected to a volume change device designed by Chan and Duncan (1966). This apparatus, seen in Figure III-12, includes a pore water pressure
FIG. III-12  B-VALUE MEASUREMENT DEVICE
transducer and a series of valves that permits one to apply and measure, in addition to volume change, the chamber pressure and pore water pressure with the same transducer. This permits very accurate determination of the B-value (see Appendix I) of the sample, which is a measure of the degree of saturation of the test sample.

A back pressure of 40 psi (all values reported are gauge pressure) was used throughout the entire testing program in combination with a confining pressure of 50 psi on the chamber. This resulted in an effective stress of 10 psi on the sample. This back pressure was applied for approximately one hour for the preliminary series of tests.

At the end of this time period the B-value of the sample was checked, and if found to be satisfactory, the acoustic signature of the sample could then be determined. Eventually this procedure was reversed, as the ability of the compressional wave to be transmitted through the sample became a non-destructive indicator of whether the back pressuring process had been carried out for a sufficient period of time. This will be discussed in greater detail in Chapter VII.

To obtain the acoustic signature of a given sample the top transducer was first connected to the signal source to act as a transmitter. The lead for this transducer had been brought out of the base of the chamber through a hole that had been drilled for this purpose. The lead was sealed into the base with a rigid setting epoxy.

A gated sine wave of 5 cycles with a frequency of approximately 236 KHz was then transmitted into the sample from the signal generator. The transducer mounted in the base cap of the sample received the
incoming signal after a period of time had elapsed that represented the time-of-flight of the acoustic wave in the test sample. The two signals were then recorded on film with the Polaroid camera attached to the oscilloscope. Figure III-13 shows a typical transmitted and received pulse replica.

Once the acoustic portion of the test had been completed the sample was either allowed to consolidate for future testing, or the pressures were reduced and the sample removed from the chamber.

Results of Tests

The results of the preliminary series of twenty five tests were for the most part qualitative in nature. However, a value of approximately 1600 m/sec was determined for the compressional wave velocity in the saturated samples. Since the ability to measure time-of-flight was rather limited with the Tektronix oscilloscope, all samples tested in this group were recorded as having a similar velocity. It was felt that as the density increased the velocity increased, but this could not be supported by actual measurements.

A check on the compressional wave velocity in a column of deaired water of dimensions similar to that of the test sample resulted in a velocity of approximately 1500 m/sec. This value was in agreement with the generally reported compressional wave velocity of sea water, and provided an encouraging check on the basic measurement technique. This procedure will be discussed in greater detail in the next chapter.

The remaining results of the preliminary series of tests indicated that there appeared to be a relationship between the shape of the envelope of the received signal and the method of sample preparation,
FIG. III-13 TYPICAL TRANSMITTED AND RECEIVED PULSE REPLICA
as seen in Figure III-14. The moist tamped samples appeared to be more symmetric about a central vertical axis, while the dry pluviated fabric appeared to reach a maximum value of signal strength more quickly, and then decay for a longer period of time.

There were also differences observed in the maximum peak-to-peak strength of the received signal, or alternatively the attenuation, which seemed to vary with the method of preparation and the sample density. In most cases it appeared that the attenuation decreased as sample density increased.

Perhaps the most important result of these early tests was the information learned about the relationship of sample saturation and signal attenuation. Below a B-value of approximately 0.85 a received signal could not be detected at even the most sensitive scale on the oscilloscope. For larger B-values as the percent saturation of all samples increased the attenuation decreased. As a result, a B-value of 0.93 was adopted as a minimum acceptable level in these early tests. As testing proceeded, and the ability to saturate test samples improved, this value was increased. In addition, it was felt that the attenuation of the acoustic wave was also related to the level of effective stress in the sample, with increasing effective stress resulting in decreased attenuation.

Some final observations included the strong dependence of attenuation on signal frequency, the relative insensitivity of velocity to changes in frequency, and the seeming lack of dependence of either on temperature, although the latter was not varied by more than a few degrees centigrade. It should be noted that the acoustic signals were very stable in time, and that measurements could be repeated at
a) DRY PLUVIATED

b) MOIST TAMPERED

FIG. III-14 SHAPE OF RECEIVED SIGNAL ENVELOPE
many hours of separation, so long as no gross differences in the test environment existed.

Discussion

From the preliminary series of tests, the proposed acoustic method seemed at the very least, feasible. The R-283E transducers behaved as expected, the electronic components provided stable, relatively accurate time measurements within their design limitations, and test samples of known density and fabric had been constructed, saturated, and tested at known levels of effective stress.

Improvements in the measurement of time-of-flight, signal attenuation, and temperature were needed to make a more quantitative analysis, however. While investigations were being carried out to determine the best approach to solving these instrumentation problems, a series of tests were run to verify the validity of the acoustic test procedure, and further add to the somewhat limited data base. These will be discussed in the following chapter.
CHAPTER IV

TEST SERIES I

Before continuing with the test procedure as outlined in the previous chapter, a number of tests were performed to identify what, if any, effect the components of the test apparatus such as the triaxial chamber, cell water, and rubber membrane were having on the acoustic transmissions in the test samples. These other potential travel or multipaths were isolated systematically in order to determine whether they were contributing to the received signal. So long as they did not interfere with the direct arrival their effect could be ignored.

In addition, another series of tests were performed just as in the previous chapter. The received signals from these tests were analyzed using an existing signal processing software package made available by the Earth Sciences Department at the University of New Hampshire. This provided a quantitative description of the attenuation characteristics of the two methods of sample preparation.

Description and Results of Tests Performed to Determine the Acoustic Response of the Test Apparatus

In an effort to determine whether "multi-path" effects were contributing to the acoustic response of the test samples a series of tests were carried out to determine the operating characteristics of the test apparatus.
The first series of these were performed by placing the R-283E transducers in close proximity to each other separated only by thin films of light grease, deaired water, and common dishwashing liquid. The result, in all cases, was a very time stable acoustic signature, which did not change from day to day. The only variation was seen when hand pressure was applied to the transducers, thereby changing the thickness of the thin film, and consequently the transducer separation.

The acoustic response of this configuration, with deaired water, as the coupling medium was adopted as the so-called "system response". This procedure was used to check the stability of the electronic components at the start and finish of all tests in this series. No changes in the system response were found in any of the tests of this series, or for that matter throughout the testing program.

The next series of tests were run to determine the acoustic response of the rubber membrane used to encapsulate the sample and separate it from the cell fluid. The membrane was first attached to the two end caps using the O-rings as in the previous chapter. It was then filled with CO₂ such that the two R-283E transducers were separated by a gas sample similar in dimensions to the sand specimens. The top transducer was supported by attaching the lead to a ring stand. A signal could not be detected at the receiver in this manner.

The membrane was then filled with deaired water. The response was a time-delayed signal which was very similar in frequency content to the control water column used in the soil sample testing procedure. A possible effect of the membrane was seen as a very small "ringing" long after the direct transmission was received.
The final series of tests were designed to analyze the effect of the plexiglass triaxial chamber itself. With the membrane filled with deaired water, the chamber was put in place. No change in the signal was observed. The chamber was then filled with deaired water, surrounding the membrane as in the soil tests. A very small amplitude "signal" was observed between the end of the transmitted signal and the arrival of the direct transmission. This result was thought to be an artifact of this special test program since nothing similar was observed in the normal testing procedure.

As a result of these tests it was concluded that multi-path effects were not contributing in any significant manner to the acoustic response of the test samples.

Description of the Testing Equipment

The only addition to the test apparatus described in Chapter III was a frame used to support the previously mentioned water column standard. This device provided a time invariant medium in which the velocity and attenuation of the compressional wave should be essentially constant.

As seen in Figure IV-1 the frame basically consisted of a metal base plate, support platform and adjustable top plate. A lucite cylinder with the same dimensions as the triaxial test sample was placed on the support platform, and filled with deaired water at the start of each test. A pair of R-283E transducers, identical to those used in the triaxial chamber, were mounted at the two ends of the cylinder. The bottom one was epoxied into the lucite cylinder, while the top one was free to be positioned at the same separation from its receiver as in the test sand.
FIG. IV-1 WATER COLUMN STANDARD FRAME
Description of the Test Procedure

Samples in this test series were prepared by the two methods of sample preparation, dry pluviation and moist tamping, as described in Chapter III. The samples ranged in relative density from 45% to 65%.

At the start of each test in this series the system response was recorded with a positive/negative type Polaroid film. As described above, this acoustic record was obtained by placing the two transducers in direct contact with each other using deaired water as the coupling agent. This procedure was termed pre-calibration. These same transducers were then used to determine the acoustic signature of the soil sample. At the end of each test, a post-calibration signal was also recorded for the same system response procedure. None of the settings on the signal generator or oscilloscope were changed during the test procedure, except for changes in scale. In this manner it was believed that any instability, or changes in the performance of the acoustic system, would be detected.

A further means of insuring that the acoustic system was performing properly a signal from the water column standard was also recorded on film, immediately after each soil sample was tested.

Results of the Test

For all samples tested in this series, and in fact for all tests using the R-283E transducers, the pre-calibration and post-calibration signals were identical for a given sample, and from day to day. Figure IV-2 represents a typical system response. The top signal is the input at a scale of 10 volts/cm, and the bottom is the received at a scale of 1 volt/cm.
FIG. IV-2 SYSTEM RESPONSE REPLICA
Results of the water column standard revealed a velocity in all tests of approximately 1500 m/sec for the deaired water. The temperature of the water, which represented room temperature, ranged from 23°C to 29°C. In Figure IV-3, a typical water column trace, the top signal as in all photos, is the input at 10 volts/cm and the bottom is the received at 1 volt/cm. The time scale was 0.2 millisecond per centimeter with a sweep magnification of times 10. By determining the number of units along the time axis (approximately 5.6 for Figure IV-3) between the start of the input and the start of the received pulse, and by knowing the separation of the transducers the velocity can be calculated to within ±20 m/sec.

In an attempt to obtain more accurate, quantitative information on the effect sample fabric might be having on the acoustic transmissions of this test series, the energy content of the signals was also investigated.

To make use of an existing UNH Earth Science signal processing software package, the analogue traces of the Polaroid photos had to be first converted to a digital record. As mentioned in Chapter III, a positive/negative type film was being used to record the oscilloscope trace. From the negative portion of the film, enlargements to a 11" x 14" format were obtained.

A digital record of the trace in question was then created from the enlarged photos by hand measurement. The values of each peak and valley were scaled from a line drawn horizontally through the apparent center of the signal.

Once this digital information had been obtained it was combined, through one of the software routines, with a knowledge of the driving
FIG. IV-3 TYPICAL WATER COLUMN TRACE
frequency of the acoustic system to produce a data file for each trace.

Each data file was first verified by plotting back the digital record to see if it matched the analogue signal. Figure IV-4 is a typical computer plotted replica of the photographed trace. If any corrections in the data file were needed, the changes were made.

Once the data file had been verified, the Fast Fourier Transform was calculated using the SPECTR routine from the above referenced software package. The cospectrum of the transformed series was next computed to determine the distribution of energy density with frequency. Since this energy density can be related to the amplitude and acoustic power of the input signal, the maximum values of this computed function were termed the "Peak Power" of the acoustic pulse.

Table I is a summary of the results of this effort for the fifteen test samples of this series. A sample computer plot comparing the peak power values of a typical pre-calibration trace, a dry pluviated also termed poured sample, and a moist tamped sample are shown in Figure IV-5.

From the test results of Table I, Figure IV-6 was prepared showing the calculated peak power values of the samples of this test series plotted against relative density. As can be seen in the figure, for a given relative density the maximum power transmitted by the poured fabric was significantly larger than the moist tamped. Alternately, the moist tamped fabric exhibited a larger signal attenuation than did the poured technique, when samples with the same relative density were compared. It can also be seen, that as the relative density increased, for either preparation technique, the peak power value also tended to increase.
FIG. IV-4  COMPUTER PLOT OF DATA FILE
ENERGY DENSITY \( \frac{\text{Vols}^2}{\text{MHz}} \)

SYSTEM RESPONSE

DRY PLUVIATED
MOIST TAMPED

FREQUENCY, MEGAHERTZ

FIG. IV-5 PEAK POWER COMPUTER PLOT
FIG. IV-6  MAXIMUM VALUE OF DENSITY FUNCTION VS. RELATIVE DENSITY

PREPARATION METHOD:
○ DRY PLUVIATED
△ MOIST TAMPED

NOTE: LINES INDICATE GENERAL TRENDS \( \lambda = \text{CONSTANT} \)
### Table I

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Type of Sample</th>
<th>Relative Density, %</th>
<th>B-Value</th>
<th>Temp. °C</th>
<th>Peak Power $\left(\lambda \frac{\text{volts}^2}{\text{MHz}}\right)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>#25 pre-calibrate</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>280.8</td>
</tr>
<tr>
<td>#25 pre-calibrate</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>283.2</td>
</tr>
<tr>
<td>#25 Poured</td>
<td>45.9</td>
<td>.94</td>
<td>23°</td>
<td></td>
<td>6.37</td>
</tr>
<tr>
<td>#26 Tamped</td>
<td>49.9</td>
<td>.94</td>
<td>23°</td>
<td></td>
<td>4.35</td>
</tr>
<tr>
<td>#29 Poured</td>
<td>63.2</td>
<td>.94</td>
<td>29°</td>
<td></td>
<td>6.24</td>
</tr>
<tr>
<td>#30 Poured</td>
<td>49.8</td>
<td>.97</td>
<td>28°</td>
<td></td>
<td>6.42</td>
</tr>
<tr>
<td>#31 Poured</td>
<td>57.8</td>
<td>.98</td>
<td>26°</td>
<td></td>
<td>5.74</td>
</tr>
<tr>
<td>#32 Poured</td>
<td>53.0</td>
<td>.96</td>
<td>26°</td>
<td></td>
<td>6.63</td>
</tr>
<tr>
<td>#33 Poured</td>
<td>56.3</td>
<td>.96</td>
<td>26°</td>
<td></td>
<td>7.62</td>
</tr>
<tr>
<td>#34 Tamped</td>
<td>65.9</td>
<td>.96</td>
<td>27°</td>
<td></td>
<td>5.25</td>
</tr>
<tr>
<td>#35 Tamped</td>
<td>52.1</td>
<td>.96</td>
<td>28°</td>
<td></td>
<td>4.08</td>
</tr>
<tr>
<td>#36 Tamped</td>
<td>52.1</td>
<td>.96</td>
<td>29°</td>
<td></td>
<td>4.10</td>
</tr>
</tbody>
</table>
The scatter seen in the results of the poured technique were felt to be the result of the inherently more random nature of this preparation technique as compared to the moist tamped. This tendency was seen throughout the entire testing program.

Discussion

By applying a simple "Rank Test" it was determined that there was less than one chance in 250 that the observed ordering was due to a random process. Thus, it was concluded that there were significant differences in the attenuation characteristics of the compressional wave for the two sample preparation techniques used in this test series.

In an attempt to explain why the moist tamped fabric was exhibiting these larger values of attenuation it was first noted that Mulllis (1975) found the moist tamped fabric to be more dynamically rigid than the poured, in terms of its resistance to liquefaction. A more rigid fabric must be the result of an increase in the number and area of interparticle contacts, or in other words, an increased area of frictional resistance, all other things being equal.

It is this increased frictional resistance of a particular fabric which must also lead to an increase in the energy dissipation or attenuation of a transmitted acoustic signal. Consequently, one would expect, that a more dynamically rigid fabric such as the moist tamped, would exhibit a greater attenuation than the less rigid, poured technique. This line of reasoning assumes the dominant cause of wave-energy damping in the saturated sand to be the result of intergrain friction and not viscous losses due to relative motion of
the pore fluid with respect to the frame. Hamilton (1972) used a similar approach in explaining the effect of mean grain size on dynamic rigidity and related signal attenuation.

Although the results of Test Series I indicated that compressional wave attenuation and the associated test method provided a reliable acoustic indicator of fabric, it was felt that the velocity portion of the acoustic signature would be even more sensitive to these differences. In order to obtain the necessary time-of-flight information, however, certain changes in the test equipment and procedure had to be made before testing could proceed. These will be discussed in detail in the next chapter.
It has been shown from elastic theory that the compressional wave and shear wave velocity of a sediment can be related to the elastic constants of shear modulus, \( G \), dynamic Young's Modulus, \( E \), and Poisson's Ratio, \( \nu \), by the following equations:

\[
\text{Young's Modulus } E = \rho V_c^2 \frac{(1 + \nu)(1 - 2\nu)}{(1 - \nu)}
\]

\[
\text{Shear Modulus } G = \rho V_s^2
\]

\[
\text{Poisson's Ratio } \nu = \frac{1 - 1/2 (V_c/V_s)^2}{1 - (V_c/V_s)^2}
\]

where:

\( \rho \) = mass density

\( V_c \) = \( P \) or Compressional wave velocity

\( V_s \) = \( S \) or shear wave velocity

It can be seen from these equations that if one can obtain the two wave velocities and the density of a particular soil sample, that all of the above elastic parameters can be determined. Although no quantitative relationship is known to exist between these parameters and the resistance of a saturated sand to liquefaction, it is obvious that they must be directly related. Albeit, the level of strain at which such elastic parameters are determined (probably less than \( 10^{-6} \) for acoustic transmissions) is significantly different from that experienced during liquefaction.
In this series of tests, precise velocity measurements were made for the first time in the test program. Through the use of an additional acoustic device and a digital oscilloscope, both the dry and saturated compressional wave velocities were obtained for two different methods of sample preparation. In addition, a number of previously reported results, concerning the effect that varying such parameters as confining stress, and moisture content would have on the compressional wave velocity and attenuation, were also investigated.

Description of Methods of Sample Preparation

At the completion of Test Series I it was recognized that the poured method of sample preparation resulted in a rather significant level of scatter, at least as compared to the moist tamped technique. The cause of this scatter was thought to be the result of variations in the intensity of the sand rain, or to a lesser extent, in the height of drop.

In an attempt to standardize the dry pluviation technique a number of tests were run using a lucite cylinder, some 3 feet in length, that contained a series of screens, which extended across the inside diameter of the tube. The idea behind this apparatus, was that by passing through the series of screens, all of the sand exiting the cylinder would be falling at a constant velocity. The bottom screen in the device was located approximately 20 inches above the top of the test mold. This separation was chosen since Mulilis (1975) reported that above it the height of drop had no effect on the sample density.
A number of techniques were tried for pouring the sand into the lucite cylinder. This proved to be the critical factor in the procedure, since it was found that if the rain of sand was not uniform across the diameter of the sample, such that the sand surface being deposited was maintained level, that significant variations in the density of the sample were found from top to bottom. Eventually the method had to be abandoned, since consistent results could not be obtained.

Based on the insights gained from the above effort, however, a second pouring technique was developed for the tests of this series. The method, termed high-frequency-vibrated/poured or HFV/P was similar to one shown by Mulilis (1975) to produce intermediate results in terms of resistance to liquefaction, as compared to the dry pluviated and moist tamped procedures. It was assumed that the degree of preferred orientation of the contact planes in the HFV/P fabric would fall somewhere between the random nature of the dry pluviated, and the strongly horizontal character of the moist tamped.

For the HFV/P method, instead of rotating the 1000 ml. flask by hand, as in the dry pluviation method, the flask was placed inverted into a laboratory ring stand, fixed approximately 15 inches above the base of the sample. The rain of sand from the flask was directed into the center of the sample mold as seen in Figure V-1.

As the sample height was increasing, a high frequency vibration was applied circumferentially to the outside of the split mold. A vibro-engraver tool, seen in Figure V-2, was used to produce the vibration. The stopper opening was varied to achieve the desired density in this method. Samples were easily constructed that ranged in relative density from 40 to 80 percent.
FIG. V-1 HFV/P SAMPLE PREPARATION METHOD
FIG. V-2 VIBRO ENGRAVER TOOL
The development of this technique was necessitated by the inclusion of a third acoustic sensor mounted inside the test sample. It was felt that the previously used tamping procedure would dislodge and/or damage this new sensor. This device will be discussed in detail in the next section.

Description of the Testing Equipment

The additional acoustic sensor was a delta shear wave accelerometer manufactured by B & K instruments. The technical specifications of this device are included in Appendix II. The accelerometer was mounted inside the sample, attached to the base, with its sensitive axis in the horizontal direction, 0.47" above the upper surface of the bottom cap and R-283E transducer.

Figure V-3 is a schematic representation of the location of the three acoustic sensors used in this test series. The actual device can be seen in Figure III-6. The R-283E transducers were the same as those used in the previous test series. The output signal of this device was first amplified using a B & K Charge Amplifier, Model 2635.

As a result of an in-depth investigation to determine the best method for accurately determining the travel times of acoustic pulses in the test samples, it was determined that a digital oscilloscope would provide the most feasible option. The one obtained, the Explorer III Model which can be seen in Figure III-7, is manufactured by the Nicolet Instrument Corporation.

This digital oscilloscope, with the 204-2 high speed plug-in, has the ability to convert from analogue to digital record at a
FIG. V-3 SCHEMATIC OF ACOUSTIC TRANSDUCER LOCATIONS
maximum sampling rate of 50 nano seconds. This extremely fast rate
was needed due to the relatively high frequency of the acoustic
pulses being transmitted. Expansion of the X and Y scale to 64 times
the original size permit very accurate analysis of time and voltage.

The Nicolet oscilloscope also has a floppy disk memory with
32K capacity for permanently recording the digitized signal. This
feature permits the recall and further analysis of stored data at any
time in the future.

Additional features of the unit are its ability to output a
digital record to a flat bed plotter, and interface with mini-computers
such as the UNH Civil Engineering Tektronix 4061.

The final equipment-related effort was an attempt to design a
pair of shear wave transducers that could be incorporated into the
two sample end caps, thereby eliminating potential problems associated
with the accelerometer being located inside the sample. Working with
a radial expander, piezoelectric crystal manufactured by Transducer
Products, Inc., a number of configurations were attempted.

The crystals, which were 1/4 inch in thickness and 2.8 inches
in diameter, were positioned at the top and bottom of the test sample,
just as in the case of the R-283E compressional wave transducers. A
number of materials, including glass and aluminum, were used to
promote coupling of the shear wave in the test sand, while protecting
the actual crystal from being in direct contact with the saturated
soil sample. None of these designs resulted in a workable system.
As a result, it was decided that additional expertise would be sought
in this area. For the interim, tests would be conducted using the
three acoustic sensors previously described.
Description of the Test Procedure

With the addition of the digital oscilloscope to the test equipment, a number of minor changes were required in the test procedure described in Chapter IV. First of all, the system calibration traces were eliminated, since the previous tests had demonstrated the stability of the components. Furthermore, since each digital record contained the transmitted, as well as the received pulse, any variation of the input, from test to test, could be determined during future signal processing.

It should be noted, as indicated some unsuccessful tests carried out between Test Series I and II, that any remaining film of dishwashing liquid, used as a coupling agent in the system response, resulted in samples which could not be saturated to a satisfactory B-value.

A second change in the test procedure was the addition of a layer of sand grains to the radiating face of the transmitting R283-E transducer. This was accomplished by applying a thin coat of epoxy to the existing window surface, and then applying a sufficient amount of the test sand so as to essentially provide a one grain thick layer.

The purpose of this procedure was two-fold in design. First, it was felt that the sand layer would improve coupling of the transmitted signal into the test sample. Secondly, it was hoped that this improved coupling would result in a mode-conversion of the compressional wave signal to a shear wave at the window/soil boundary. If this did occur it was felt that the extremely sensitive delta shear wave accelerometer would be able to detect its transmission. After a
significant testing and analysis effort in this area it was found that such a conversion was not taking place, at least at a level detectable with the available test equipment. This will be discussed in greater detail in the following section on Test Results.

A number of preliminary tests, similar to those described in Chapter IV, were also performed to determine whether there were any contributions from multipath effects in the received signal of the shear wave accelerometer. None were found in the first arrival, other than transient vibrations produced by background noise in the laboratory.

The actual test procedure of this series began with the construction of a test sample by either the dry pluviated or HFV/P technique. The sample was next placed under vacuum, and its density determined as described previously. The samples of this series ranged in relative density from 40 to 80 percent.

Unlike the previous test procedures, before beginning the saturation process, an acoustic signal was transmitted into the dry sand sample from the top R-283E transducer. Using the bottom R-283E a signal could not be detected to the limit of sensitivity of the digital oscilloscope. The driving frequency of the pulse being transmitted was approximately 9600 HZ.

Switching from the lower R-283E to the shear wave accelerometer, a stable signal was received. Obviously an acoustic pulse was being transmitted through the dry sand in both instances, it was just that the increased sensitivity of the shear wave accelerometer was required to detect it.
Using the digital oscilloscope, the time between an easily identified reference point in the transmitted pulse, and a similar characteristic point in the received pulse can be very accurately determined. If these reference points are chosen, as seen in Figure V-4, such that they represent an equal time shift from the true starting point of the signal in both cases, then the difference in time of the two points must represent the time-of-flight of the acoustic pulse in the test sand.

This technique eliminates the difficult problem of trying to determine the exact start of the received pulse. It does however assume that the frequency of the received pulse is the same as the transmitted, but this was verified during subsequent analysis of the test data.

Once this time-of-flight is known for a test sample the velocity can be simply calculated from a knowledge of the path length between the two transducers.

One potential problem with this approach is that it is sometimes difficult to determine whether the received signal is negative or positive going at the start. If the starting direction is not known the time measurement could be in error by one-half of a cycle. This usually occurs when the sample is nearly saturated and under a low value of effective stress. After discussing this problem with a number of experienced acousticians it was agreed that the starting direction of the received pulse was a constant for the given electro-acoustic system. Thus any traces in which the starting direction was not clear could be assumed to have the known starting direction for that acoustic system configuration. The determination of time-of-flight
FIG. V-4  TYPICAL TIME-OF-FLIGHT MEASUREMENT
and velocity throughout the entire testing program were based on this premise. This assumption was supported by the overall consistency of the test results, and their high degree of correlation with similar reported laboratory and in situ values.

The acoustic velocity of the dry test samples were recorded at vacuums of 15 and 19 inches of mercury. These vacuum levels were determined from readings on a 4 in. diameter dial gauge.

Time-of-flight measurements were also recorded with the internal accelerometer during the saturation process. Each time the level, or type of confining stress was changed a signal was recorded. The effect of increasing moisture content and the variation of velocity with effective stress were thus investigated in this manner.

At the end of the first back pressuring period, usually one hour, the B-value of the sample was checked. The minimum acceptable level for this series of tests was taken to be 0.94, with the majority of samples reported herein falling in the range from 0.96 to 0.98. Every effort was made to achieve the highest B-value possible. As mentioned previously, a period of eight hours of flushing deaired water was felt to be a minimum for the higher density samples. Eventually the back pressuring period was also extended, to 24 hours, in an attempt to improve and standardize the test results of this series. It should be noted that the accelerometer's performance was excellent throughout this test series, requiring virtually no maintenance.

Once an acceptable B-value was achieved the bottom R-283E transducer was substituted for the shear wave accelerometer as the receiver of the acoustic transmission. This permitted, for the first time in the test program, the computation of the saturated compressional
wave velocity of a test sample. The water temperature was recorded at this time to the nearest 0.1°C.

The driving frequency was once again the resonant frequency of the R-283E transducer or 235 KHZ.

Results of the Tests

Before the absolute propagation velocity of the compressional wave transmissions of this test series could be computed, any time delays associated with the electronic components or acoustic transducers would have to be taken into consideration. As will be discussed in greater detail in Chapter VII, the calibration scheme indicated that a time correction was not needed for the R-283E transducers.

As a result, the only correction to the raw data of this test series were a path length correction of 0.47 inches, and a volume correction of 1.0 cu in. to account for the presence of the accelerometer inside the test sample. The latter was determined from a measurement of the weight of water that the device displayed. Both of these values were subtracted from the preliminary sample dimensions.

As seen in Table II the dry compressional wave velocity of both methods of sample preparation increased rather significantly with increases in the effective stress for a given test sample. In fact, these increases were nearly exactly in the ratio of the two pressures raised to the 1/4 power.

This ratio has been commonly accepted as a general "rule-of-thumb" relationship for the increase of shear wave velocity with increasing confining stress. This result initially indicated that the acoustic transmissions being received by the accelerometer could be shear wave
Table II

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Preparation Method</th>
<th>Relative Density, %</th>
<th>$V_p$, Dry @15 in. Hg., M/Sec.</th>
<th>$V_p$, Dry @15 psig, M/Sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>73</td>
<td>Pour</td>
<td>74.0</td>
<td>368.1</td>
<td>447.2</td>
</tr>
<tr>
<td>75</td>
<td>HFV/P</td>
<td>65.8</td>
<td>373.8</td>
<td>443.9</td>
</tr>
<tr>
<td>76</td>
<td>HFV/P</td>
<td>65.5</td>
<td>376.0</td>
<td>453.0</td>
</tr>
<tr>
<td>77</td>
<td>HFV/P</td>
<td>87.1</td>
<td>387.0</td>
<td>465.1</td>
</tr>
<tr>
<td>78</td>
<td>Pour</td>
<td>66.9</td>
<td>350.2</td>
<td>420.8</td>
</tr>
</tbody>
</table>
in nature. Later it was determined that the dry shear wave and compressional wave velocity should respond similarly to changes in confining stress (Hardin and Richardt, 1963).

Significant differences in the dry compressional wave velocity can be seen in Figure V-5, when two samples with the same relative density, but different fabric are compared. The differences ranged from 15 to 30 meters per second, with the HFV/P technique exhibiting the more acoustically rigid behavior. Since the dynamic rigidity, as measured by resistance to liquefaction, of samples prepared by a similar vibration technique was shown by Mulilis to be superior to samples prepared by the dry pluviated method, once again an acoustic parameter had been developed which accurately related the fabric of a sand to its dynamic rigidity.

The effect of increasing moisture content on the compressional wave transmission was seen to first result in a decrease in compressional wave velocity in all samples, as compared to the dry results. These decreases ranged from 20 to 50 m/sec.

It was observed that the percent decrease in velocity seemed to be less in the HFV/P samples. Quantitative results could not be accurately determined, however, with the test procedure being used, since the increase in moisture content was not uniform throughout the sample. This qualitative result, however, would seem to indicate that the more rigid fabric was less affected by the presence of moisture.

Eventually, as the level of saturation increase in the sample, the attenuation of the front portion of the signal being received with the accelerometer increased until it was no longer possible to
PREPARATION METHOD:
- O DRY PLUVIATED
- △ H F V / P

FIG. V-5  DRY COMPRESSIONAL WAVE VELOCITY VS. RELATIVE DENSITY
distinguish the starting point of the signal from the background system noise. A number of attempts at improving the signal to noise ratio were unsuccessful.

One important results of this effort, however, was that as the sample became more saturated, changes in effective stress no longer produced variations in acoustic velocity that obeyed the $1/4$ power law. It was this result, that further confirmed that the internal accelerometer was detecting compressional wave arrivals and not shear wave.

The saturated compressional wave velocities of this test series, corrected to a common temperature at $24^\circ$C, are presented in Figure V-6. The temperature correction was based on a formula reported by Wilson (1960) for the variation of compressional wave velocity of water alone. Recently reported test results by Bell and Shirley (1980) indicate that this is a valid approach.

Just as in the case of the dry compressional wave results, the saturated velocities are seen to generally increase with increasing relative density. However, due to the significant scatter in the test results it seems best to conclude that there is very little difference in the saturated compressional wave velocity of samples prepared by either of the two techniques of this test series. The presence of water in the sample voids has obviously tended to reduce the differences observed with the dry compressional wave transmissions.

The most important observation that can be made about the results of Figures V-5 and V-6 is that the saturated compressional wave velocities are some four to five times faster than the dry, despite the fact that the dry velocity was at first observed to decrease with increasing moisture content.
FIG. V-6 SATURATED COMPRESSIONAL WAVE VELOCITY VS. RELATIVE DENSITY

PREPARATION METHOD:
○ DRY PLUVIATED
△ HFV/P
CORRECTED TO 24°C
PREPARATION METHOD:
- ○ DRY PLUVIATED
- △ HFV/P
CORRECTED TO 24° C

FIG. V-6 SATURATED COMPRESSIONAL WAVE VELOCITY VS. RELATIVE DENSITY
This result can be explained by the fact that since in the dry, and partially saturated case, the sand frame is transmitting the acoustic energy. Once a sufficient continuous path of pore fluid is established in the sample however, the compressional wave transmission shifts from the slower frame to the faster water path, hence a compressional wave velocity much closer to that found in the previously reported, water column standard results.

The range of values from 1550 m/sec to 1600 m/sec, and the observed relative difference from the dry results, are in the range of those typically reported for compressional wave studies.

The attenuation of the compressional wave signals of this test series were not analyzed to the same detail as in the previous one. Observations that were made included an increase in the attenuation with increasing moisture content for a given sample, so long as the compressional wave was being carried by the frame. Once the pore water began transmitting the acoustic wave the opposite trend was seen, i.e. the attenuation decreased with increasing B-value.

Comparisons of the level of the attenuation for the two fabrics of this test series with the previous results indicated that the maximum peak-to-peak analogue voltages were similar for poured samples with the same density. The HFV/P and moist tamped technique were observed to result in approximately the same level of signal attenuation. That is, the HFV/P preparation technique produced a fabric that attenuated the compressional wave signal more than the poured when compared at the same relative density. Once again attenuation was observed to decrease with increasing density for both preparation techniques.
The latter result may perhaps be explained by the fact that as the density increased the individual sand grains become packed more closely together. The displacements associated with the transmission of the acoustic pulse from grain to grain should therefore be reduced. Thus if attenuation is directly related to frictional losses in the frame, the smaller displacements should result in less frictional loss, or less attenuation.

Discussion

Based on the dry compressional wave velocity results, samples prepared by the dry pluviation method were found to be slower than the HFV/P samples when compared at the same relative density. This would seem to indicate just as in the previous test series, that the fabric associated with the dry pluviated method resulted in samples of relatively low acoustic rigidity, albeit in this case the HFV/P technique was used as a basis of comparison, not the moist tamped. As noted earlier, a somewhat similar high frequency vibration technique was shown by Mulilis (1975) to produce samples with a liquefaction resistance that was between the dry pluviated and moist tamped preparation methods.

The saturated compressional wave results did not exhibit the same clear behavior as the dry. The scatter in these results may be due in part to the presence of the accelerometer in the transmission path of the receiving R-283E, and/or insufficient saturation of the sample. It may also be that the acoustic rigidity of the saturated HFV/P frame was not that significantly different from the dry pluviated.
The dry compressional wave velocity was seen to behave similar to that predicted for a shear wave in that increasing the confining pressure on a sample resulted in a velocity increase in the sample that obeyed the commonly reported 1/4 power relationship. Increasing the moisture content, on the other hand, resulted in a decrease in compressional wave velocity, until a sufficiently continuous, pore fluid transmission path had been established. Once the compressional wave could be transmitted by a sufficiently continuous pore water path, the velocity increased by approximately a factor of 4.5.

The observed behavior of a sample with respect to attenuation was also consistent with this explanation. Attenuation increased until the compressional wave shifted to the pore fluid path, and then decreased during the final stages of saturation.

Increasing the level of effective stress for a given saturated sample was seen to have very little effect on the compressional wave velocity of either fabric, as is the case for water alone. Decreasing signal attenuation was observed as the effective stress increased, as in the previous test series.

The fact that differences in fabric resulted in relatively small differences in the saturated compressional wave velocity pointed once again to the need for making shear wave measurements in the sand. The latter would obviously always be transmitted by the frame, whether dry or saturated, since the pore water cannot support shearing forces.

A concerted effort was thus undertaken to obtain the necessary shear wave instrumentation. After an extensive investigation of the available equipment, the decision was made to hire a consultant to assist in the design and fabrication of our own acoustic devices.
While the new transducers were being prepared a series of tests were run to verify the relationship between fabric differences and liquefaction resistance for the Dover 40-50 sand. Test Series III was performed to document that the observed differences in the acoustic rigidity of two sand fabrics did correlate with differences in their inherent resistance to liquefaction. These tests will be discussed in the next chapter.
CHAPTER VI

TEST SERIES III

With both the dry compressional wave velocity and saturated compressional wave attenuation proving to be reliable acoustic indicators of sample fabric, the ultimate goal of relating acoustic signature to liquefaction resistance could now be realized. Although Mulilis (1975) had conclusively proven the effect of fabric on the liquefaction resistance of saturated triaxial sand samples, the fact that he had used a different sand and test equipment, created concern about the repeatability of his findings.

As a result, Test Series III was performed where, in addition to determining the acoustic parameters as in the previous tests series, each sample was cyclically loaded to failure in undrained triaxial conditions. The results of these tests provided, for the sand of this test program, the necessary data to relate sample fabric, acoustic signature and resistance to liquefaction.

Description of the Testing Equipment

The major addition to the equipment used in the previous tests series was the cyclic loading device, seen in Figure VI-1. This electro-pneumatic, sinusoidal loading system was designed and constructed by Clarence K. Chan (1976).

The main components of the system are a sine wave generator, a volume booster relay, and a double acting air piston. The latter
FIG. VI-1 CKC CYCLIC LOADER
is connected to a load frame such that it is positioned vertically above the triaxial chamber.

The loader is connected to a Revere load cell, Model UMP1-.25A, which in turn is attached to the top cap of the sample via a loading rod, as seen in Figure VI-2. A double swivel connection is used on one side of the load cell to reduce any eccentricity in the loading.

In addition to the load cell, a Schaevitz Engineering LVDT, Type 1000HR, was connected to the loading ram to measure deformations of the sample.

The output from the LVDT, and load cell was first amplified with the Validyne Model MCI signal conditioner. They were then connected to a Brush Strip-Chart Recorder Mark 280, as seen in Figure VI-3. The pore pressure transducer output was also recorded in a similar manner. Thus, during a liquefaction test, the applied stress, deformation and pore pressure buildup were simultaneously recorded. This permitted the analysis and comparison of the liquefaction characteristics of the test samples of this series.

Description of the Test Procedure

Samples, during the initial testing of this series, were prepared by either the dry pluviation or HFV/P method. The range of relative densities was from 45 to 70 percent. The dry and saturated compressional wave signatures were recorded exactly as in the previous test series.

Once an acceptable B-value had been obtained, which for this series of tests was established as a minimum of 0.97, the final procedure was to determine the sample's resistance to liquefaction.
FIG. VI-2 CYCLIC TRIAXIAL TEST EQUIPMENT
FIG. VI-3 STRIP CHART RECORDER
To accomplish this the sample was first connected to the cyclic loader, through the load cell connector. Next the LVDT was connected and zeroed.

After checking that the loading device and Brush recorders were functioning properly, the cyclic triaxial test was begun by first closing off the back pressure line, thereby establishing undrained conditions for the test procedure. With an effective normal stress, $\sigma_C'$ of 10 psi on the sample, a pre-determined sinusoidal cyclic deviator stress, $\pm \sigma_D$, was then applied via the cyclic loading device. The frequency of the loading was 0.4Hz. This value was selected as being typical of loadings found in nature.

This cyclic loading resulted in a buildup of the pore pressure in the undrained test sample until the increase became equal in value to the initial effective stress, or the effective stress had been reduced to zero. At this point the sample was said to have liquefied, as the deformations became very large. This marked the end of the test procedure.

From an analysis of the strip chart records for the test, the liquefaction resistance of the sample could be simply determined. A typical set of test results can be seen in Figure VI-4. The cyclic stress, $\pm \sigma_D$, was first found by dividing the cyclic load by the area of the test sample. With this information the cyclic stress ratio, $\pm \sigma_D/2\sigma_C'$, could then be calculated. The remaining liquefaction resistance parameter, the number of cycles to liquefaction, was found by counting the number of load cycles required to increase the pore pressure by an amount equal to the initial effective stress, or 10 psi for this test series.
FIG. VI-4  TYPICAL CYCLIC TRIAXIAL TEST RECORDS
The first liquefaction test results were disappointing, in that they exhibited a larger degree of scatter. After a thorough analysis of the test procedure, it was concluded that the presence of the accelerometer inside the sample, was probably producing stress concentrations that caused premature liquefaction of the test sample in that zone.

As further evidence of this problem a poured test was performed with the same sand used by Mulilis (1975), Monterey No. 0. The cyclic stress ratio was approximately 25 percent less than what he reported when compared at the same number of cycles and relative density.

After considering a number of modifications to the HFV/P method including densifying the sand immediately surrounding the accelerometer, it was decided that the accelerometer would have to be removed from inside the sample.

Once this decision had been made, the moist tamped procedure of preparing samples was again adopted, since the concern for damaging the shear wave accelerometer had been eliminated. Further, as Mulilis had not used the HFV/P, the return to moist tamping would provide a better check on the test results.

One other variation of the cyclic triaxial test procedure was included in this test series. As reported by Seed (1976), one of the important factors, in addition to fabric, that effects the liquefaction behavior of saturated sands is the prior stress history to which the sand has been subjected.

To investigate this phenomena, a pair of test samples one moist tamped and the other dry pluviated, were subjected to several
preliminary shocks, before being tested to liquefaction. In each shock, which was intended to simulate the effects of a small ocean storm, a cyclic stress ratio was selected so as to induce a peak pore pressure ratio (see Appendix I) of approximately 50% in five to ten undrained loading cycles. At the end of this procedure, the excess pore water pressure was allowed to dissipate, the volume change was measured, and an updated compressional wave acoustic signature recorded. Five preliminary shocks were applied to each sample, before testing the sample to liquefaction. It should be noted that the increase in relative density produced by this preshaking process was only 1 to 2 percent.

**Results of Tests**

With the internal accelerometer eliminated from the equipment, the acoustic portion of the test results were limited to an analysis of the saturated compressional wave transmissions. To maximize the information which could be obtained in this manner, the velocity and attenuation were both analyzed using the digital records stored on floppy disk with the Nicolet oscilloscope.

The velocity was calculated and corrected to 24°C as in Test Series II. As seen in Figure VI-5, the saturated compressional wave velocity increases with increasing relative density, in a similar manner to that seen previously, for both the pluviated and moist tamped samples. A least squares linear regression line was fit to both data sets to indicate the general trend of the results. Although once again it appears that the frame is not the major transmitter of
FIG. VI-5 SATURATED COMPRESSIONAL WAVE VELOCITY VS. RELATIVE DENSITY
compressional wave energy, the velocity differences are still significant, averaging some 15m/sec faster for the moist tamped fabric when compared at the same relative density. It is important to note that the compressional wave velocity of water alone at 24°C was found to be 1523 m/sec indicating that the structure of the soil does contribute to the propagation velocity of the test samples. The effect of pre-stress can be seen as an increase in velocity for both methods of sample preparation.

In addition to velocity, the attenuation of the saturated compressional wave signal was also investigated. Careful analysis of this parameter, with the digital oscilloscope, revealed it to be very sensitive to even minor variations in B-values, hence the adoption of 0.97 as a minimum for this test series.

As seen in Figure VI-6, the transmission loss in decibels, neglecting spherical spreading which is constant for the transducer configuration, is fabric-related, when plotted against relative density. Just as in Test Series I, the moist tamped fabric exhibits a larger transmission loss, or signal attenuation than the dry pluviated for samples with the same relative density. The input and received peak-to-peak voltages were measured to the nearest 0.01 and 0.001 volt, respectively. The general trend of the results were found from a least squares linear regression analysis.

The effect of pre-stress is once again evident in the results of Figure VI-6. In this case, the transmission loss tends to increase, indicating a more acoustically rigid fabric, for samples with prior stress history. The larger number of samples seen in Figure VI-6, as compared to Figure VI-5, are the result of including some of the
TRANSMISSION LOSS, db

PREPARATION METHOD:
- DRY PLUVIATED
- MOIST TAMPED
- PRE-STRESS

RELATIVE DENSITY, $D_R$, %

FIG. IV-6 COMPRESSIONAL WAVE TRANSMISSION LOSS VS. RELATIVE DENSITY
applicable results of Test Series I in which the velocity was not determined.

As seen in Figure VI-7, the moist tamped samples required larger cyclic stress ratios to produce liquefaction when compared to the dry pluviated at the same number of load cycles. This indicates, as was assumed, that the moist tamped fabric is more dynamically rigid than the dry pluviated. All samples in this test series were reduced to a common relative density of 60% by assuming the standard straight line ratio relationship between cyclic stress ratio and relative density (Seed and Lee, 1966).

With respect to the results reported by Mulilis (1975) the cyclic stress ratios required to produce liquefaction at the same number of cycles in the Dover 40-50 sand ranged from 10 to 20 percent less than for the Monterey No. 0. This indicated a slightly less dynamically rigid sample was being produced by both of the sample preparation techniques.

One possible explanation for this variation, is the fact that the Dover 40 to 50 sand is somewhat finer in size than the Monterey No. 0. Unfortunately, very little information exists in the literature on the liquefaction characteristics of sands other than Monterey No. 0. It was felt, however, that the results obtained were certainly within a reasonable range of experimental error.

The expected correlation between acoustic signature and liquefaction resistance can now be confirmed by comparing the results of Figures VI-5, VI-6 and VI-7. As predicted by both the velocity and peak-to-peak components of the saturated compressional wave signal, the more acoustically rigid, moist tamped fabric was also the more dynamically rigid in terms of resistance to liquefaction.
FIG. VI-7 CYCLIC STRESS RATIO VS. NUMBER OF CYCLES TO LIQUEFACTION
It should be noted that the differences in liquefaction resistance, on a percentage basis, were a great deal larger than the differences in compressional wave velocity. Since the two tests procedures were performed at significantly different strain levels, however, this expected variation in behavior may indicate that there is some minimum, or threshold level of strain required in order to fully mobilize the dynamic strength inherent in a particular sand fabric.

One further comment now seems appropriate on the previously discussed variation of liquefaction characteristics of the Dover 40-50 sand and the Monterey No. 0. A single test value, determined for the saturated compressional wave velocity of the Monterey No. 0 sand, was some 45 m/sec faster, for the appropriate relative density, than the trend line of Figure VI-5. This would indicate that in fact the Monterey No. 0 sand did produce samples with fabrics that were more dynamically rigid than those prepared with the Dover 40-50 sand.

Finally, the effect of stress history on the liquefaction resistance of the two previously discussed samples can also be seen in Figure VI-7. As inferred from the acoustic test results of Figure VI-5 and VI-6, those samples subjected to preliminary shocks showed an increase in their resistance to liquefaction as compared to the virgin samples, which could not be explained by the small increase in relative density. Thus for this case, increases in the acoustic rigidity of a test sample resulted in similar increases in the dynamic rigidity of that same sample when tested to liquefaction.
Discussion

Results of this test series have shown that the acoustic parameters of saturated compressional wave velocity and transmission loss are reliable indicators of the effect of fabric on the acoustic and dynamic rigidity of Dover 40-50 sand. The test procedure confirmed the liquefaction resistance results of Mulilis (1975), and provided insights into the effect of stress history on the acoustic and dynamic behavior of saturated triaxial sand samples.

During this test series, the research and development of a new acoustic transducer that would be capable of operating in both the compressional and shear wave modes was in progress. The results of this effort will be discussed in the next test series chapter.
CHAPTER VII

TEST SERIES IV

In order to more fully characterize the acoustic behavior of the Dover 40-50 sand, a knowledge of the shear wave signature of the test samples was needed in addition to the previously obtained compressional wave results. It was felt that the shear wave would provide an even more sensitive and useful tool than the compressional wave, particularly in the saturated case, for detecting differences in the fabric arrangements of the triaxial sand samples. For instance, one need only review the equations presented in Chapter V to see that once the shear wave velocity is known, the Dynamic Shear Modulus, G, can be directly calculated. The problem was not in realizing the importance of these acoustic measurements, but rather in finding the necessary instrumentation to perform them.

Once the shear wave, and compressional wave velocity have been determined for a sample of known density, the Shear Modulus, the ratio of compressional wave velocity to shear wave velocity, and Poisson's ratio can be calculated as presented in Chapter V. Computation of these parameters have provided the most accurate acoustic-derived indicators of sample fabric, to date, in the test program.

Description of the Testing Equipment

The major addition to the test apparatus of the previous test series was the development of a new acoustic transducer. As was
previously discussed, an initial attempt at designing and fabricating a radial expander type shear wave transducer was unsuccessful. Eventually, the services of an independent consultant, Kenneth Baldwin, experienced in this field, were obtained to research and develop designs for manufacturing, in-house, the necessary components.

Based on a review of some of the more recently reported shear wave studies, particularly those of Shirley (1975), it was decided that a transducer comprised of a series of ceramic bender, or bimorph elements would exhibit the best characteristics for the particular application being proposed.

The ceramic bender element, seen in schematic form in Figure VII-1, is composed of two layers of piezoelectric ceramic, rigidly bonded together, and driven out of phase so that one side is expanding in the length mode while the other is contracting. This produces a bending action similar in character to deflecting the end of a cantilever beam.

The ceramic bender is particularly well suited for use in porous media, such as the saturated sand samples being tested, since it inherently possesses two important operating characteristics. First it has low frequency, wide bandwidth characteristics which tend to minimize attenuation. Second, it has a higher compliance, or impedance match, than other ceramic crystals, which tends to produce better coupling characteristics in the relatively soft soil sediments.

The overall transducer performance can be improved even further, if an array of bender elements is used. The final design of the shear wave transducer, used in this test series, consisted of 4 bender elements, separated by approximately a 1/16 inch air space. The individual crystals were manufactured by Gulton Industries.
FIG. VII-1 SCHEMATIC OF SHEAR WAVE BENDER ELEMENT
Figure VII-2 and VII-3 are a photo and schematic, respectively, of the various components of one of the acoustic transducers fabricated at the University of New Hampshire, Kingsbury Hall Machine Shop. Essentially the transducer consisted of a shear wave and compressional wave crystal seen in Figure VII-4, window material, and two housings, one aluminum, one plexiglass.

The plexiglass housing provided space for the mounting of the piezoelectric crystals. Initially, the aluminum housing was to act as a reservoir for pressure compensating the interior side of the window with a transducer oil. This would be necessary due to the required flexible nature of the window material. The use of the oil was eliminated however, before the tests began. It was replaced with a more simple operating air back pressure procedure. The latter permitted adjustment of the pressure on the interior face of the window to the necessary level required to maintain essentially zero pressure differential across the window, except during the actual cyclic triaxial testing.

The requirement that the window material be flexible so as to transmit the shear wave, yet strong enough to resist small pressure differentials proved to be the most challenging part of the transducer development. Two different flexible-setting silicon compounds were tried. The first, Emerson and Cumming, Inc., Eccosil 4122, was a general purpose RTV silicone rubber. This material could not be adequately bonded to the transducer housing, however. The second compound, Emerson and Cumming, Inc. Eccosil 2CN, was a crystal clear silicone potting compound. With the aid of a surface primer, this material was eventually satisfactorily bonded to the plexiglass housing.
FIG. VII-2 KB-GR TRANSDUCER COMPONENTS
FIG. VII-3 SCHEMATIC OF KB-GR TRANSDUCER
The compressional wave piezoelectric crystals were manufactured by Transducer Products, Inc. These 1/4 inch thick, 1/2 inch diameter disks were designed to operate in a thickness expander mode, just as in the R-283E transducers. The crystal was mounted on top of a pedestal that positioned the radiating face very close to the soil sample. The window thickness at this location was less than 0.05 of an inch.

The resulting acoustic transducers, hereafter referred to as the KB-GR transducers, were thus capable of either transmitting, or receiving, both shear and compressional wave transmissions. For the most part, the design provided a rugged, reliable device that performed satisfactorily throughout all stages of the cyclic triaxial test.

The final addition to the testing equipment of this test series was a simple, small signal, pre-amplifier designed and constructed by the Instrumentation Center at UNH. In addition to the amplification which this device provided, improvements in the signal to noise ratio were also achieved through the bandpass frequency characteristics of the circuit. The amplifier provided a theoretical gain of 100 for all the tests of this series.

Description of the Testing Procedure

Preliminary testing in this series was performed to determine the operating characteristics of the newly constructed transducers. As discussed previously, the majority of the problems that developed were associated with the selection of the proper window material. Once this difficulty had been resolved the transducers basically operated as they had been designed.
The first pair of transducers that were built consisted of a single bender element and the compression wave disk. Although the performance of these devices was satisfactory, it was found that a 4 bender array resulted in a significant increase in amplitude of the received shear wave signal.

The optimum driving frequency for the 4 bender array was found to be approximately 3500 HZ, and for the compressional wave disks 145 KHZ. Time measurements were made as in the previous test series, and signals were recorded with the digital oscilloscope.

As part of the development of the new transducers a series of tests were performed to determine whether a time correction, or calibration factor, was needed to account for any small travel times in the flexible window material, or time delays in the acoustic system. As referred to earlier, the R-283E transducers were also investigated as part of this procedure.

The calibration study was based on the empirically derived equation (see Appendix I) for the compressional wave velocity of water, reported by Wilson (1960), and used previously to correct the compressional wave velocities of Chapters V and VI to a common temperature.

First, the triaxial chamber was assembled and filled with deaired water, just as in all previous tests; the only difference being that the soil sample was omitted from the system. The temperature of the water was next determined, and monitored through the tests to the nearest 0.1°C. The top cap and KB-GR transducer were then positioned at an arbitrary separation from the fixed bottom acoustic device, utilizing the loading ram assembly from the cyclic
trial testing equipment (see Figure VI-2). An initial dial gauge reading was then made on the top of the load ram shaft, and a compressional wave trace was recorded for the deaired water, at the initial transducer separation.

The top transducer was then raised approximately one inch to a new separation, the change in path length recorded to the nearest 0.001 inch, and a second compressional wave signal recorded. This process was repeated a third time. The entire procedure was then repeated with the R-283E transducers. It should be noted that every effort was expended to insure that the test conditions were as nearly identical for the calibration of the R-283E and the KB-GR transducers as was possible.

The resulting test data was then analyzed to determine the time-of-flight for each transducer separation. Since the change in time, corresponding to a pre-determined change in path length, was known, the velocity could be directly calculated. These values were then averaged for each transducer, and compared to the predicted compressional wave velocity of water, corrected to the appropriate test temperature. Any discrepancy in the two velocities would represent the calibration factor needed to correct the test results so that absolute, rather than relative values, could be reported.

Remarkably, both pairs of transducers were found to yield a compressional wave velocity for the deaired water that was within 5 m/sec, or 0.3% of the predicted value. As a result of this finding, the small variation, which could have been a result of measurement errors in the calibration procedure itself, was assumed to be negligible, and thus no correction was made to the time measurements determined
with the KB-GR, or the R-283E transducers. It should be noted that this error, if it exists, is systematic (always of the same sign) in nature and not accidental. Thus it would not produce random results that would tend to interfere with interpretation of the test data.

An analogous calibration procedure was used with the shear wave crystals. Instead of deaired water, a standard, medium-size Ottawa silica sand was used to prepare a sample, of progressively increasing height, by the dry pluviation method. The sample was rained into the split mold as in previous tests, with the exception that the encapsulating membrane was omitted. This resulted in a sample that was being tested in an unconsolidated state.

Time-of-flight measurements were made and recorded, as in the previous tests, for three sample heights by stopping the pouring process and simply resting the top KB-GR transducer on the sand surface. The sample height, or path length was measured to the nearest 0.001 inch, and the time was recorded for the nearest 0.001 millisecond.

From this data a plot of time versus distance (as seen in Appendix III) resulted in a very accurate straight line relationship, and corresponding time intercept for zero path length of essentially zero. Thus it was concluded that a time correction was not required for the shear wave electro-acoustical system. The inverse slope of the above plot resulted in a velocity of 103.4 m/sec for the unconsolidated Ottawa sand prepared by the dry pluviation method.

The final shear/compression wave testing procedure consisted of first preparing triaxial samples of Dover 40-50 sand by either the dry pluviated or moist tamped technique, as in previous tests. Once
prepared the sample was then placed under a vacuum of 4 in. Hg, the split mold removed, and the sample density determined.

With the addition of the KB-GR transducers to the testing equipment it was once again possible to make acoustic measurements in the dry sample. Shear wave signals were thus recorded for each sample at 4 in., 10 in., and 15 in. Hg. This procedure provided information on the variation of acoustic signature with confining stress, as well as the shear wave velocity and attenuation.

After checking that there were no vacuum leaks in the sample, the triaxial chamber was then assembled, filled with deaired water and pressurized to 2 psi. The vacuum was then removed from the sample.

To reduce the pressure differential on the window material of the transducers, the same vacuum that was being applied to the sample was also applied to the transducer housing. When the sample was subjected to the confining stress of 2 psi, a 1 psi backpressure was applied to the transducer thereby reducing the stress on the window to what was found from preliminary tests to be an acceptable level.

A dry shear wave record was made of the sample at this point in the test to determine what effect pre-stressing of the sample to 15 in Hg, and assembling the triaxial chamber might have had on the previously recorded signature.

The saturation process was then begun by flushing CO$_2$ through the sample as in all previous tests. Deaired water was then allowed to flow into the sample at a very slow rate. A shear wave signal was generally recorded at the time the water began exiting from the top of the sample, usually one hour after the water first entered the sample base.
The deaired water was flushed through the sample for a period of from 8 to 16 hours. During this time visual observations of the change in received shear wave velocity and attenuation were made.

To determine whether the sample had been adequately saturated the shear wave signals were replaced with the more saturation-sensitive, compressional wave transmissions. The relative level of signal attenuation was found to be a very good, non-destructive indicator of whether the sample had been flushed with deaired for a sufficient period of time. If a well-defined signal could not be detected the flushing process was continued.

Once a significant compressional wave arrival was detected with the KB-GR transducer, a shear wave signal was recorded for the nearly saturated sample at the confining stress of 2 psi. This provided data on the effect saturation of the sample was having on the shear wave signature. The B-value device was then connected to the sample and the back pressuring process began.

To accomplish this, the chamber pressure was increased to 50 psi and the back pressure on the sample and the transducers to 40 psi, in 5 psi increments. The final effective stress of 10 psi represented the highest level of effective stress that the sample had experienced at any time during the test.

Both the shear wave and compressional wave signals were then recorded at the effective stress level of 10 psi. The sample was then allowed to "age" under these stress conditions for a period of approximately 24 hours, as in previous tests.

At the end of this back pressuring period the B-value of the sample was determined, and a saturated shear and compressional wave
signal recorded. The pressure on the soil and transducers were then slowly decreased in 5 psi increments, and the sample removed from the chamber.

To determine the effect of stress history on the saturated shear wave velocity a limited number of cyclic triaxial tests were run during this test series using essentially the same procedure as in the previous chapter. The pore pressure was slowly built up in the undrained test sample to a level equal to approximately one-half the initial effective stress, or for these tests 5 psi, in 5 to 10 cycles of pre-determined loading.

At the end of each load cycle a shear and compressional wave signal were recorded and analyzed to determine the effect of pre-stressing on the acoustic signature of the sample. A total of five load cycles were applied before loading the sample to liquefaction.

The pressure on the transducer housings was first increased at the start of the cyclic triaxial test by 5 psi above the back pressure present in the undrained samples. This was done in anticipation of the pore pressure increase that would develop on the sample side of the window as a result of the applied cyclic load. This procedure was found to be satisfactory for the pre-stress cycles as well as the final load cycle in which the sample was liquefied.

Results of the Tests

The use of the KB-GR transducers permitted, for the first time in the test program, the determination of shear wave velocity in the test sample before and after saturation. As seen in Figure VII-5, the so-called "dry" shear wave velocity results, determined at
PREPARATION METHOD:
- O DRY PLUVIATED
- □ MOIST TAMPED

CONFINING STRESS = 2 psi

FIG. VII-5 DRY SHEAR WAVE VELOCITY VS. RELATIVE DENSITY
the confining stress of 2 psi, were very similar for the two methods of sample preparation, dry pluviation and moist tamping. A small increase in velocity can be seen with increasing relative density.

In analyzing these results it must be realized that, in fact, the samples produced by the moist tamping procedure are obviously not dry in the same sense as the pluviated. Rather, they possess a moisture content of 8 percent, from the moment the sample is first prepared.

To determine whether this seemingly small moisture content was affecting the shear wave velocity, one of the first moist tamped samples, was "dried out". By opening the bottom drain line to the atmosphere, and pulling a small vacuum through the top drain line, dry room air was circulated through the sample for a period of 48 hours. The shear wave velocity increased 50 m/sec, or 25% at the end of this time period. Similar results were reported by Hardin and Richart (1963). They reported that a moisture content of as low as 1.6 percent significantly reduced the shear wave velocity of sand samples. If the velocity of the moist tamped samples was corrected to an air dry condition, assuming a 25% increase, they would obviously plot significantly above the dry pluviated specimens.

Significant differences in the saturated shear wave velocity, can be seen in Figure VII-6, which are dependent on the fabric of the test sample. The results were determined at an effective stress of 10 psi. The dry pluviated group show increasing velocity with relative density, ranging from 140 m/sec to 180 m/sec, while the moist tamped exhibit significantly faster, albeit less variable velocities, ranging from 205 m/sec to 215 m/sec.
Figure VII-6 shows the relationship between saturated shear wave velocity and relative density. The preparation methods used were dry pluviated and moist tamped. The effective stress was 10 psi. The graph indicates a positive correlation between shear wave velocity and relative density.
In order to compare the results of Figures VII-5 and VII-6 the effect of increasing moisture content, and effective stress must first be separated. This was done by analyzing the shear wave velocity, determined at a constant effective stress of 2 psi, just before and at the end of flushing the sample with deaired water. These results are presented in Table III. As can be seen, significant decreases in shear wave velocity, at a constant effective stress, were seen for both methods of sample preparation. Undoubtedly, the presence of moisture reduced the acoustic rigidity of the frame.

The effect of changes in the level of confinement on the shear wave velocity were investigated before saturation by changing the level of vacuum, and after by changing the level of external pressure. On the average the dry velocities varied in proportion to the two levels of confining stress being compared, raised to the 0.13 power, with the higher value of confining stress resulting in the faster velocity.

For the saturated case, increases in the level of effective stress resulted in corresponding increases in the shear wave velocity for most samples in the proportion of the two stresses raised to the 0.25 power. This value was noted earlier as having been reported in a number of previous sediment studies.

Although the flexible nature of the window material introduces a difficult-to-control variable that effects the coupling and resulting analysis of signal attenuation, it can be confidently stated that as the moisture content of a sample increased the signal attenuation increased for both fabrics. Also, as the level of confinement or effective stress increased, signal attenuation of the dry and saturated
<table>
<thead>
<tr>
<th>Test Number</th>
<th>Preparation Method</th>
<th>Relative Density, %</th>
<th>$V_s$, Dry @ 2 psi, M/Sec.</th>
<th>$V_s$, Saturated @ 2 psi, M/sec</th>
<th>$V_p/V_s$ @ 10 psi</th>
<th>Poisson's Ratio @ 10 psi</th>
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<tr>
<td>128</td>
<td>Poured</td>
<td>53.6</td>
<td>180.6</td>
<td>131.5</td>
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<td>129</td>
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<td>7.8</td>
<td>0.492</td>
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<tr>
<td>130</td>
<td>Poured</td>
<td>60.2</td>
<td>183.2</td>
<td>129.2</td>
<td>11.3</td>
<td>0.496</td>
</tr>
<tr>
<td>132</td>
<td>Moist Tamped</td>
<td>52.4</td>
<td>182.1</td>
<td>141.1</td>
<td>7.5</td>
<td>0.491</td>
</tr>
<tr>
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<td>Moist Tamped</td>
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<td>179.7</td>
<td>138.8</td>
<td>7.7</td>
<td>0.491</td>
</tr>
<tr>
<td>134</td>
<td>Poured</td>
<td>73.0</td>
<td>180.5</td>
<td>127.6</td>
<td>8.4</td>
<td>0.493</td>
</tr>
<tr>
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<td>Poured</td>
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<td>165.1</td>
<td>144.3</td>
<td>9.0</td>
<td>0.494</td>
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<tr>
<td>141</td>
<td>Poured</td>
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<td>166.5</td>
<td>145.4</td>
<td>8.8</td>
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<tr>
<td>142</td>
<td>Poured</td>
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<td>164.3</td>
<td>146.8</td>
<td>8.6</td>
<td>0.493</td>
</tr>
<tr>
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<td>146.0</td>
<td>8.0</td>
<td>0.492</td>
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<td>Moist Tamped</td>
<td>57.7</td>
<td>160.6</td>
<td>139.4</td>
<td>8.1</td>
<td>0.492</td>
</tr>
</tbody>
</table>

*Corrected to 24°C
shear wave decreased. Both of these results indicate, as previously demonstrated, that changes in the acoustic rigidity of a sample can be relatively predicted by changes in the level of signal attenuation.

As in the two previous test series, the saturated compressional wave velocities of the triaxial samples of this group were also found to be related to sample fabric. As can be seen in Figure VII-7, samples prepared by the moist tamped technique exhibited, on the average a 15 m/sec faster velocity than the dry pluviated fabric, when compared at the same relative density. The minimum acceptable B-value for this series was 0.97. The saturated compressional wave velocities can be seen to increase with increasing relative density, as in previous compressional wave results. All velocities of this test series were also corrected to 24°C by the Wilson (1960) formula.

It is important to note that the compressional wave velocities measured with the KB-GR transducers show fairly good agreement with those determined with the R-283E devices, particularly with respect to the relative differences in the velocity of two samples with the same density, but with different fabrics.

A closer examination of Figures VII-7, VI-5, and V-6 reveals, that on the average, the KB-GR transducers resulted in saturated compressional wave velocities some 25 m/sec faster than those found with the R-283E devices. This equates to approximately a 2.3 micro-second difference in the time-of-flight, as measured with the two different transducers. Since this value was within 0.2 microsecond of one-half of the period of the 236 KHZ driving frequency used with the R-283E device, it was felt that perhaps the first half cycle of R-283E signal was not being properly detected.
FIG. VII-7  SATURATED COMPRESSIONAL WAVE VELOCITY VS. RELATIVE DENSITY
By re-examining the compressional wave arrivals recorded in the R-283E time calibration study this hypothesis was confirmed. In the deaired water the starting direction was opposite from that observed in the analysis of the test samples. Since the calibration study had resulted in excellent agreement with the predicted values for the compressional wave velocity of the water, the observed negative starting direction had to represent the correct acoustic system response. As a result, the positive starting direction (which was re-observed in a number of test records) used in the analysis of R-283E signals produced a one-half wavelength error that would cause the observed time-of-flights to be slower by one-half the period of the pulse, as was observed. The better coupling of the R-283E in the deaired water versus the soil-water mixture was probably most responsible for this observed behavior.

Thus, it was concluded that the faster velocities found with the KB-GR transducers more accurately represented the absolute compressional wave velocities of the Dover 40-50 sand. Of course, the relative differences in velocity caused by the difference in sample fabric were unchanged by this systematic error. It should also be noted that the same starting direction found in the calibration of the KB-GR transducers was used in the analysis of the test sample results, thereby eliminating the potential for the discrepancy described above.

Once the shear wave velocity and density of a sample are known the Shear Modulus, G, can be calculated as in Chapter V. From Figure VII-8, as expected from the velocity results, the Shear Modulus of the saturated samples can be seen to be strongly dependent on
PREPARATION METHOD:
- ○ DRY PLUVIATED
- ▲ MOIST TAMPED
EFFECTIVE STRESS = 10 psi

FIG. VII-8 SHEAR MODULUS VS. RELATIVE DENSITY
sample fabric. The moduli increase with increasing relative density, ranging from approximately 5600 to 10,600 psi for the dry pluviated, and from 11,400 to 13,100 psi for the moist tamped, determined at an effective stress of 10 psi.

Hardin and Richart (1963) reported a Shear Modulus of approximately 13,000 psi (based on the results of resonant column tests) for an angular grain quartz sand at a similar confining pressure. As noted in Chapter II, they also reported that the effective added mass of water moving with the frame in a saturated granular material was approximately only 40 percent of the total mass of water in the voids. This behavior, although not singularly studied, could not be adequately justified on the basis of the results of this test series. Thus, rather than arbitrarily applying this correction, the full weight of pore fluid was assumed in the computation of Shear Modulus. This topic should be studied in greater detail in future testing.

Two other parameters, the ratio of saturated compressional wave velocity to shear wave velocity, or \( V_p/V_s \), and Poisson's ratio, \( \mu \) were also determined for the samples of this test series. As can be seen in Table III, these computed results, which agree well with those reported by Hamilton (1979) for similar in situ conditions, also indicate the ability of the acoustic method to reliably identify the fabric of a test sample. In fact, the differences in \( V_p/V_s \) and \( \mu \) are such that the relative density of the sample does not even have to be known in order to correctly identify the sample fabric. This observation is also true for the Shear Modulus results.

A number of tests were performed, just as in the previous test series, to further document the effect of stress history on the
acoustic signature of the Dover 40-50 sand. The only difference in the two test series was that the R-283E transducers were replaced with the KB-GR devices. This permitted both the saturated shear and compressional wave velocities to be recorded at the end of each pre-stress cycle.

Only very minor changes were found in the two acoustic velocities, including both increases and unexplainable decreases from the virgin values for the moist tamped and dry pluviated fabrics. Since this result does not correlate with the known and observed effect of stress history on the liquefaction resistance of saturated sands, which has been shown to be directly related to acoustic rigidity, the most obvious explanation for this anomaly would have to be the KB-GR transducers.

In particular, it is felt that the flexible window of the KB-GR transducers, unlike the rigid design of the R-283E devices, when combined with the relatively compressible air back pressure system produced an end boundary condition in the sample unlike that experienced in previous cyclic triaxial tests. Whether this resulted in coupling problems, migration of pore water, changes in path length, or some other unknown effect cannot be confidently stated. Perhaps the use of a less compressible fluid, such as transducer oil, in the back pressure system would result in a better system performance.

One final observation with respect to stress history, in particular static stress history, or overconsolidation, can be made from the results of this test series. Increases in the dry shear wave velocity, ranging from 5 to 10 m/sec, were observed in both the dry pluviated and moist tamped samples when the confining stress was
increased from 4 in. Hg to 15 in. and then decreased to 4 in. again. This would indicate, as expected, an increase in acoustic rigidity, due to the effect of stress history.

Discussion

With the development of the KB-GR transducer the acoustic test method reached a new level of sophistication. As expected, the use of both compressional and shear wave transmissions provided the necessary data to compute a number of parameters that were sensitive to the fabric arrangement of the Dover 40-50 sand. These included Shear Modulus, the ratio of $V_p$ to $V_s$ and Poisson's Ratio. Anyone of these parameters could be used to reliably identify sample fabric, even without knowing the sample density.

Regardless of the acoustic parameter chosen, the moist tamped fabric was found to be more acoustically rigid than the dry pluviated, confirming the results found in the previous test series. The effect of pre-consolidation loads was also seen to result in an increase in the acoustic rigidity of both sample fabrics.
CHAPTER VIII

SUMMARY AND CONCLUSIONS

Before discussing the more quantitative results of this investigation, it seems appropriate to summarize a number of less quantifiable, but equally significant findings. Since the majority of these results are related to the development of the test method and related equipment, these will be presented under the topic heading of instrumentation. The experimental results will follow.

Instrumentation

1. The cyclic triaxial test equipment, developed in stages during this test program, performed as expected, providing the necessary control of test conditions to insure repeatability and standardization of the test procedure. This control resulted in the ability of the test program to simulate in-situ stress, saturation and loading conditions heretofore not reported in the literature of acoustic-based sediment studies.

2. The R-283E transducers were found to be extremely dependable, rugged and accurate for use in determining the compressional wave transmission characteristics of the test sand and fabrics. The fact that these devices are relatively inexpensive (less than $20) and readily available, only adds to the strong recommendation for their future use in similar or related studies.
3. All of the electronic components of the acoustic portion of the test equipment performed adequately throughout the majority of this investigation. Of course, the most important element was the Nicolet oscilloscope. The ability of this component to convert from analogue to digital record at a rate of up to 20 MHz permitted extremely accurate time measurements to be made. It was this accuracy that allowed the sometimes small differences in acoustic behavior of the sand fabrics to be detected and confidently reported. The storage capability of the scope has provided a permanent and retrievable data base, that can be further analyzed in future testing programs.

4. The research and development of the KB-GR transducers is certainly the most significant instrumentation accomplishment of the testing program. The ability of these devices to accurately provide both the shear and compressional wave components of the acoustic signature of a laboratory test sample from the same acoustic device adds significantly to the validity of the test method. To this author's knowledge only Shirley (1978) has previously used a design that incorporated both shear and compressional wave crystals into the same acoustic transducer.
Experimental Results

1. The three preparation techniques and accompanying saturation process resulted in laboratory samples with consistently different fabrics in which the length, density and level of saturation were all precisely known. This, when combined with the accurate control and simulation of in situ stress conditions discussed above, resulted in a non-destructive test method that could truly isolate and identify the effect of fabric on the acoustic transmission characteristics of a saturated sand. This point cannot be overemphasized, since all previously reported studies seem to be lacking in at least one of these test procedure areas.

2. Both the dry and saturated compressional wave velocity provided a reliable acoustic indicator of sample fabric as seen in Figures V-5, V-6, VI-5, and VII-7. In the dry material the compression wave was transmitted through the frame. Once a sufficiently continuous pore fluid path was established the velocity increased by approximately a factor of 4.5, to a velocity only slightly faster than water alone. This indicated a shift in transmission path from the relatively compressible soil frame to the relatively incompressible, and consequently higher velocity pore fluid. This behavior was also confirmed by the fact that the dry compressional wave velocity varied with approximately
the 0.25 power of effective stress, as seen in Table II, while the saturated velocity was essentially unchanged by the changes in effective stress utilized in the test program.

3. The saturated compressional wave acoustic signature was found to be very sensitive to the B-value of the test sample. This was particularly true for signal attenuation. Once a minimum B-value had been achieved, however, this portion of the acoustic signature also provided a reliable indicator of sample fabric as seen in Figures IV-6 and VI-6. Further study is needed in this area, particularly with regard to the effect the flexible window of the KB-GR transducers has on the coupling of both the shear and compressional wave transmissions.

4. Both the dry and saturated shear wave velocity provided excellent indicators of sample fabric as seen in Figure VII-5 and VII-6, respectively. For most conditions, they were found to be even more sensitive, on a percentage basis, than their compressional wave counterparts. The resulting dynamic strength parameters of Shear Modulus, $V_p/V_s$, and Poisson's Ratio, which inherently contain information on both wave velocities and the sample density, proved to also be sensitive indicators of fabric as seen in Table III and Figure VII-8. The values obtained throughout the test program were in general agreement with those reported
in a number of related studies. (Hardin and Richart (1963), Hamilton (1979), Shirley (1978)).

5. The shear wave velocity and signal amplitude were found to decrease with increasing moisture content, with as little as 8 percent moisture producing a decrease in velocity in excess of 25 percent. The opposite trend was seen with respect to effective stress. That is, the shear wave velocity and signal amplitude increased with increases in effective stress.

6. In consequence, the fabric of those samples of Dover 40-50 prepared by the moist tamped technique, was found by all of the above parameters to be more acoustically rigid than the dry pluviated. The dry compressional wave results of Figure V-5 showed differences ranging from 10 to 40 m/sec, but the use of this parameter cannot be recommended unless an acoustic sensor could be developed that would not have to be placed in the interior of the sample. The saturated compressional wave velocity component of the acoustic signature, determined particularly with the KB-GR transducer, has proven to be a very reliable indicator of sample fabric. As long as a minimum B-value of 0.97 is maintained, even the relatively small differences of 15 m/sec observed in the Dover 40-50 sand can be confidently reported. As seen in VII-5 and VII-6, the dry and saturated shear wave
velocity appear to be even more sensitive to differences in sample fabric, on a percentage basis. On the average, the moist tamped fabric was found to possess a saturated shear wave velocity approximately 15 percent faster than a similar density dry pluviated sample at an effective stress of 10 psi. The computation of the related dynamic strength parameters seen in Table III and Figure VII-8 represent, in this author's opinion, the most promising parameters for relating acoustic signature to liquefaction resistance. If a sufficient data base could be collected from future laboratory tests so that an empirical relationship between these parameters, and resistance to liquefaction could be developed then the extension of the test method to the in situ case would be greatly simplified.

7. The same relative behavior observed with the acoustic signature can also be seen in the liquefaction resistance results of Figure VI-7. That is, the moist tamped fabric was found to be significantly more rigid than the dry pluviated when compared at the same number of load cycles. Thus, an acoustic method has been developed that accurately relates the fabric of a saturated triaxial sand sample to its laboratory resistance to liquefaction. The effect of stress history, determined with the R-283E transducers, was also observed to produce similar increases in both the acoustic and dynamic rigidity of the test samples.
In summary, an acoustic technique has been developed which is capable of accurately and reliably distinguishing between laboratory samples of the same sand and density but with different fabrics. This information can in turn be related to the relative differences in liquefaction resistance of the same test specimens. Based on these results, future testing can now proceed to extend this method to the equally challenging in situ case.
REFERENCES


Hvorslev, N.J., "Subsurface Exploration and Sampling of Soils for Civil Engineering Purposes", Vicksburg Mississippi Waterways Experiment Station 521 (1949).


Shirley, D.J. and D.W. Bell, "Acoustics of In Situ and Laboratory Sediments", in Report No. ARL-7R-78-36, Applied Research Laboratory, Univ. of Texas at Austin (1978).


GLOSSARY OF GEOTECHNICAL TERMS

Liquefaction - a failure mechanism in sands denoted by a condition where a soil will undergo continued deformation at a constant low residual stress, or with no residual resistance, due to the build-up and maintenance of high pore water pressures which reduce the effective confining pressure to a very low value.

Standard Penetration Resistance - The number of blows of a drop weight required to drive a 2" diameter hollow steel sampling spoon 12" into the soil layer. A weight of 140 lb. and a drop height of 30 in. are considered standard.

Compressibility, β - as used by Hamilton (1971), is defined by the following equation:

\[ \beta = \frac{1}{V_p^2 \rho - 4/3 \mu} \]

where \( V_p \) is the compressional wave velocity
\( \mu \) is the shear (rigidity) modulus
\( \rho \) is density

\( D_{50} \) Size - That screen opening at which 50 percent of the sample will pass through.

Minimum and Maximum Dry Density - Represents the most loose and most dense state of packing respectively, for a particular soil type. These values were determined in accordance with ASTM D2049-69.

Relative Density - Defined by the following equation:

\[ D_R(\%) = \frac{1/y_{\min} - 1/y}{1/y_{\min} - 1/y_{\max}} \]
\[ y_{min} = \text{Minimum Dry Unit Weight} \]
\[ y_{max} = \text{Maximum Dry Unit Weight} \]
\[ \gamma = \text{Unit Weight of Sample Being Tested} \]

Porewater Pressure - The level of stress acting in the solid and in the water in every direction with equal intensity.

B-Value - The ratio of the increase in porewater pressure to an increase in cell pressure, in an undrained sample.

Back pressure - A term referring to the level of stress applied to the porewater of a soil specimen to promote more complete saturation.

Pore Pressure Ratio - The ratio of built-up pore water pressure in a soil sample to the initial effective stress present at the start of the test.

Wilson Equation - The following empirical equation for the compressional wave velocity of water, with temperature correction, was reported by Wilson (1960):

\[ V = 1449.2 + \Delta V_T, \]

where

\[ \Delta V_T = 4.6233T - 5.485 \times 10^{-2} T^2 + 2.822 \times 10^{-4} T^3 - 5.07 \times 10^{-7} T^4 \]

\[ T = \text{Water Temperature in } ^\circ\text{C} \]
APPENDIX II
SPECIFICATIONS

Housing Material: ABS Plastic

Sensitivity
- Receiving (dB vs. 1V/microbar) -76.5
- Transmitting (dB vs. 1 microbar/yd/watt) -91.5

Total Beam Width (conical)
- at -3 dB points: 13°
- at -6 dB points: 18°
- at -10 dB points: 22°

Resonant Frequency (series): 200 kHz

Resistance at Resonance (tuned with 0.8 mh choke): 2000 ohms

Power Handling Capacity (Maximum peak watts): 100

Dimensions: 1½” dia x 3” long

Weight: 7 oz.

Cable: Coax. 10 ft.

*Over a Generation of Outstanding Leadership in Electroacoustics*
Calibration Chart for Accelerometer Type 4367

Brüel & Kjær

Serial no. 782746... Nørsum Denmark

Reference Sensitivity at ...50... Hz at ...24... °C
Cable Capacitance of ...110... pF
Charge Sensitivity**
....2.08... pC/ms−1, or ...2.04... pC/g*
Voltage Sensitivity**
....1.78... mV/ms−1, or ...1.71... mV/g
Capacitance (including cable) ...1.72... pF
Maximum Transverse Sensitivity at 30Hz ...1.3... %
Weight ...13... grams

Undamped natural frequency ...29... kHz
For mounted Resonant Frequency and for Frequency
Response relative to Reference Sensitivity, see at­
tached individual Frequency Response Curve
Polarity is positive on the center of the connector for
an acceleration directed from the mounting surface
into the body of the accelerometer.
Resistance minimum 20000 MO at room temperature.

Date 2-4-79 Signature JE

* 1 g = 9.807 ms−2

** This calibration is traceable to the National Bureau of Standards Washington D.C.
INVERSE SLOPE YIELDS

$V_s = 103.4 \text{ m/sec}$