A FIELD TEST FOR DYNAMIC SOIL PROPERTIES

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1. Introduction

The propagation velocity of waves through the ground has been used for many years in seismic surveys for the detection of underlying strata. From a knowledge of the percussion (P) and shear (S) wave velocities in different materials, together with their bulk densities, it is possible to derive dynamic moduli and properties, such as the shear modulus (G) and poisson's ratio (n), which are essential in the solution of problems relating to dynamic earth pressure, soil structure interaction and the dynamic analysis of foundation strata relating to earthquake engineering.

The principle involved in finding the wave velocities in ground materials is the same as used in finding velocities in any material. A simple wave form or pulse is generated at one point and the travel time to several other points is detected with suitable signal receivers.

For field work all equipment must be easily portable, self contained for power supply and reasonably robust.

The dynamic moduli of soils can be found in laboratory tests which have the advantage that strain can be controlled and measured accurately; this is important because G is known to be strain dependent. The disadvantage of a laboratory test is that it finds the properties of only a very small sample of material. This is where the field test has a primary advantage in that it averages out small variations in the material and provides values which apply to a generally larger body of material. The disadvantage of the field test is the difficulty of controlling and measuring the strain applied to the ground during the test. Theoretically the strain can be determined from the ratio of the particle velocity over the wave propagation velocity⁽¹⁾ but the tests made so far in developing the method described below have not provided an absolute measure of the particle velocity, and hence the strains cannot be accurately found, although it is known that they are very small.

The detecting seismometers, although very sensitive and effective for many dynamic measurements, were found to have a ringing frequency which completely disguised the true amplitudes of the ground pulse. Attempts have been made to correct this mathematically on the records of the instrumental response output, but this method cannot give any amplitude precision. An instrument without a ringing response at or near the ground pulse wave

frequencies is needed to complete this part of the work.

Despite these measurement difficulties, which were properly interpreted only after most of the field work had been done, the testing technique has shown -

- (1) It is possible to obtain unique values of V_p and V_s for ground materials.
- (2) From in situ densities and the velocities found, the appropriate values of elastic modulus, shear modulus, poisson's ratio can be calculated.
- (3) The presence of sub surface strata changes can be inferred, but should in general be checked by drilling.

2. Elastic Properties

Derivation of the following relationships can be found in text books on elasticity⁽²⁾. They are summarised here to show how test results can be applied.

E = Youngs modulus of elasticity.

G = Modulus of rigidity or shear modulus.

n = Poisson's ratio.

ρ = Density.

λ and G are Lamé's constants.

$$n = \frac{\lambda}{2(\lambda+G)} \quad \text{or} \quad \lambda = \frac{2Gn}{1-2n} \quad \dots\dots (1)$$

$$G = \frac{E}{2(1+n)} \quad \text{or} \quad E = 2(1+n)G \quad \dots\dots (2)$$

From equations of motion and the solution of the wave equation the seismic wave velocities can be found as (2).

Primary or percussion wave speed

$$V_p = \left(\frac{\lambda+2G}{\rho} \right)^{\frac{1}{2}} \quad \dots\dots (3)$$

Secondary or shear wave speed

$$V_s = \left(\frac{G}{\rho} \right)^{\frac{1}{2}} \quad \dots\dots (4)$$

$$\text{It follows that } G = \rho V_s^2 \quad \dots\dots (5)$$

And in lb.sec.units

$$G = \frac{W}{g} \frac{V_s^2}{144} \quad \text{lbs/sq.in.} \quad \dots\dots (6)$$

Where W = bulk density (in lbs/c.ft.) and $\rho = \frac{W}{g}$

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From (3) and (4) with the substitution from (1) it can be shown that -

$$V_s = \left(\frac{1-2n}{2(1-n)} \right)^{\frac{1}{2}} \times V_p \quad \dots\dots (7)$$

$$\text{From which } n = \frac{V_r^2 - 2}{2(V_r^2 - 1)} \quad \dots\dots (8)$$

$$\text{Where } V_r = \frac{V_p}{V_s} \quad \dots\dots (9)$$

With field test results for V_s and V_p used in equations (6), (8) and (9), values can be found for G and n and then from equation (2) the value of E .

The values of V_s depend on G as seen in equation (5). The shear modulus (G) has been found to be strain dependent in soils and is also closely related to void ratio, moisture content, and to a lesser extent is influenced by other factors such as frequency of wave motion and confining pressure (3) (4).

It seems very likely that the shear wave velocity (V_s) in soil materials would be affected also by strain level, void ratio and moisture content.

3. Test Method

The layout of equipment is similar to that used in seismic surveys but on a much reduced scale. The signal, either a P wave or S wave pulse, is transmitted a distance of up to 100 ft depending on the amount of ground absorption. Signal detectors are located at 10 ft intervals from the signal source.

If sufficient detectors could be used all the data could be collected from one pulse signal with all the detected signals received into a multi channel recorder. Only two sensitive seismometers were available, so the tests were done using a series of signals with the seismometers being moved further away each time.

In general for a uniform material unique values for V_s and V_p were found. In the example considered later where the material was initially thought to be uniform, a variety of velocities were detected and these formed the basis of a depth study of stratification. In addition 3 ft diameter holes were bored for inspection, sampling and subsurface velocity tests.

When the signal generator was used for an S wave pulse in uniform material, the predominant signal received was an S wave although a small amplitude of P wave was also recorded. However when the material shows stratification a reflected P wave can return as an S wave (5). The P and S waves are usually obvious when the records are analysed because the wave velocities V_p and V_s are quite different.

In stratified material waves may be refracted after travelling some distance in the lower material. The geometry of this is illustrated in Appendix I. Alternatively the wave may be simply reflected and travel entirely in the top strata (See Appendix II). If this occurs the reflected wave from an original P wave may be both S and P wave. Hence the velocity calculated for a mixed return wave

(e.g. half the journey as P wave and returning as an S wave) will be rather lower than the true P wave velocity. The true P wave velocity can be found from the measured S wave velocity and the "average" (S+P) velocity as shown in Appendix III.

4. Apparatus

(1) The signal generator is a compound pendulum impacting on a 4 ft long steel bar (4" x 2" hollow section) keyed to the ground. This is triggered by a magnetically released pin operated by a remote push button at the recording set. Different impact intensities can be selected by setting the start position of the pendulum at different levels. The time of impact is transmitted from a contact at the point of impact, and this is recorded with other timed data. Two impact intensities were generally used: these were (2) and (4). The values are arbitrary but impact (4) is greater than impact (2).

(2) Wilmore Seismometers Mk II (S.G.450) detected the ground wave impulse. These seismometers were mounted on triangular three pronged bases driven into the ground about six inches. The signals from the seismometers were transmitted through cables to a six channel amplifier.

(3) The amplifier was made to match (on two circuits) the seismometers to provide the correct electrical damping to give 0.6 critical damping. The amplifier channels each have five stages of amplification with ranges 0 - (no gain), 1 - (x 2.55 gain), 2 - (x 17.69 gain), 3 - (x 35.8 gain), 4 - (x 89.8 gain), 5 - (x 276 gain). It was found that a gain of (2) was generally adequate, but sometimes (0) or (1) was needed for low loss materials. Generally gains of (3), (4) and (5) registered too much microtremor vibration which interfered with the test signal, or these amounts of amplification put the test signals off scale. This amplifier was built in the electronics section of the Civil Engineering Department of the University of Canterbury.

(4) The amplified signal was recorded by a Kyowa "Rapet" recorder having a travelling paper chart with speeds of 5, 10, 50, 100 cms/sec. A speed of 50 cms/sec. was found most suitable for field work. This recorder has an incandescent light source and the signal trace is recorded by a light beam from miniature galvanometers. Special paper is used which can be semi developed by exposure to a fluorescent light for initial examination. Permanising with chemical intensifier and fixer can be done later if needed. The paper is stable in dim light or artificial light even before fixing.

(5) A small 12 volt motorcycle battery was the power source for the Rapet recorder and the magnetic release. Sometimes this was supplemented with a lead to the battery in the car engine.

The apparatus is essentially quite simple and easy to use, but experience has shown that further improvements could be made, particularly to the triggering device and the type of signal detector.

(5) Types of Ground Tested

To obtain a range of results the field test

has been applied to the several sites including the following.

1. Gravel at the University field station at Shipleys Road, Christchurch.
2. Sand at New Brighton.
3. Silty clay at Ilam University where it overlies sand and gravel at about 10 ft.
4. Saturated silty clay at Heathcote Valley, Christchurch.
5. Loess clay at Glenmore brickworks, Port Hills Road, Christchurch.

This last test included sub surface tests and is described in detail below.

The results from these tests are shown in Table I which lists the measured values of V_s & V_p with other deduced dynamic properties.

6. The Glenmore Brickworks Test

(1) The Site

Geological data was available from a previous investigation done in 1966 by N.Z. Geological Survey Section of D.S.I.R. in Christchurch. The area is on a fairly steeply sloping hillside and access for vehicles governed the location of a test area. The cross section of the site is shown in Figure 1. The geological evidence indicated a good depth of loess of a generally uniform nature except for slight moisture variations. The rock sides of the valley were sufficiently remote to eliminate unwanted reflections and the previous seismic survey indicated an interface at a depth of about 40 ft.

(2) Installation and Layout

On a reasonably level area a line was set at 345°Mg and pegged at 10 ft intervals for 80 ft. The sequence of test is shown in figure 2. This shows diagrammatically the arrangement and direction of the impact pendulum and instrument bases in plan view.

Two series of tests were made on the ground surface; the first for S wave pluses with lateral orientation of the impact pendulum and the seismometers, and the second for P wave pulses with the impact pendulum and seismometers orientated longitudinally.

Following the surface tests, sub surface tests were made in holes bored to 11 ft and extended to 20 ft at pegs 30, 50, 60, 70 ft. These holes were 3 ft in diameter and were just large enough to set equipment in albeit a little cramped. They were dug with a Calweld rig having a rotating cutter bucket. Down to 20 ft there was no problem with wall collapse and no linings were used.

The down hole tests were made to check the data inferred from the surface tests and also to get in situ densities and obtain samples for moisture content tests and other physical checks.

It proved very much more difficult and slower setting up tests in the holes, particularly when moisture and dirt prevented the impact pendulum from triggering properly which meant repeated trips down the hole on a winch rope to re-set the trigger.

The sequence of drilling was arranged so that the first test at 11 ft was made with only two holes drilled 40 ft apart (at 30 ft peg and 70 ft peg). This eliminated the possibility of interference from the in between holes. When other holes were drilled there appeared to be no significant change caused by interference with S wave pulses, but at the 20 ft level, an anomaly occurred with the P wave pulse. The hole at peg 60 ft was masked in some way by the hole at peg 50 ft as only a very small amplitude signal was received at peg 60 hole. The signal at peg 70 was much bigger.

At the conclusion of the wave pulse tests the hole at peg 70 was deepened to find the interface indicated on the geological section. Wet conditions were encountered below 35 ft. and drilling had to be stopped at 41 ft because the walls at this level were caving in with flowing water.

Samples were taken at 5 ft intervals down this hole and the results of density and moisture tests are shown in Table II and in figure 3. Below about 40 feet the saturated material was soft and a probe was pushed down to 55 ft without finding any rock although there seemed to be hard and soft layers.

The relative hardness values shown in figure 3 were obtained from a Soiltest pocket penetrometer. This was pushed on to the sides of the hole at one foot intervals down to 35 ft. The pressure applied was almost to the maximum value of the instrument. The depth of indentation was estimated and this varied from less than $1/32$ nd of an inch to about $1/4$ inch. This method of measurement is somewhat arbitrary but does give an indication of relative hardness changes. The scale of hardness was obtained by inverting the fractions of an inch indentation and dividing by 4, thus giving a range of 1 to 8 from soft to hard.

(3) Test Procedure

For each test the pendulum was released by the push button at the same time as the Rapet recorder was started. At a speed of 50 cms/sec. about 12 inches of paper is needed to get a record, and about half this length is taken up with the recorder accelerating to about its right speed. Time pips automatically recorded on the paper at $1/100$ th second intervals overcame any problems with paper speed variation. Actual speeds during recording varied between 40 cm/s and 60 cm/s, but were generally around about the design speed of 50 cm/s. For a short run the recorder must be stopped about half a second after starting. This could be done with a timer device (as an improvement) but for simplicity the stop button was hand operated. After a little practice and a "feel" for the time required, the right amount of paper could be passed without too much waste. The exposed paper was semi developed (photolysed) under a battery operated fluorescent lamp to see if a successful result was achieved.

On the surface tests two impact values (2) and (4) were used to find out if the magnitude of the pulse had any influence on the velocities. For the down hole tests impact (4) was generally used as the transmitted signal from impact (2) was attenuated more quickly and the received signals were not sufficient.

(4) Seismometer Response

The seismometers are supposed to be undirectional and respond only to a signal along the main axis. There is, however, a small response to signals at right angles to the axis. This means that both P and S waves get recorded together, but these can generally be identified by the magnitude on the record and the calculated velocity.

The response of the seismometers to a sharp small tap is not a single spike type of signal but it is an attenuating oscillation as shown in figure 4. The frequency of this oscillation is a function of the instrument and the ground coupling or firmness of the base. After an initial impact or pulse is received the "ringing" oscillation effectively forms a base on which all other arriving impulses are superimposed. Changes in the wave trace show the position and time of arrival of later pulses but the amplitude of the signal cannot be determined. Figure 5 shows a typical record where times are shown on each trace for the initial arrival (P-small) and the main S wave beginning, followed by some later arrival waves.

(5) Results

The surface tests results are summarised in Tables III and IV in which are shown the distance travelled by the wave pulse and the time of arrival from impact point. The squared values of distance and time are also included in the tables as these values were plotted for the reflected wave analysis. The graphs of T against D for the refractive method are shown in figures 6 to 7, and for the reflective plot in figures 9 and 10. Figures 8 and 11 show the refractive and reflective plot for the P wave pulse on the surface.

In addition to the first arrivals of the P and S waves it was possible on the longer distance records to identify a late wave arrival as a disturbance in the instrument response oscillation (see figure 5). These values are listed in Table V and graphed in figure 12 as a reflective plot.

The S wave tests made at 11 ft deep are listed in Table VI and graphed in figures 13 and 15. No P wave tests were taken at 11 ft, but the results for the S wave pulse show that P wave velocities were being recorded. Although the instruments were oriented to transmit and receive S waves it seems that the influence of the holes created a P wave from the originating S wave impulse and caused this to be recorded quite strongly with instruments oriented for S waves. Both S and P wave pulse tests were made at 20 ft. These results are given in Tables VII and VIII and plotted in figures 14, 16, 17, 18. At this depth both P and S waves were recorded from the S wave impulse, but only S wave velocities were found from the P wave test. Again it seems that the presence of the hole in some way caused a rotation of the initiated wave (from P to S). This phenomena has not been investigated any further.

(6) Interpretation of Results

(i) The wave velocity data has been plotted in two ways.

(a) As a refracted wave graph illustrated in Appendix I.

(b) As a reflected wave described in Appendix II.

The same values of time and distance are used in each method, but only in the direct arrival wave is the velocity found to be the same in each method. Which method should apply for the return waves is not easy to decide in some cases. The material has no sharp discontinuities, but there are distinct density changes revealed from the physical tests. Also the reflective method (Appendix II) leads to indicated layer depths which agree in general with the density and moisture changes.

(ii) Surface Tests

These are plotted by the refractive method in figures 6, 7, 8 which indicate a higher velocity layer at 7ft to 10 ft. Apart from a small change in moisture between 5 ft and 10 ft (figure 3) there is little evidence to support this. The shear wave velocity for impact (2) shows two values ($V_s = 550$ ft/s. and 765 ft/s.) which compare with the velocity ($V_s = 620$) from the impact (4) tests. Although not convincing there is here small evidence that different impact values create different velocities.

The same surface test data is plotted by the reflective method and shown in figures 9, 10, 11. The "average" reflective velocities of 725 ft/sec. in figure 9 and 860 ft/sec. in figure 10 seem to be too high to be S waves and not high enough to be P waves when the direct S wave velocities are 550 ft/sec. and 625 ft/sec. If the reflected wave velocity is considered in this case as a P wave travelling down and reflecting as an S wave, the method of Appendix III can be applied and the P wave velocities calculated as 1065 ft/sec. and 1385 ft/sec. respectively. These compare with the lower of the P wave values ($V_p = 1440$) found in figure 11.

From this method the following information can be inferred.

	Average
1. Upper layer S wave velocity 550-620	585
2. Upper layer P wave velocity 1065-1380	1200
3. A reflective layer exists at 14 to 16 ft, which agrees reasonably with the physical data in figure 3.	

(iii) Down Hole Tests

Because of the limitations on the number of holes, the results from these tests are rather limited, but some comparative information can be deduced.

At 11 ft deep the tests shown in figure 13 indicate an increased shear wave velocity ($V_s = 850$) which is consistent with an increase in density just below 10 ft. This value of shear wave velocity is also close to that found from the late arrival waves in the surface tests illustrated in figure 12 ($V_s = 913$ ft/sec.).

Although no P waves tests were made at 11 ft the records for S wave tests give wave arrivals with P wave velocity.

At 20 ft deep the S wave graph, figure 14,

indicates a shear wave velocity of 900 ft/sec. and a lower strata velocity of 1650 ft/sec., but there is no physical evidence of this strata. The reflective plot in figure 16 shows similar S wave velocity and a reflective layer which agrees with a change in density.

The P wave velocity is a little lower in this layer (20-27ft) with $V_p = 1300$ to 1500 ft/sec.

The P wave tests in figure 17 and 18 indicate S wave velocities.

The deductions from the down hole tests can be summarised as:

	11 ft	20 ft
S wave velocity	850	925
P wave velocity	1580	1700

A reflective layer exists at 25 - 27 ft; this could be a change in density and saturation level, as shown in figure 3.

It is difficult to know how far to take the finer interpretation of some of the down hole results but figures 15 and 16 present interesting data for speculation. In figure 15 two alternative velocity lines are shown for V_2 . This gives P wave velocities of 1250 ft/sec and 1380 ft/sec. The first of these is through the origin (as is $V_3 = 1660$) and is therefore not a reflected wave; and the second indicates a reflecting layer at (11 ft + 7 ft =) 18 ft. With a shear wave $V_s = 856$ ft/sec and density values from figure 3 the derived properties in Table X are deduced.

According to these wave reflections there is a relatively hard layer at 11 ft and a soft layer close to it. The relative hardness profile indicates that this could be so with a hard band between 10ft and 12 feet. The velocity reflection from 18 ft could correspond to the hard layer found between 14 ft and 18 ft. In figure 16 two velocities appear to be reflected from one hard layer at about 27 ft. Taken separately these gave the results shown in the last two lines of Table X.

When compared with the more general deductions given in Table IX the analysis to a finer degree does not greatly alter the values found for G and E.

7 Derived Properties

The relationship between n , V_s and V_p given in section 2, is plotted in figure 19 and the equations relating G, V_s and W are plotted on the chart in figure 20. These can be used to deduce the values of the elastic properties from the velocity data and densities found from tests. The calculation for E is from equation (2).

In table IX all the values of V_s , V_p and density are tabulated together with the derived properties.

The surface layer properties would apply for about 14 ft as revealed by changes shown in figure 3. The second layer between 14 - 20 ft has a higher and relatively uniform density and moisture content. Below 20 ft the density increases steadily to 25 ft and moisture increases to 25 ft after which it is fairly

stable at saturation. The bottom layer values apply at about 20 ft to 25 ft, but sampling down to 35 ft revealed a continuation of the very hard saturated material. It would be reasonable to use the same property values down to this depth.

The moisture content shows a slight increase between 35 ft and 40 ft which could indicate a decrease in density. This is consistent with the fact that the hole walls were soft and collapsed at a depth of about 41 ft and a rod probe was pushed down to a depth of 55 ft below the surface.

8. Conclusions

This investigation of the loess material was intended to reveal the characteristics of a uniform material and compare results from surface tests with down hole tests. It has in fact shown that the loess is stratified in density and moisture and these changes can be detected by the pulse wave method. The main purpose of this field test was to deduce the elastic properties of the ground material and it has been shown that with additional information from a large bore hole, these properties can be found. When applied to other materials (e.g. gravel and sand etc.) of a uniform nature, the different values of the elastic properties found are quite distinct and characteristic of the material. The moduli found by this method are related to very small strains and for greater strain the values would be smaller.

References

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- (4) Chae, Y. S. "Material Constants of Soils as determined from Dynamic Testing" - Proc. Int. Symp. Wave Propagation and Dynamic Properties of Earth Materials 1964.
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TABLE III

Surface Tests : S Wave Pulse

Impact (2)

Impact (4)

Test No.	D ft.	D ²	T sec.	T ²	Test No.	T secs	T ²
82201	10	100	.01395	1.946×10^{-4}	84201	.01465	2.15×10^{-4}
	20	400	.0259	6.71×10^{-4}		.02915	8.49×10^{-4}
82202	30	900	.0496	24.6×10^{-4}	84202	.0505	25.5×10^{-4}
	40	1600	.0637	40.57×10^{-4}		.0608	39.4×10^{-4}
82203A	50	2500	.0838	70.2×10^{-4}	84203A	.0801	64.2×10^{-4}
	60	3600	.109	118.8×10^{-4}		.0946	89.5×10^{-4}
82203C	50	2500	.0705	49.7×10^{-4}	84203B	.0701	49.1×10^{-4}
	60	3600	.0801	64.2×10^{-4}		.0796	63.4×10^{-4}
82204	70	4900	.0924	85.4×10^{-4}	84204	.0863	74.5×10^{-4}
	80	6400	.1029	105.8×10^{-4}		.1027	105.5×10^{-4}

See Figure Nos. 6

9

7

10

TABLE IV

Surface Tests : P Wave Pulse

(Impact (4))

Test No.	D ft	D ²	T sec	T ²
84107	10	100	.0234	5.47×10^{-4}
	20	400	.0747	55.8×10^{-4}
84106	40	1600	.0357	12.72×10^{-4}
	50	2500	.04125	17.0×10^{-4}
84105	70	4900	.0489	23.8×10^{-4}
	80	6400	.0551	30.35×10^{-4}

See Figure Nos.

8

11

TABLE V

Surface Tests : Late Arrivals, P Wave Pulse

Test No.	D ft	D ²	T sec	T ²
84106	40	1600	.0807	6.5×10^{-3}
			.1370	18.76×10^{-3}
	50	2500	.0805	6.48×10^{-3}
			.1190	14.15×10^{-3}
84105	70	4900	.090	8.1×10^{-3}
			.1357	18.44×10^{-3}
	80	6400	.099	9.8×10^{-3}
			.1370	18.76×10^{-3}

See Figure No. 12

TABLE VI

Down Hole Tests : 11 ft : S Wave Pulse

First Arrival Second Arrival

Test No.	D ft	D ²	T ₁ sec	T ₁ ²	T ₂ sec	T ₂ ²
84210	20	400	.012	1.44×10^{-4}	.0160	2.56×10^{-4}
	30	900	.0186	3.24×10^{-4}	.024	5.76×10^{-4}
84209	30	900	.0186	3.24×10^{-4}	.0239	5.71×10^{-4}
	40	1600	.0304	9.25×10^{-4}		
84208	40	1600	.0308	9.5×10^{-4}	.04916	24.19×10^{-4}
82206	40	1600	.0319	10.7×10^{-4}	.0443	19.64×10^{-4}

See Figure Nos. 13 15 13 15

TABLE VII

Down Hole Tests : 20 ft : S Wave Pulse

First Arrival

Second Arrival

Test No.	D ft	D ²	T1sec	T1 ²	T2sec	T2 ²
84211	20	400	.0157	2.465×10^{-4}	.0188	3.535×10^{-4}
	30	900	.02645	6.99×10^{-4}		
84212	30	900	.022	4.84×10^{-4}	.0334	11.66×10^{-4}
			.0251	6.30×10^{-4}		
	40	1600	.0279	7.78×10^{-4}		
			.0323	10.44×10^{-4}	.0446	19.9×10^{-4}

See Figure Nos. 14 16 14 16

TABLE VIII

Down Hole Tests : 20 ft : P Wave Pulse

Test No.	D ft	D ²	T sec	T ²
84114	20	400	.0212	4.5×10^{-4}
	30	900	.0339	11.5×10^{-4}
84113	30	900	.0335	11.2×10^{-4}
	40	1600	.0413	17.06×10^{-4}

See Figure Nos. 17 18

TABLE IX
Summary of Properties

Depth ft	Density lbs/c.ft	V_s ft/sec	V_p ft/sec	$V_r = V_p/V_s$	n -	G lbs/sq.in	E lbs/sq.in
0 to 14 ft.	108	585	1200	2.05	0.34	7,800	21,000
14 ft to 20 ft	121	850	1600	1.855	0.3	18,000	46,800
20 ft to 35 ft	125	915	1400	1.53	0.15	22,000	53,000

TABLE X

Depth ft	Density lbs/c.ft.	V_s ft/sec	V_p ft/sec	$V_r =$ V_p/V_s	n	G lbs/sq.in.	E lbs/sq.in.
11	109	856	1250	1.46	0.1	17,000	37,400
		856	1660	1.915	0.32	17,000	45,000
11-18	120	856	1380	1.61	0.15	18,000	41,400
20-27	125	900	1513	1.68	0.22	22,000	53,800
			1315	1.46	0.07	22,000	47,000

DEPTH OF SUBSURFACE LAYERS

REFRACTION METHOD

Velocities, strata (1) = V_1
 strata (2) = V_2

Wave paths S-R
 SABR

Travel time

(1) path S-R = $\frac{X}{V_1} = T_1$

(2) path SABR

$$T_2 = \frac{2D \sec \theta}{V_1} + \frac{X - 2D \tan \theta}{V_2}$$

For minimum time

$$\frac{dT_2}{d\theta} = \frac{2D \sin \theta}{V_1 \cos^2 \theta} - \frac{2D \sec^2 \theta}{V_2} = 0$$

Hence $\sin \theta = \frac{V_1}{V_2}$

and $T_2 = \frac{2D(V_2^2 - V_1^2)^{\frac{1}{2}}}{V_1 V_2} + \frac{X}{V_2}$

For $T_1 = T_2$

$$X_c = 2D \left[\frac{V_2 + V_1}{V_2 - V_1} \right]^{\frac{1}{2}}$$

$$V_1 = \frac{X_1}{T_1}$$

$$V_2 = \frac{X_2}{T_2}$$

$$\therefore D = \frac{X_c}{2} \left[\frac{V_2 - V_1}{V_2 + V_1} \right]^{\frac{1}{2}}$$

DEPTH OF SUBSURFACE LAYERS

REFLECTION METHOD

For path SOR

$$L = (4D^2 + X^2)^{\frac{1}{2}}$$

Travel time

$$T = \frac{L}{V}$$

$$\therefore T^2 = \frac{4D^2 + X^2}{V^2}$$

At $X=0$

$$T_0 = \frac{4D^2}{V^2}$$

$$\text{Hence } D^2 = \frac{T_0 V^2}{4}$$

$$\frac{d(T^2)}{d(X^2)} = \frac{1}{V^2} \quad V = \left(\frac{X_1^2}{T_1^2} \right)^{\frac{1}{2}}$$

MODIFIED REFLECTED WAVE VELOCITY

Assumptions

- (1) S wave velocity for layer is $V_1 = V_3$ (measured)
- (2) P wave velocity is V_2
- (3) P wave reflects as S wave
- (4) 'Average' velocity on path ABC is V_4 (measured)
- (5) Corresponding travel times are T_1, T_2, T_3 : $T_4 = T_2 + T_3$

$$\text{P wave path } L = V_2 T_2 = V_3 T_3$$

$$= V_1 T_3$$

$$T_2 = \frac{V_1 T_3}{V_2}$$

$$\text{'Average' velocity } V_4 = \frac{2L}{T_2 + T_3}$$

$$= \frac{2V_1 T_3}{\frac{V_1 T_3}{V_2} + T_3} = \frac{2V_1 V_2}{V_1 + V_2}$$

$$\text{so } \underline{\text{P wave velocity } V_2} = \frac{V_1 V_4}{2V_1 - V_4}$$

Glenmore Brickworks : Christchurch.

CROSS SECTION N° 12 GEOLOGICAL SURVEY (DSIR) 1966

scale 1"=100'

FIG N° 1

GLENMORE BRICKWORKS TEST SEQUENCE

		distances : feet									
Test nº	Imp nº	0	10	20	30	40	50	60	70	80	
		<u>surface : S wave pulse</u>									
82201	2	↓	▽	▽							
84201	4										
82202	2	↓			▽	▽					
84202	4										
82203	2	↓					▽	▽			
84203	4										
rep 03	2	↓					▽	▽			
84203	4										
82204	2	↓							▽	▽	
84204	4										
		<u>surface : P wave pulse</u>									
84105	4	→							◁	◁	
84106	4	→				◁	◁				
84107	4	→	◁	◁							
rep 07	4	→	◁	◁							
rep 07	4	→	◁	◁							
		<u>down holes 11 ft : S wave pulse</u>									
84208	2			⬇					⬇		
84208	4										
84209	4			⬇				⬇	⬇		
84210	4			⬇			⬇	⬇	⬇	⬇	
		<u>down holes 20ft : S wave pulse</u>									
84211	4			⬇			⬇	⬇	⬇	⬇	
84212	4			⬇			⬇	⬇	⬇	⬇	
rep 12	4			⬇			⬇	⬇	⬇	⬇	
		<u>down holes 20ft : P wave pulse</u>									
82113	2			→			⬅	⬅	⬅	⬅	
84113	4			→							
84114	4			→			⬅	⬅	⬅	⬅	

FIG Nº 2

DEPTH PROFILE of Hole at 70 ft

FIG No 3

Ringing response from a small impact

TEST N° 84204

FIG N° 5

S WAVE PULSE : IMPACT 2 : ON SURFACE

FIG № 6

WAVE PULSE: IMPACT 4: ON SURFACE

P WAVE PULSE : IMPACT 4 : ON SURFACE

FIG N° 8

S WAVE PULSE : IMPACT 2 : ON SURFACE

FIG N° 9

S WAVE PULSE : IMPACT 4 : ON SURFACE

FIG № 10

P WAVE PULSE: IMPACT 4: ON SURFACE

FIG N° 11

P WAVE PULSE: IMPACT 4: LATE ARRIVALS: ON SURFACE

FIG N° 12

S WAVE PULSE: IMPACT 4:20ft DEEP

FIG N°14

S WAVE PULSE: IMPACT 4:11ft DEEP

FIG N°13

S WAVE PULSE : 11ft DEEP

FIG. N° 15

S WAVE PULSE: IMPACT 4: 20ft DEEP

FIG. N° 16

P WAVE PULSE : IMPACT 4: 20 ft DEEP

FIG N° 17

P WAVE PULSE : IMPACT 4: 20 ft DEEP

FIG N° 18

FIG. N° 19