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Location of Solution Channels and Sinkholes at Dam Sites and Backwater Areas by Seismic Methods: Part II

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Vincent P. Drnevich
University of Kentucky

D. Raghu
University of Kentucky

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Location of Solution Channels and Sinkholes at Dam Sites and Backwater Areas by Seismic Methods: Part II
Correlation of Seismic Data with Engineering Properties

Dr. Vincent P. Drnevich
Principal Investigator

Graduate Student Assistant: D. Raghu

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ABSTRACT

Four seismic field methods and a laboratory method are used to determine shear wave propagation velocities and shear moduli for two sites. The four seismic methods are: standard seismic refraction survey, down hole shooting refraction survey, transient Rayleigh wave survey, and crosshole shooting survey. A torsional resonant column apparatus was used for the laboratory tests. The cross hole shooting method gave the best results because direct measurements were made. Criteria for using this method are given. Methods which measure compression wave velocity give inconsistent results because the conversion to shear wave velocity is very sensitive to Poisson's ratio. Laboratory tests data gave consistently low values. Strength reduction due to sampling was one cause advanced. Laboratory tests also showed increase in values with time. Strength and time effect corrections were applied to the laboratory data and then comparisons were made with the field data.

KEY WORDS: drilling, dynamic laboratory tests*, field tests*, geophysical methods sampling, seismic methods*, seismic refraction surveys*, soils*, subsurface investigation, time effects, wave propagation velocities*.

ACKNOWLEDGMENTS

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A Master of Science Thesis by D. Raghu provided the bulk of the data given herein. He deserves much credit for his ideas and efforts.

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CHAPTER I

INTRODUCTION

The main objective of this project was to adapt the methods of seismic refraction surveying to the accurate determination of depth and undulation of the rock surface where the depth to rock is less than 50 feet. A secondary objective was to correlate the refraction survey data to useful engineering properties of both the soil and the rock. This part of the report is concerned with only the secondary objective of the project.

Seismic wave velocities have been used for many years as a means of determining the modulus of soil. Until the recent works of Hardin and Drnevich (1, 2) these moduli were referred to as dynamic moduli and were only used in estimating the response of the soil to very small loadings such as result from traffic vibration, machinery vibration and from other microseismic activity. No use of the dynamic moduli was made for calculating response due to static loads (dead weight and live weight) or to strong motion earthquakes. However, Hardin and Drnevich (1) were able to show the functional relationship between modulus and its major controlling parameters. Their results showed that modulus is basically a function of the seismically measured value, the shear strength, and the strain amplitude. Thus, seismically measured values of modulus take on a new importance. This importance is already recognized in the design of major facilities such as dams, power plants, etc. where seismic investigations of soil and rock are becoming routine.

Seismic wave velocities are measured by a number of methods with the Seismic Refraction method being the most common. In all of the methods, a disturbance is applied to the soil which produces waves and then the wave propagation velocity is measured by one of several techniques. A disturbance usually generates two types of waves (body waves and surface waves) and each of these may have more than one component. The difficulty arises from the fact that each component has a different wave propagation velocity. Body waves may be either compression waves or shear waves. The compression wave has the highest propagation velocity and is related to the bulk modulus. The shear wave has a much lower propagation velocity and is related to the shear modulus. The surface wave is called a Rayleigh wave and it has a propagation velocity which is just slightly lower than the shear wave propagation velocity (87% to 96% depending on Poisson's ratio). The compression wave velocity is easiest to measure but it is the least useful in practice particularly if the soil is saturated because the bulk modulus of the pore water is obtained. The conventional seismic refraction survey measures the compression wave velocity.

Other methods recently have been developed for measuring the wave propagation velocities of the various components. These may be categorized as steady state methods (See Refs. 3, 4) and transient methods. The steady state methods rely on rather heavy and expensive vibrators to produce waves if significant depths are to be sampled. Transient techniques rely on an impact to provide a transient wave train. Here the equipment is less expensive and cumbersome but the results are sometimes more difficult to interpret.

This report will be concerned with four transient methods to determine wave propagation velocities. The methods were applied to two typical sites and the results were evaluated. In addition, the soil samples from these sites were tested in the laboratory using another wave propagation technique called the resonant column method (5). The results from the field and laboratory were then compared and will be reported herein.

Finally, a procedure for the use of these methods in practice will be given. It is based on the principles of wave propagation and the experience at the two sites.

Additional details of the work reported herein are given in a thesis by Raghu (6). All basic data are included in the thesis.

CHAPTER II

RESEARCH PROCEDURES

Standard Seismic Refraction Method - This method was discussed in Part I of this report (Ref. 7). The resulting compression wave (P-wave) propagation velocities can be used to estimate the shear modulus by use of the following relationship

$$G = \frac{1 - 2\nu}{2(1 - \nu)} \rho V_p^2 \qquad (1)$$

where G is the shear modulus

ρ is the mass density of the soil or rock

ν is Poisson's ratio

V_p is the compression wave velocity

The mass density of soil or rock can be measured or estimated rather closely and usually does not present much of a problem. The value of Poisson's ratio is much harder to estimate correctly. If the value is between 0.35 and 0.5 as it is for many saturated cohesive soils, the shear modulus calculated from Eq. (1) could be in serious error. A second difficulty with the standard seismic refraction survey is that the slopes of the second and subsequent branches of the travel time curves are often difficult to accurately establish because of weak signals (the head wave has very little energy associated with it) and because of localized velocity variations. For more than two or three layers and for survey depths greater than about 30 feet, sledge hammer energy is not sufficient and explosives are necessary. Thus, the conventional seismic refraction survey has some serious drawbacks for the accurate measurement of layer moduli.

Rayleigh Wave Velocity Method - Rayleigh waves are surface waves that propagate at velocities that range between 87 and 96 percent of the shear wave propagation velocity. The exact percentage depends on Poisson's ratio. An approximate expression for the variation is given by

$$V_s = (0.873 + .164\nu)\, V_R \qquad (2)$$

where V_s is the shear wave velocity

ν is Poisson's ratio

V_R is the Rayleigh wave velocity.

If the Rayleigh wave velocity is known, then the shear wave velocity can be calculated with reasonable accuracy using Eq. (2). The shear modulus is related to the shear wave velocity by

$$G = \rho V_s^2 \qquad (3)$$

where ρ is the mass density of the soil or rock. In terms of Rayleigh wave velocities and Poisson's Ratio, Eq. (3) becomes

$$G = \rho (0.873 + 0.164\nu)^2 V_R^2 \qquad (4)$$

For impact loadings at the surface, the majority of the energy is consumed by Rayleigh wave propagation. Furthermore, Rayleigh waves propagate with a cylindrical wave front and hence attenuate much more slowly than body waves. The greatest difficulty in measuring Rayleigh wave propagation velocities is that the faster travelling compression and shear waves tend to mask the Rayleigh wave arrivals.

Considering the above facts, a new method for measurement of Rayleigh wave propagation velocities was developed. It involved an alteration in the procedure for the standard seismic refraction survey. Instead of starting with the source and receiver close together, the source was moved to about 200 feet from the receiver. At this distance, all of the shear wave and compression wave components are attenuated and the Rayleigh wave is the only detected arrival. The source was subsequently moved closer and closer to the receiver and at each location, the arrival of the Rayleigh wave was determined. As the spacing got less than about 100 feet compression and shear waves started becoming significant. However, based on the shape of the wave forms, it was possible to detect the Rayleigh wave arrivals for source to receiver spacings as small as 50 feet.

A plot of the Rayleigh wave travel times versus distance between the source and receiver usually gives a fairly good straight line that can be extrapolated to pass through the origin. The inverse of the slope of this line is the Rayleigh wave propagation velocity.

When layered systems exist, the Rayleigh wave velocity obtained by the above method will not necessarily be the Rayleigh wave velocity for the top layer. From the theory of Rayleigh wave propagation, Rayleigh wave motion attenuates rapidly with depth and at depths greater than one wave length the motion is quite insignificant. It can be argued that the Rayleigh wave propagation velocity is a function of the material within a depth of one wave length from the surface. For the procedure outlined above, the wave length can be determined from the period of the waves (the record of the passing wave trains can be used for this determination) and the wave propagation velocity. The wave length is given by

$$L_R = V_R T_R \tag{5}$$

where L_R is the wave length of the Rayleigh wave

T_R is the period of the Rayleigh waves.

Following the currently accepted practice developed by the U. S. Army Waterways Experiment Station (4) for steady state Rayleigh Wave surveys, the Rayleigh Wave velocity (and associated shear modulus) is assigned to a depth equal to one half a wave length. For cases investigated in this research, the wave lengths ranged from 3 ft. to 15 ft.

Down Hole Shooting Method - This method is identical to the method discussed in Part I of this report. For cases where the geophone is situated at the interface between the first and second layers, the compression wave velocity in the top layer is simply the thickness of the layer divided by ordinate intercept of the travel time curve. If the interface is not grossly irregular, the compression wave velocity in the second layer can be estimated from

$$V_p = 2/(S_u + S_d) \tag{6}$$

where

V_p = compression wave velocity of second layer

S_u = best fit slope of forward profile survey travel time curve

S_d = best fit slope of reverse profile survey travel time curve.

If there are more than two layers, the determination of compression wave velocities is dependent on layer thicknesses, geophone placement, and relative compression wave velocities. The analysis is complicated and a digital computer is required to make the calculations. Raghu (6) has evaluated the compression wave velocities for some typical cases but in general, the method is neither the most practical nor the most reliable. As in the standard seismic refraction survey moduli must be calculated from compression wave velocities.

Cross Hole Shooting Method - This method utilizes two boreholes spaced from 5 to 40 or more feet apart. A schematic diagram of the procedure is given in Fig. 1. It is common to use explosives as sources of excitation in the borehole. However, a recent innovation described by Stokoe and Woods (8) was used for this program. A standard split barrel soil sampler was placed in the borehole and driven one foot into the bottom. Both holes were drilled such that the sampler and the geophone were at the same elevation. Excitation was produced by hitting the top of the string of drill rods with a hammer as shown in Fig. 2. The striking action triggered the oscilloscope so that wave travel times could be measured in the same fashion as in the standard seismic refraction survey. Travel time from the top of the string of rods to the samples were determined and subtracted from the total travel times.

The use of the split barrel sampler has a distinct advantage in that most of the energy transmitted to the soil was in the form of shear waves. Raghu (6) made quantitative estimates that ranged from 40% for sands to 86% for clays. These estimates were qualitatively confirmed by observing the geophone output. The compression wave component (the first arrival) had relatively small amplitudes and usually attenuated before the shear wave component arrived. The shear wave component always had a much larger amplitude. Its arrival time was usually easily determined.

For cases where the ray path for the shear wave is completely in one layer, the shear wave velocity is simply the borehole spacing divided by the travel time. The shear modulus is obtained by use of Eq. (3). For other cases, data reduction is more complicated and a computer solution is usually required.

Laboratory Testing - Shear wave velocities can be determined in

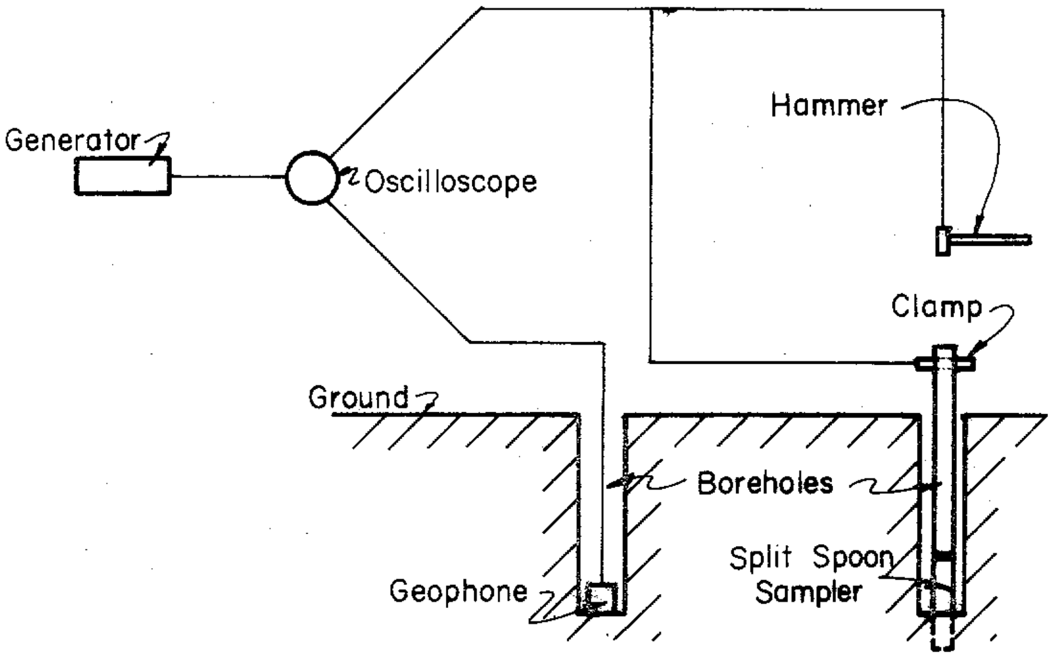

FIG. 1 SCHEMATIC DIAGRAM SHOWING EQUIPMENT USED FOR CROSSHOLE SHOOTING

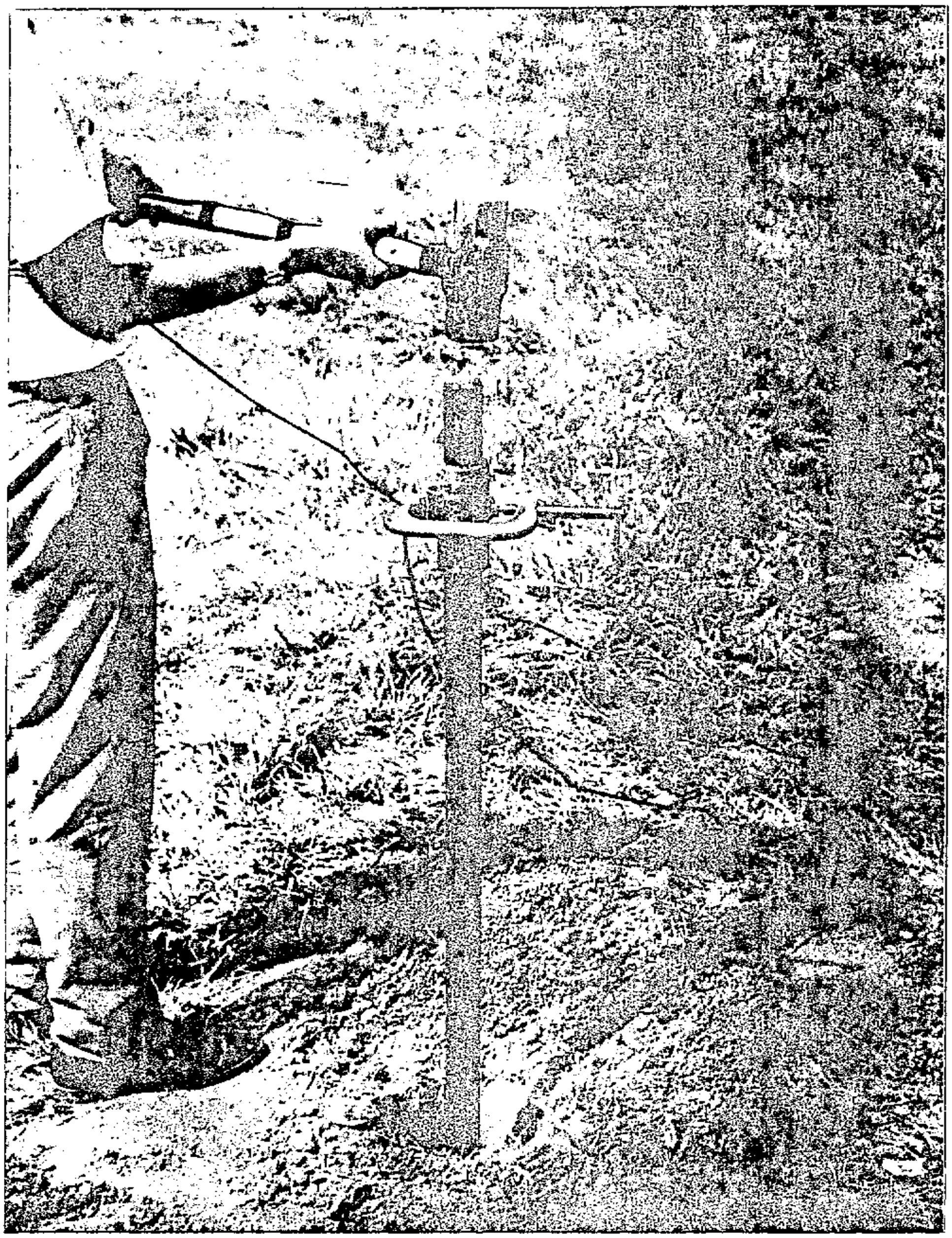

FIG. 2 - HAMMER CLAMP SYSTEM FOR CROSS HOLE SHOOTING

the laboratory by resonant column tests. The apparatus used in this program was developed by Drnevich (5). In this test, a cylindrical soil specimen jacketed in a membrane and acted upon by a static confining pressure to simulate insitu conditions, is fixed at the bottom and torsionally oscillated at the top. The soil-apparatus first mode resonant frequency is determined and the shear wave velocity is determined by putting this value into a standard solution. The shear modulus again is determined by use of Eq. (3).

CHAPTER III

DATA AND RESULTS

Field Data - Field investigations were carried out at two widely differing but typical field sites. One was at U. S. Army Corps of Engineers, Lock No. 9 on the Kentucky River near Valley View, Kentucky. The soils were sedimented silty sands and gravels that commonly occur along rivers. Bedrock was more than 55 ft. below the ground surface. The second site was on the north side of Lexington, Kentucky at the location where the new U. S. Post Office is being constructed. This site was chosen because it appeared typical of those where the soils were residual in nature and the limestone bedrock was relatively close to the surface. It was also chosen because some subsurface investigation had already been performed at the site for the purpose of constructing the Post Office.

At each site the test program included series of: standard seismic refraction surveys, Rayleigh wave surveys, down hole surveys, and cross hole shooting surveys. In addition, conventional auger borings, standard penetration tests, and Dutch Cone penetration tests were made. Finally, "undisturbed" Shelby tube specimens were taken and brought to the laboratory for resonant column and conventional testing.

The average data for the seismic refraction surveys, Rayleigh wave surveys and for the cross hole shooting surveys, are given in Table I. Except for very near the surface, the compression wave (P-wave) velocities are in good agreement. The Rayleigh wave (R-wave) velocities are roughly the same as the shear wave (S-wave)

TABLE I

WAVE VELOCITIES AT LOCK 9 SITE BY VARIOUS METHODS

Depth below ground level (ft) 1	P-Wave velocity from SRS (ft/sec) 2	P-Wave velocity from crosshole shooting (ft/sec) 3	S-Wave velocity from crosshole shooting (ft/sec) 4	R-Wave velocity from SRS (ft/sec) 5	Remarks 6
0	1205	-	-	840	
0.75'	1250	1512	440	745 ++	
6'	2039	2122	798	675 ++	
15'	2051	2198	705	715 ++	
30'	2256	2236	808	+	

Note:

+ R-Wave velocities could not be determined. See text.

++ From Rayleigh Wave arrivals in down hole shooting

SRS - Seismic Refraction Survey using "sledge hammer method" velocities except very near the surface. Similar results for the Post Office site are given in Table II.

The cross hole shooting method measures the shear wave velocity directly and thus is the most accurate method. The Rayleigh wave velocities at each site were converted to shear wave velocities by use of the procedure outlined in Table III. First, an estimate of Poisson's ratio, ν, is needed. The ratio of the compression wave velocity to shear wave velocity was used for this estimate. The values of Poisson's ratio (see Col. 4) are about 0.42 and appear consistent with values in the literature for these types of soil. Next, the ratio of shear wave velocity to Rayleigh wave velocity is determined from a graph in Richart, Hall, and Woods (9) which is reproduced in Fig. 3. The calculated values of shear wave velocities are given in Col. 7 and appear to be in agreement with those from cross hole shooting which are given in Col. 9.

Shear wave velocities could have been estimated from the compression wave velocity using the P-wave curve in Fig. 3 but the value of Poisson's ratio must be accurately known because the curve is very steep in the vicinity of $\nu = 0.42$. If the cross hole shooting surveys had not been made and a value of Poisson's ratio = 0.4 was estimated, the shear wave velocities calculated from the seismic refraction survey compression wave velocities would be those given in Col. 8. Comparison of Cols. 8 and 9 shows only fair agreements which is typical when compression wave velocities are used to estimate shear wave velocities.

Differences in shear moduli are even greater than differences in shear wave velocities because according to Eq. (3), shear modulus is proportional to the square of the shear wave velocity. The shear moduli corresponding to the velocities in Table III are presented in Table IV. Note that errors can be significant.

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TABLE II

WAVE VELOCITIES AT U. S. POST OFFICE SITE BY VARIOUS METHODS

Depth below ground level (ft) 1	P-Wave velocity from SRS (ft/sec) 2	P-Wave velocity from crosshole shooting (ft/sec) 3	S-Wave velocity from crosshole shooting (ft/sec) 4	R-Wave velocity from SRS (ft/sec) 5	Remarks 6
0	1700	1700	--	1111	Reflects only the velocity in Layer II
3	1700	1700	820	1087 +	
9	3700	3700	1280	1111 +	

Note:

SRS - Seismic Refraction Survey using "sledge hammer method"

\+ From Rayleigh wave arrivals in down hole shooting

TABLE III
COMPARISON OF S-WAVE VELOCITIES USING POISSON'S RATIO

Location (1)	Depth from Ground Surface (ft) (2)	$V_P/V_S = A$ (3)	ν (4)	V_R SRS (ft/sec) (5)	$\frac{V_S*}{VR}$ SRS (6)	V_S R-Wave ft/sec (7)	V_S SRS (8)	V_S Crosshole (ft/sec) (9)
Lock 9	** .7	$\frac{1250}{440} = 2.84$	0.428	-	-	-	615	440
	6	$\frac{2122}{798} = 2.66$	0.415	675	1.059	715	870	798
	15	$\frac{2198}{808} = 2.72$	0.420	715	1.059	757	901	808
	** 30	$\frac{2236}{705} = 3.17$	0.447	-	-	-	917	705
U.S. Post Office Site, Lexington	** 3	$\frac{1700}{820} = 2.07$	0.350	-	-	-	697	820
	9	$\frac{3700}{1280} = 2.89$	0.430	1111	1.057	1174	1517	1280

Note: + ν = Poisson's ratio = $\frac{A^2/2-1}{A^2-1}$

* Based on Richart, Hall, and Woods (9)

** R-wave velocities for these could not be determined by SRS

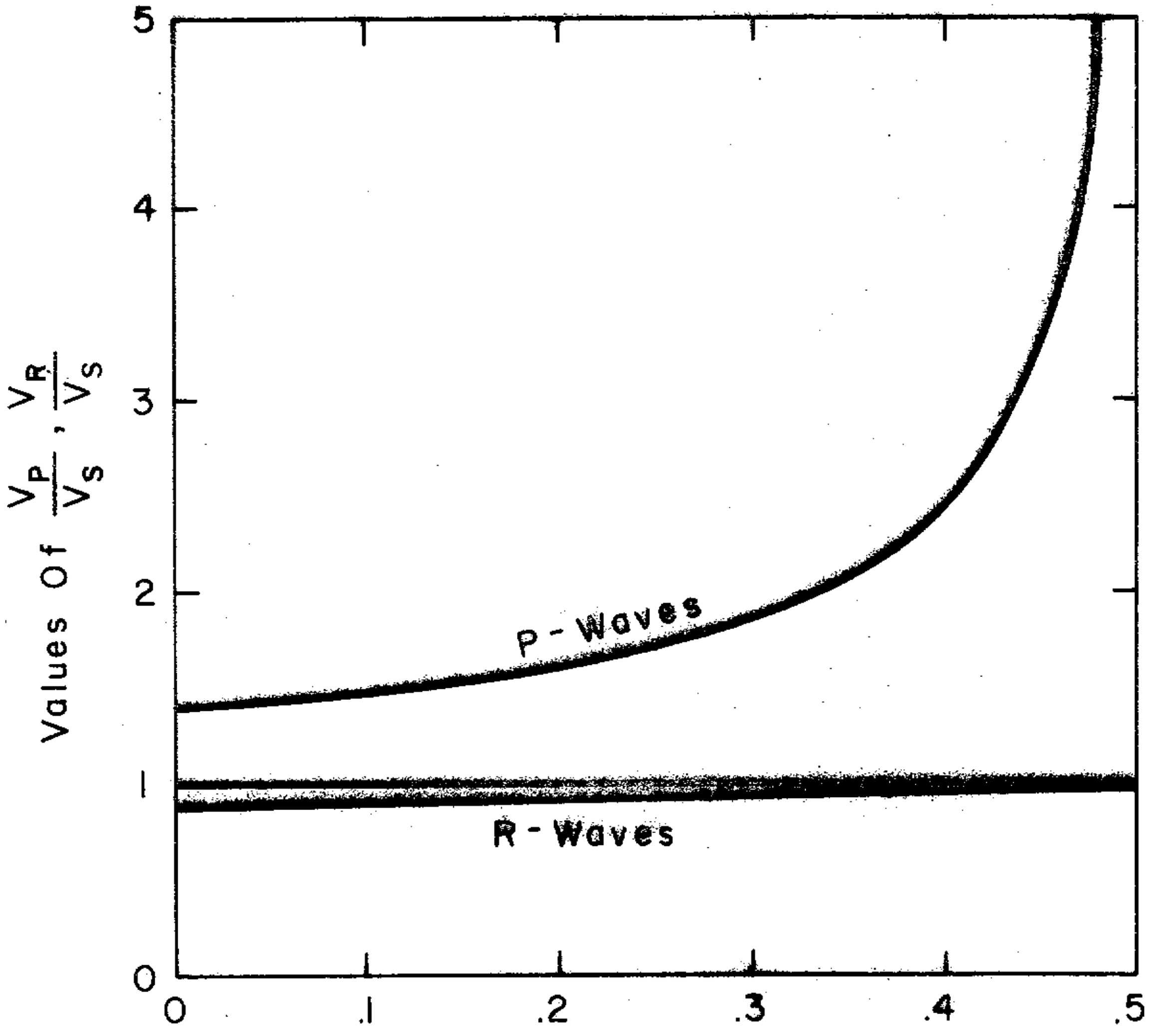

Fig. 3 Relation Between Poisson's Ratio And Ratios Of Wave Propagation Velocities.

TABLE IV

COMPARISON OF SHEAR MODULUS DETERMINED BY THREE WAVE VELOCITY METHODS

Location	Depth	G R-Wave (k/ft^2)	G SRS (k/ft^2)	G Crosshole (k/ft^2)
Lock 9	.7	-	1398	715
	6	1985	2938	2472
	15	2225	3151	2534
	30	-	3343	1976
U.S. Post Office, Lexington	3	-	1886	2610
	9	5222	8719	6208

Laboratory Data - Resonant column tests to determine shear wave velocity and shear modulus were run on specimens extruded from the Shelby tubes. Static confining pressures were applied to the specimens simulating effective confining pressures less than, equal to, and greater than the insitu mean effective confining pressures for that specimen. The reason for using three confining pressures was to bracket the possible insitu effective stress conditions because it is impossible to accurately determine them. At each confining pressure, sufficient time was allowed for primary consolidation to be completed. Vibratory shear strain amplitudes were kept less than 10^{-5} in/in. Hardin and Drnevich (1) have shown that for shear strains less than 10^{-4} in/in., the shear modulus does not change significantly.

In general, the laboratory test results were much lower than those measured in the field. Two causes were advanced for this and both were connected with the fact that the sampling-specimen trimming process causes some disturbance no matter how carefully it is done. One cause is loss in strength due to disturbance. Laboratory triaxial tests on separate specimens indicated that laboratory strengths on the average were 80% of the field strengths. The second cause was termed "time effects." When the laboratory tests were run, the measured velocities continued to increase with time even after consolidation was complete. This has been noted by others (10) (11) and is commonly referred to as "secondary build-up." The increase of shear wave velocity with time is shown in Fig. 4. Note that the rate of increase is function of confining pressure. At the present time, the mechanism underlying this build-up is not understood and it is not possible to predict either rate or amount. Affifi and Woods (11) showed that data accumulated over the first 48 hrs. could be extrapolated on a semilog plot to

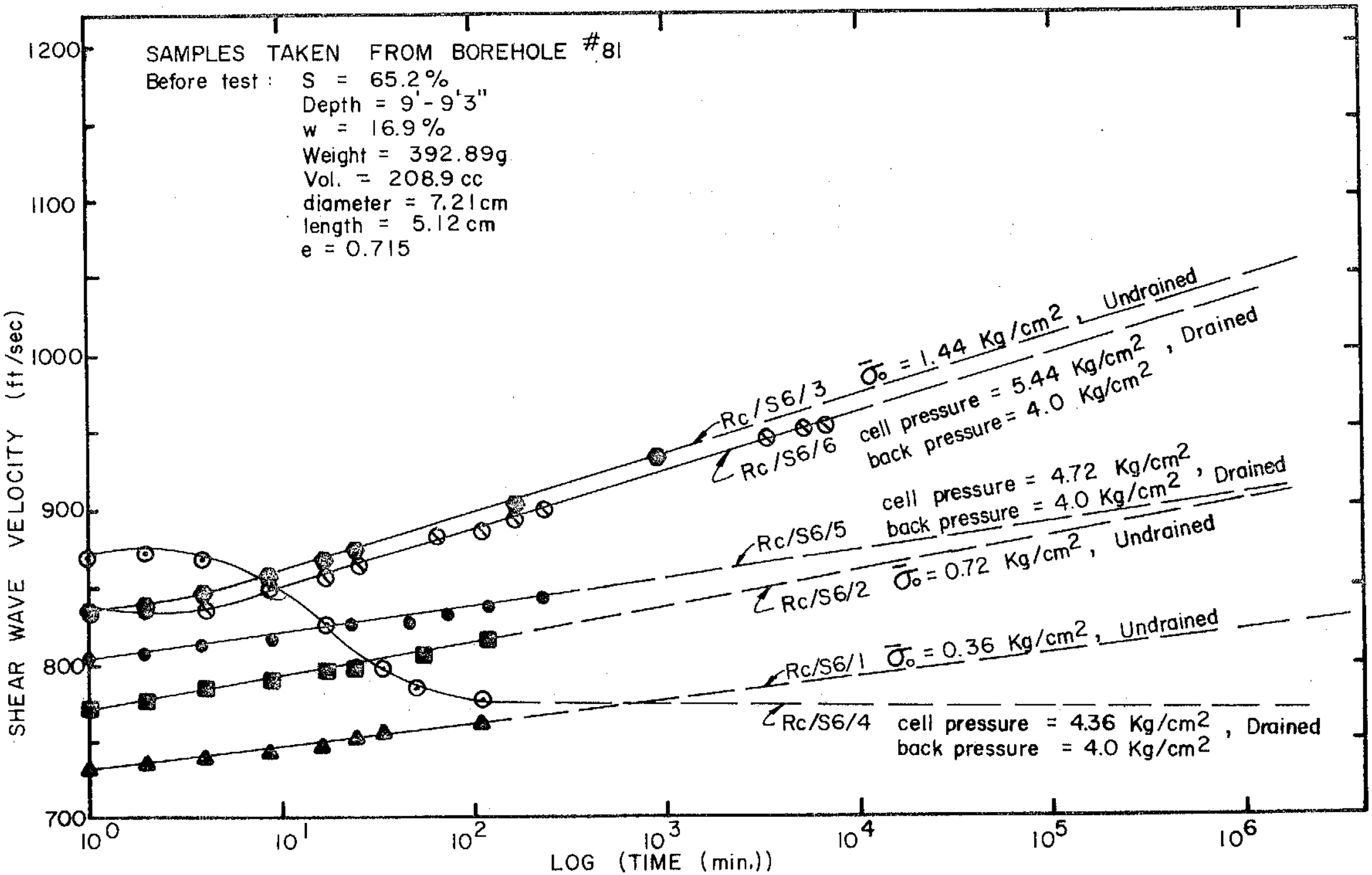

FIG. 4 RESONANT COLUMN TESTS ON SAMPLES FROM U.S. POST OFFICE SITE (SHOWING TIME EFFECTS)

times corresponding to several years. On this basis, the shear wave velocity test data was conservatively extrapolated to five log cycles (approximately 70 years). In addition to this, a correction for the differences between laboratory and field shear strengths was also applied to the shear wave velocities. The correction amounted to an increase of about 25%.

Empirical Methods for Calculating Shear Wave Velocities - In addition to the laboratory and field data for shear wave velocities, it was possible to estimate shear wave velocities with an empirical equation derived by Raghu (6) from an empirical equation for shear modulus given in the closure to a paper by Hardin and Black (10). Shear wave velocity is estimated by

$$V_s = 302.3 \left(\frac{2.973 - e}{G_s + Se/100}\right) (OCR)^{0.5K} \bar{\sigma}_o^{\,0.25} \tag{7}$$

where

V_s is the shear wave velocity in ft/sec

e is the void ratio

G_s is the specific gravity of the solids

S is the degree of saturation

OCR is the over consolidation ratio

K is a constant depending on plasticity index, and

$\bar{\sigma}_o$ is the mean effective confining pressure in lb/in^2.

Comparison of Field, Laboratory and Empirical Results - A comparison of the field, laboratory and calculated values of shear wave velocities for the two sites are shown in Figs. 5 and 6, respectively. Agreement is relatively good but the insitu measured values are always the largest. The disparity is the greatest at shallow depths where there is great difficulty in estimating insitu effective stresses. It also appears that the extrapolation of laboratory test results to 70

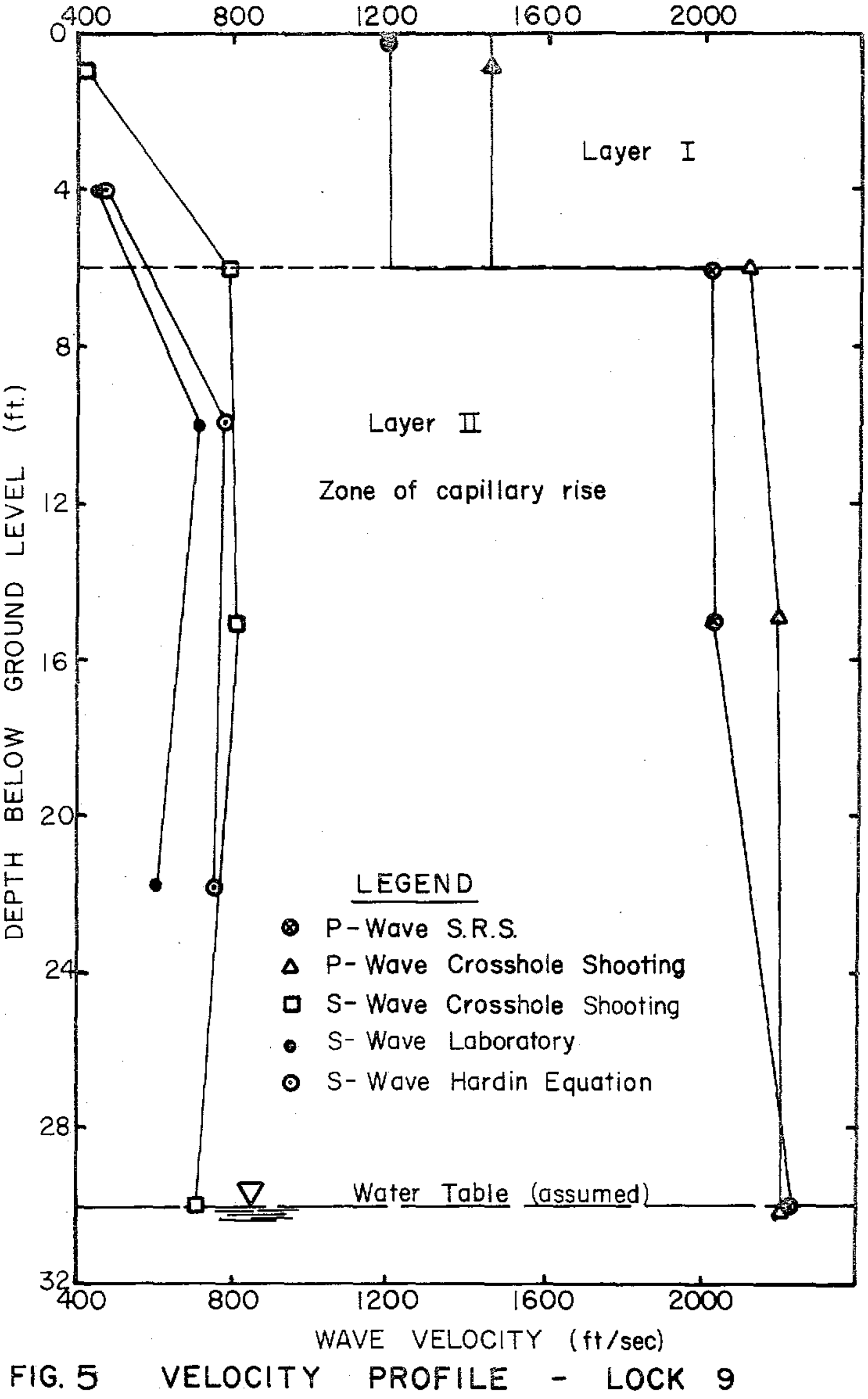

FIG. 5 VELOCITY PROFILE - LOCK 9

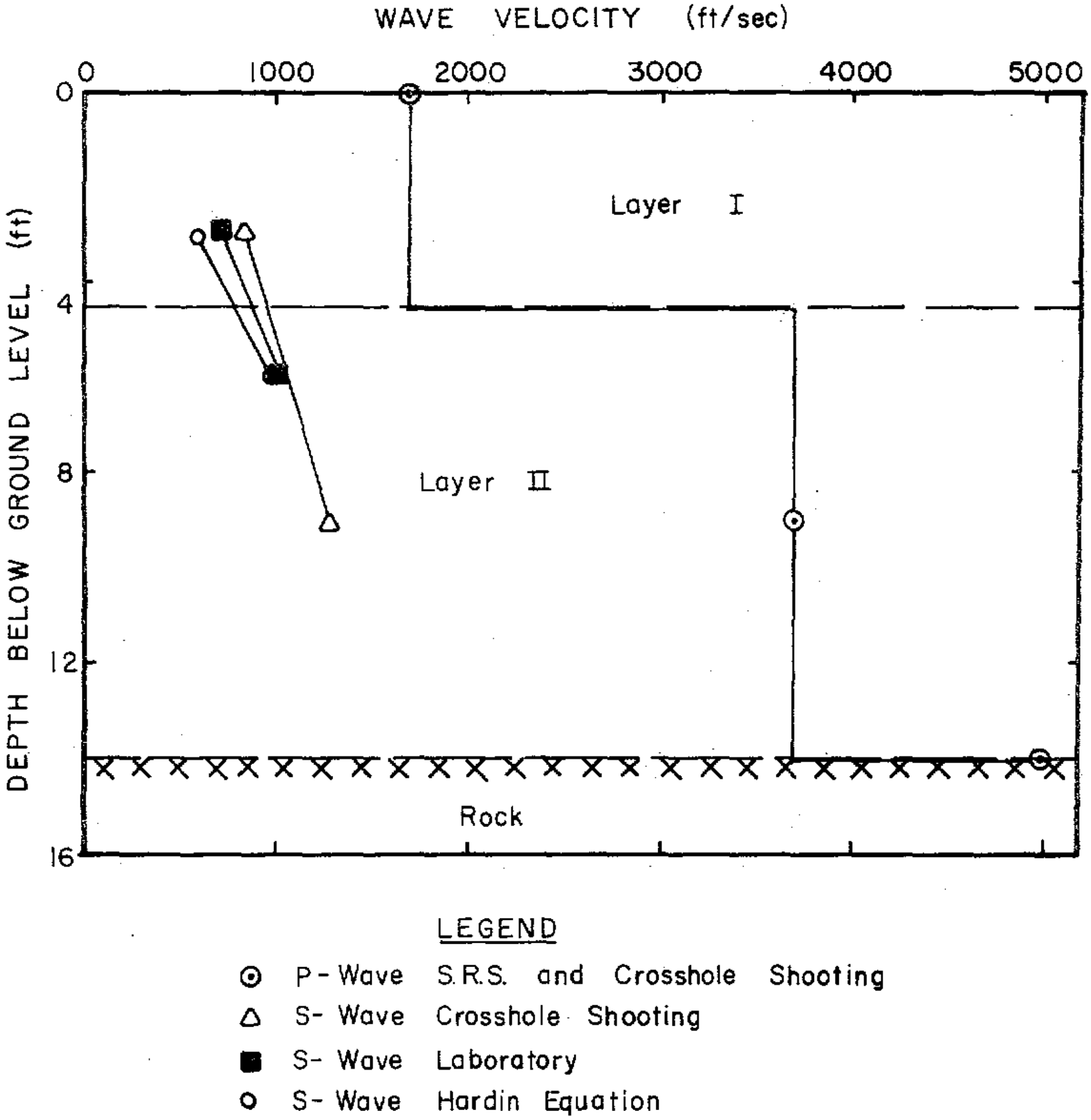

FIG. 6 VELOCITY PROFILES FOR U.S. POST OFFICE SITE

years to account for time effects gives conservative estimates of shear wave velocities and hence shear moduli.

CHAPTER IV

CONCLUSIONS

Four seismic field methods can be used to estimate insitu shear modulus. The data from the standard seismic refraction survey and the down hole shooting surveys must be converted to shear wave velocities using values of Poisson's ratio. The results are subject to considerable error because the procedure is very sensitive to the values of Poisson's ratio which are difficult to accurately establish.

The Rayleigh wave method where Rayleigh wave velocities are measured from transient wave trains gives more accurate values of shear wave velocities because the conversion from Rayleigh wave velocities to shear wave velocities is very insensitive to Poisson's ratio. However, the method is limited to determining only one value of shear wave velocity for each wave length and that velocity is associated with one depth. Steady state excitation methods where wave length can be varied must be used to find values at other depths.

The cross hole shooting method appears to be the strongest and most flexible method for both compression wave and shear wave velocity determinations. In addition to the requirement of two boreholes, additional criteria must be satisfied in order to obtain accurate results. These criteria were developed by this research and are listed in Chapter III.

Laboratory methods can give reasonable values of insitu shear wave velocities and shear modulus if insitu confining stresses are duplicated in the laboratory and if time effects are taken into account. At the present, time effects are not understood and corrections for them are very crude. Much additional research is needed on this aspect.

Empirical methods appear to give reasonable and conservative estimates of insitu shear wave velocities if insitu confining pressures and overconsolidation ratios can be established.

Finally, none of the seismic methods discussed above should be the sole subsurface investigative tool when engineering properties are desired. They must be used in conjunction with conventional boring, sampling, and laboratory testing techniques to gain a more complete picture of existing subsurface conditions.

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APPENDIX I

NOTATION

A = ratio of V_p/V_s
e = void ratio
G = shear modulus
G_s = specific gravity of solids
OCR = overconsolidation ratio
S = degree of saturation
S_d = slope of forward profile travel time curve
S_u = slope of reverse profile travel time curve
SRS = seismic refraction survey
T_R = period of Rayleigh waves
V_p = compression wave velocity
V_R = Rayleigh wave velocity
V_s = shear wave velocity
ν = Poisson's ratio
ρ = soil or rock mass density
$\bar{\sigma}_o$ = mean effective principal stress

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