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SYNOPSIS The interparticle arrangement, or fabric, of sands is a key determinant of sample rigidity. This rigidity, in large part, determines the velocity and attenuation of acoustic transmissions in a test specimen, as well as its resistance to liquefaction. Utilizing high frequency small-amplitude compressional wave transmissions, different fabric arrangements of standard triaxial samples of the same sand have been reliably identified from their acoustic response. Both the compressional wave velocity and attenuation were used to determine the acoustic signature of a sample. Cyclic triaxial testing of the same laboratory-prepared samples revealed that there is direct relationship between the acoustic response of a sample prepared by a particular method and its resistance to liquefaction. The effect of stress history, induced by pre-shaking, on the resistance to liquefaction of a test sample was also detected by changes in the acoustic signature.

INTRODUCTION

It has been shown in the laboratory by Mulilis (1975), that the susceptibility of sands to liquefaction can vary by 100% or more, depending on the method used to prepare a test sample. The reason for these large variations was reported by Mitchell et al. (1976) to be that different preparation techniques produced different fabrics in the test specimens as measured by their predominant long axis orientation. Results of tests by Mori (1976) proved that the stress history to which a sample has been previously subjected also had an important effect on liquefaction resistance: prestress, overconsolidation and age since preparation all influence dynamic behavior. These stress history effects are also considered to be fabric-related.

Mori (1976) also found that the fabric arrangements of sands are extremely sensitive to sample disturbance, and are certainly altered, if not destroyed, by conventional sampling procedures. This is particularly true in the marine environment where the lack of a stable platform and changes in pressure only complicate this already difficult procedure.

As a result, what is needed for accurate site evaluation is some means of determining in-situ the fabric, and/or liquefaction resistance of a marine sand deposit. Since a wealth of information exists on the physics of sound in marine sediments, the logical choice for such a technique would seem to be the use of acoustics.

The geophysical community uses the term "rigidity" to describe the spatial interrelationship of sand grains. Shumway (1960) reported that this rigidity is a key determinant of the velocity and attenuation of acoustic transmissions. This acoustic rigidity is at the very least, directly related to the fabric of sands. Thus, two samples of the same sand, prepared by different techniques in the laboratory so as to produce the same relative density but different fabrics, should exhibit different acoustic response. And since it has already been shown that the liquefaction resistance is dependent on fabric, then acoustic behavior should be directly related to resistance to liquefaction.

Results of the test program presented herein reveal that in fact this is the case. Both the compressional wave velocity and signal attenuation were found to be consistently different for the two preparation techniques used, when samples of the same sand were compared at the same relative density. The cyclic triaxial tests revealed that, as expected, the method of sample preparation or fabric significantly affected the cyclic stress required to produce liquefaction at a given number of load cycles.

Thus, a relationship between acoustic signature and resistance to liquefaction has been developed. The results of these tests and others to follow will be used as a basis for eventually extending the test program to in-situ measurements at offshore locations.

TEST PROGRAM

Method

The test program is based on a simple acoustic technique which permits the determination of both the compressional wave velocity and attenuation in standard laboratory triaxial sand samples. The choice of compressional waves was based on a readily available technology and extensive body of reliable data from the geophysical literature.

The acoustic method used in the test program is a direct transmission pulse technique which employs low-strain, compressional wave transducers (Massa Products R-283E) mounted in the end caps of the 7.1 cm (2.8") diameter, 16.8 cm (6.6") long specimens. This design permitted the acoustic signature and liquefaction resistance to be measured in the same sample, without disturbing the prepared fabric. Strain levels associated with the acoustic measurements were considered to be 10^{-6} percent or less.

Figure 1 is a schematic of the basic test apparatus. By utilizing one of the acoustic transducers to transmit a gated sinusoidal pulse through the test sample, and the second as a receiver, the velocity and attenuation of the acoustic transmission will obviously be directly dependent on the material transmitting the sound between the two transducers. With the aid of a high-speed digital oscilloscope very accurate measurements of the time-of-flight and peak-to-peak transmitted and received signal voltage can be made and recorded. From these measurements and a knowledge of the path length in the specimen, the velocity and attenuation can be calculated.

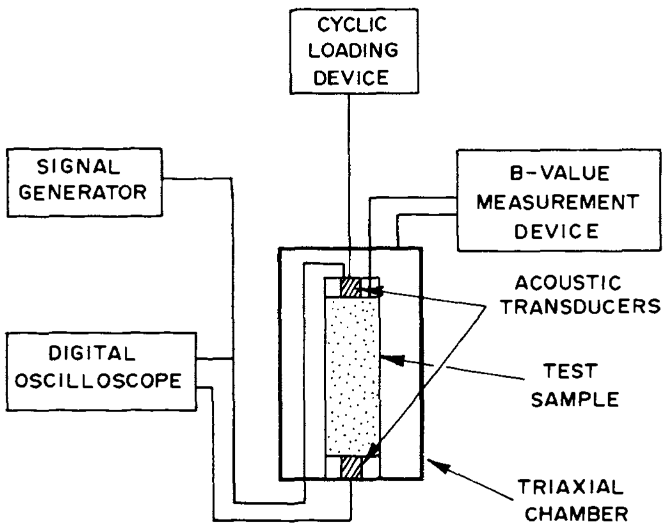

Figure 1. System Schematic

If the density, pressure, temperature and degree of saturation are the same for two samples of the same sand, and only the method of sample preparation is different, then any variation in the observed acoustic behavior must be the result of differences in fabric of the samples. Since these variables can all be controlled and/or monitored in the triaxial test, the effect of fabric on the acoustic behavior can be isolated from these other effects.

<u>Material</u>

The material used in the test program was an angular quartz sand with a specific gravity of 2.67. The D_{50} size of the natural deposit was 0.31 mm. Only that portion of the material passing the #40 sieve (0.425 mm) and retained on the #50 sieve (0.297 mm) was used for preparing samples. This caused the material to be similar in size to the sand used in the fabric studies referred to earlier. The minimum and maximum dry densities of the sorted material were 87.7 and 102.8 lbs. per cubic foot, respectively.

TEST PROCEDURE

The test procedure consisted of first preparing standard triaxial sand samples by one of two preparation techniques, next saturating the specimens, and then recording the acoustic signature. Finally, the same specimen was subjected to undrained cyclic loading to determine its resistance to liquefaction.

Two preparation methods that were known to result in different fabrics were selected from those used by Mulilis. These were the dry pluviation and the moist tamped techniques. The dry pluviation method consisted of raining the sand from a flask held inverted over the test mold. By selecting the proper stopper hole size and rotation rate, the desired density could be achieved.

The moist tamped method utilized a specially designed tool that was used to tamp each of the seven layers of a given sample to the required density. Deaired water was added to the dry material prior to tamping so as to produce a moisture content of 8%. A layer undercompaction technique as detailed by Ladd (1978) was used in order to obtain a uniform density.

Once a sample had been constructed, and the required density information obtained, the sample was flushed with CO_2. Deaired water was then allowed to slowly saturate the sample. The latter process was found to be very critical in obtaining the extremely high degree of saturation needed for accurate acoustic measurements. A minimum of 6 to 8 hours was usually required, with the higher density moist tamped samples requiring even longer saturation times. At the end of the saturation process a back pressure of 40 psi was applied with a cell pressure of 50 psi. All tests were carried out at the same effective stress, σ_c', of 10 psi.

Once a satisfactory degree of saturation, as measured by the pore pressure parameter B, (hereafter referred to as B-value) was obtained, the acoustic signature was measured. The driving frequency of the transmitted acoustic pulse was 235 KHZ. The digital oscilloscope, referred to earlier, enabled time-of-flight measurements between the two transducers to be made to the nearest 0.1 microsecond, and peak-to-peak signal voltages to be measured to the nearest millivolt. This information was permanently recorded on floppy disk for future signal analysis and processing.

With the acoustic signature recorded, the final procedure was to determine the sample's resistance to liquefaction. Each sample was loaded to failure in undrained conditions by applying a sinusoidal cyclic deviator stress, $\pm\sigma_D$. Records of strain, cyclic load and pore pressure were obtained for each test. From these tests the cyclic stress ratio, $\pm\sigma_D/2\sigma_c'$, and the number of cycles to liquefaction could be determined.

DISCUSSION OF RESULTS

As mentioned above, the significant test results include the compressional wave velocity, signal attenuation, and resistance to liquefaction for the dry pluviation and moist tamped fabrics. A range of relative densities from 45 to 70 percent was studied. Only the results of those samples in which a B-value of 0.97 or greater was achieved are presented.

As seen in Figure 2 the range of compressional wave velocities for all test samples is from approximately 1635 to 1680 m/sec. These values are typical of results reported by Shumway (1960) for fine sands both in the laboratory and in-situ, with confining pressures similar to those used in this test program. It should be noted that these velocities are not very different from the compressional wave velocity of approximately 1500 m/sec reported for sea water alone. This indicates that the sound wave is being carried predominantly by the pore water, with a lesser contribution from the frame. Thus corrections for variation in temperature from the selected standard of 24°C were made based on a formula for sea water only.

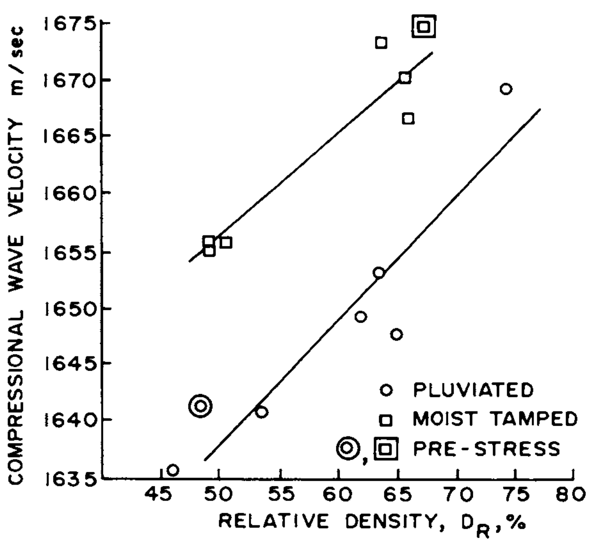

Figure 2. Compressional Wave Velocity Versus Relative Density, Dover 40-50 Sand

From Figure 2, the compressional wave velocity is seen to increase with increasing relative density in a similar manner for both the dry 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 it appears that the frame is not the major transmitter of compressional wave energy, the velocity differences are still significant since all velocities for the moist tamped group are larger than the dry pluviated, when compared at the same relative density. These higher velocities would indicate that the moist tamped fabric is acoustically more rigid than the dry pluviated.

The second portion of the acoustic signature that was investigated is signal attenuation. This parameter was found to be much more sensitive to even small variations in saturation than was the velocity. In fact attenuation was so severe in samples with a B-value of 0.90 or less that the background noise in the system prevented any reliable measurements from being obtained in these samples.

As the B-value increased, from 0.90 to 0.97 the peak-to-peak signal strength for a particular sample also increased. Above 0.97 the effect of increasing the B-value was observed to be insignificant. For this reason 0.97 was established as a minimum acceptable B-value for the test program.

In Figure 3 the peak-to-peak received signal strength is plotted versus relative density. (The input voltage was held constant at 20 volts, peak-to-peak.) Once again the general trend of the results was determined from a least squares linear regression. Results of a preliminary series of tests in which the velocity was not measured have been included in the figure. Although there is more scatter in these results than in the compressional wave velocity data, particularly for the dry pluviated samples, the differences are once again significant with the moist tamped fabric showing smaller peak-to-peak signal strength, or greater attenuation, than the dry pluviated in all cases regardless of sample density. This increased attenuation in the moist tamped samples could be the result of either larger viscous or frictional losses, or a combination of both, due to a more rigid frame. In any case, once again, the moist tamped fabric is identified as being more acoustically rigid than the dry pluviated.

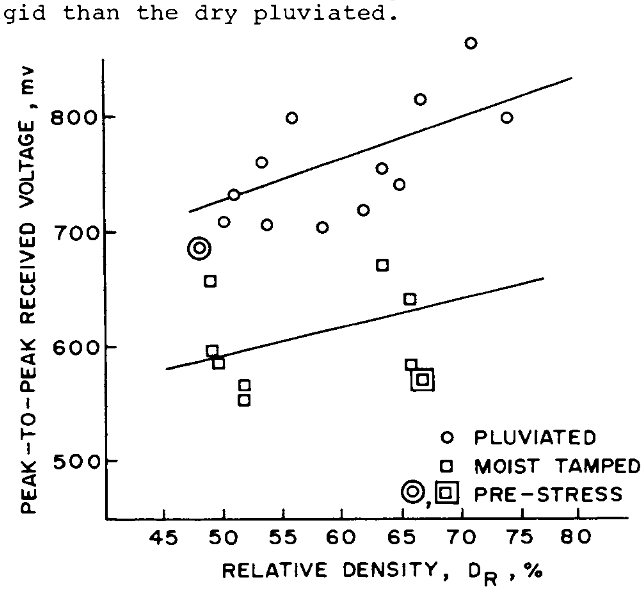

Figure 3. Signal Attenuation Versus Relative Density, Dover 40-50 Sand

As seen in Figure 4 the moist tamped samples required larger cyclic stress ratios to produce liquefaction (i.e. 100% pore pressure ratio) when compared to the dry pluviated at the same number of load cycles. It should be noted that all samples were reduced to a common relative density of 60% by assuming a straight line ratio correction. The liquefaction results for this test sand are of the same order of magnitude as those reported by Mulilis, for Monterrey No. 0 sand.

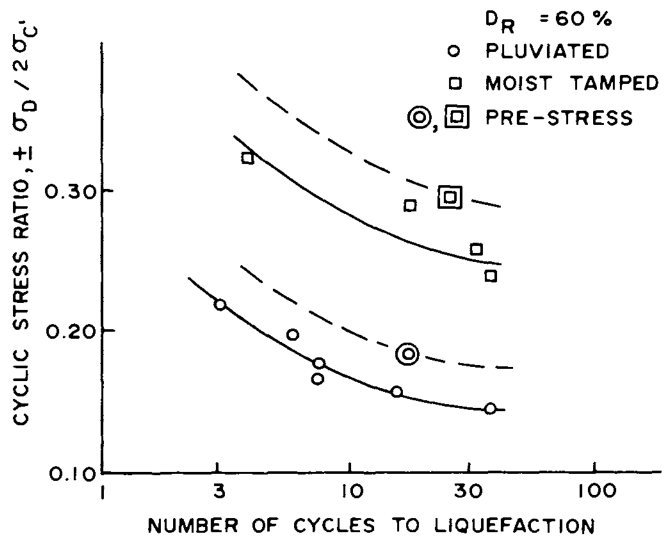

Figure 4. Resistance to Liquefaction, Dover 40-50 Sand (100% pore pressure ratio)

As predicted by both components of the acoustic signature, the moist tamped fabric did behave more rigidly than the dry pluviated, albeit the differences in liquefaction resistance relatively speaking, were much larger than those seen acoustically. Since the acoustic and dynamic strength parameters were determined at significantly different strain levels this may indicate that there is some minimum level of strain required in order to fully mobilize the dynamic strength inherent in a particular sand fabric.

The effect of stress history on the acoustic signature and resistance to liquefaction was investigated in two test samples. To create this stress history samples were subjected to several preliminary shocks. In each shock, which would represent the effects of a smaller earthquake, a cyclic stress ratio was selected so as to induce a peak pore pressure ratio of approximately 50% in five to ten undrained loading cycles. After each shock, the excess pore water pressure was allowed to dissipate, the volume charge was measured, and an acoustic signature was recorded. Five preliminary shocks were applied to each sample, before loading it to liquefaction failure. It should be noted that the increase in relative density produced by this preshaking process was only about 1-2%.

As seen in Figure 2 and 3 both the pluviated and moist tamped samples with induced stress history showed an increase in velocity and attenuation, as compared to the regression lines. From the earlier discussion, this behavior indicates an increase in acoustic rididity. It can be seen in Figure 4 that once again the increase in acoustic rigidity also resulted in an increase in the resistance to liquefaction for both fabrics.

CONCLUSIONS

1. For a given relative density, the moist tamped fabric had a higher compressional wave velocity than did the dry pluviated, throughout the range of densities investigated. This would indicate that the moist tamped fabric is acoustically more rigid than the dry pluviated. The greater acoustic rigidity of the moist tamped samples was also seen in the increased attenuation at all densities, relative to the dry pluviated.

2. As expected from previous work, the moist tamped fabric required a significantly larger stress ratio to produce liquefaction than did a dry pluviated sample of the same density when compared at the same number of load cycles. Thus, the acoustically more rigid fabric of the moist tamped samples can be correlated with an increased resistance to liquefaction, as compared to the dry pluviated.

3. Results indicate that the effect of stress history on the liquefaction resistance of both fabrics was predicted by a change in the acoustic signature. That is, samples that were preshaken showed increases in acoustic rigidity relative to virgin samples, which paralleled their increased resistance to liquefaction.

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