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DEPARTMENT OF NATIONAL DEVELOPMENT

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

RECORD No. 1964/114

MEADOWBANKS DAM SITE, SEISMIC DETERMINATION OF ROCK CONSTANTS,

TASMANIA 1963

by

W.A. WIEBENGA, P.E. MANN and J.C. DOOLEY

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SUMMARY

This Record shows how the five elastic constants of a transversely anisotropic rock can be determined in the field if boreholes are available which may be used as shot-holes. The equipment consists of a seismograph, vertical geophones, and three-component geophones.

Five constants are needed to define the elastic properties of the medium. (An elliptical law of velocity distribution in the x-z plane does not necessarily apply). Young's moduli and Poisson's ratios for various directions can be calculated from these. The results are given for one day's field work at Meadowbanks dam site, Tasmania, where the bedrock consists of horizontally layered sandstone and siltstone underlying mudstone. The accuracy of determination of the constants was limited by the accuracy of measurement of short time intervals, and four constants only could be determined for each layer.

1. INTRODUCTION

The Hydro-Electric Commission of Tasmania proposes to build a dam and power station on the Derwent River, four miles south of Hamilton. The dam site is referred to as Meadowbanks dam site and the centre of the dam site is located about 200 ft north and 2300 ft east of grid reference point 475750 on the Oatlands sheet of the Australia 1:250,000 map series.

Geological investigations started with drilling two holes in 1944. A geological reconnaissance survey was made in 1953 and a geological report prepared by Mather (1961) included geology, borehole data, and laboratory tests on core samples.

The Commission started excavating the river diversion channel and the foundation rock on both banks of the river. However, considerable doubt existed about the strength of the rock to withstand horizontal stresses. To supplement its laboratory tests, the Commission requested the Bureau of Mineral Resources, Geology and Geophysics (BMR) to determine the elastic constants of the foundation rock in situ, by using seismic methods. The work was done on 7th May 1963 by a party consisting of P.E. Mann (party leader), F. Jewell (the Commission's geophysicist), and four assistants supplied by the Commission. W.A. Wiebenga (Senior Geophysicist, BMR) was also present at the experiments.

2. GEOLOGY

According to Mather (1961) the area is underlain by gently dipping, interbedded sandstones, siltstones, and mudstones of Triassic age which are considered to be equivalent to the Knocklofty Sandstone and Shale Formation.

The sandstones are dominantly quartzose but contain varying amounts of mica, graphite, and oxides of iron and manganese. The quartz grains are sub-angular to rounded, and the size ranges from medium to fine.

The grains in the siltstones are also quartz, but clay and mica flakes are more abundant than in the sandstones. The mudstones are predominantly clay but some of them contain mica on the bedding planes. In some places the mudstones and siltstones are finely interbedded to give a closely bedded sediment.

Mather (1961, Drawing No.A9030) distinguishes five main mudstone beds, which he refers to as Beds 0 to 4. Bed 0 intersects the sides of the valley. At the time of the seismic test the right hand side of the valley floor (facing downstream) had been excavated down to the top of Bed 1 (Plate 1). Bed 1 is 10 to 15 ft thick and overlies sandstone. Bed 2, at a depth of about 20 to 25 ft below ground surface in the excavated area, consists of mudstones and siltstones.

Three main sets of joints have been observed:

(a) gently dipping close to the direction of bedding.

(b) steeply dipping, strike south-east, parallel to the river.

(c) steeply dipping, strike north-east, normal to the river.

3. METHODS

The seismic refraction method was used. A 300-ft spread was laid out in the excavated area on the right hand side of the valley about three feet from the excavation wall, and roughly parallel to the river. Vertical geophones were placed at 50-ft intervals, with three-component geophones at each end of the spread to record the ground movement in three mutually perpendicular directions. Shot distances were 60 and 170 ft from the north-western end (upstream) and 100 and 290 ft from the south-eastern end (downstream) of the spread. A shot was also placed in the centre of the geophone spread to measure the near-surface velocities. With the combination of vertical and three-component geophones in the above arrangement, velocities of longitudinal and transverse waves can be measured along the refractors, i.e. roughly parallel to the ground surface and parallel to the bedding.

To obtain the velocities of longitudinal and transverse waves in a vertical or oblique direction, shots were exploded in 'Calyx' drill hole No.318 at 85, 70, 53 and 45-ft depth; the ground motion events were recorded with three-component geophones at the surface at the top of the hole and at positions 15 ft and 20 ft away from the drill-hole collar. A spread of vertical geophones was also used, spaced at 20-ft intervals from 40 to 100 ft in line with the shot-point.

The equipment used consisted of an SIE refraction seismograph, TIC geophones of natural frequency about 20 c/s; and two Hall-Sears omni-directional vibration detectors, Model HS-1-LP 3D, of natural frequency about 14 c/s.

The seismic method of determining elastic constants of rocks in situ is a dynamic method. It has the advantage that the rock is not disturbed or changed by sampling methods, and that the determination applies to a large body, or sample, of rock.

4. THEORY OF TRANSVERSE ANISOTROPIC ELASTICITY

The theory of elastic wave propagation in a medium with elastic properties symmetrical about one fixed direction (the vertical axis x = y = 0 in the instance of Meadowbanks dam site) has been worked out by Love (1927) and Stoneley (1949). Such a medium is called transversely anisotropic. The elastic properties of a transversely anisotropic medium are described by five elastic constants (A, C, F, L, and N) in the following stress-strain relations (see Fig. 1).

$$\left.\begin{aligned}
X_x &= Ae_{xx} + (A - 2N)\, e_{yy} + F\, e_{zz} \\
Y_y &= (A - 2N)\, e_{xx} + A\, e_{yy} + F\, e_{zz} \\
Z_z &= F\,(e_{xx} + e_{yy}) + C\, e_{zz} \\
X_y &= Y_x = N\, e_{yx} \\
Y_x &= Z_y = L\, e_{zy} \\
Z_x &= X_z = L\, e_{xz}
\end{aligned}\right\} \qquad (1)$$

where X_x, e_{xx} are the extensional stress and strain along the x axis,

X_y, $e_{yx} = e_{xy}$ are the shear stress and strain for the x, y axes,

and similarly for the other quantities.

Note that for an isotropic body with Lame parameters λ and μ, $A = C = \lambda + 2\mu$, $F = \lambda$, and $L = N = \mu$ (μ is shear modulus).

First let us study the two-dimensional case for motion confined to the plane y = 0. The stress-strain relations become:

$$\left.\begin{aligned} X_x &= Ae_{xx} + Fe_{zz} \\ Z_z &= Fe_{xx} + Ce_{zz} \\ Z_x &= X_z = Le_{zx} \end{aligned}\right\} \qquad (2)$$

Stoneley (<u>op. cit.</u>, p.345, equation 9) developed the following wave-velocity relation :

$$n^2\left[(A - J)\ l^2 + Ln^2 - \rho c^2\right]\left[(J + L)\ l^2 + Cn^2 - \rho c^2\right]$$
$$+l^2\left[Al^2 + (J + L)\ n^2 - \rho c^2\right]\left[(C-J)\ n^2 + Ll^2 - \rho c^2\right] = 0 \qquad (3)$$

in which l, m = 0, n, are direction cosines, and $l^2 + n^2 = 1$;
$J = F + L$, and A, C, F, and L are four of the elastic constants referred to in (1) and (2), c is the velocity, and ρ the specific gravity of the medium.

The following cases are of practical importance to measuring techniques :

(a) for rays in the x direction (l = 1; n = o)

$A = \rho c^2$ (longitudinal P wave) (4)

$L = \rho c^2$ (vertical polarised transverse SV wave) (5)

(b) for rays in the Z direction (l = o; n = 1)

$C = \rho c^2$ (longitudinal P wave) (6)

$L = \rho c^2$ (transverse S wave) (7)

Equation (3) can be reduced to :

$$2\rho c^2 = Al^2 + Cn^2 + L \pm \left[\left\{(A-L)\ l^2 - (C-L)\ n^2\right\}^2 + 4\ J^2l^2n^2\right]^{\frac{1}{2}} \qquad (8)$$

Equation (8) gives two solutions for ρc^2. In general for oblique paths, neither of the waves is purely compressional or purely distortional. For almost-isotropic media, the higher value of c is applicable to predominantly longitudinal waves, and the lower value to vertically polarised and predominantly transverse waves.

For an isotropic medium in terms of Lame constants equation (8) reduces to:

$$2\rho c^2 = 2\lambda + 4\mu$$

$$\text{or}\quad 2\rho c^2 = 2\mu$$

To compute the elastic constant N, Stoneley (op. cit. p.347, equation 11a) shows that for horizontally polarised wavse SH

$$\rho c^2 = l^2 N + n^2 L \tag{9}$$

and for the x direction (n = 1) :

$$N = \rho c^2 \tag{10}$$

If A, C, and L have been obtained as above, F = J - L can be theoretically obtained from surface recordings of rays following oblique paths from borehole shots, using the following equation :

$$F = \sqrt{(\rho c^2 - Ln^2 - Al^2)\ (\rho c^2 - Ll^2 - Cn^2)}\ /\ ln - L \tag{11}$$

In dealing with a single layer, it would suffice to record the time taken over a path at a convenient angle (say 45 degrees, with geophone distance equal to shot-depth), and substitute the measured value of c and appropriate values of l and n in equation (11).

For a two-layer problem, an exact solution depends on solving the following equations :

$$t = h_1/n_1c_1 + h_o/n_oc_o \tag{12}$$

$$x = h_1l_1/n_1 + h_ol_o/n_o \tag{13}$$

$$c_1/l_1 = c_o/l_o \tag{14}$$

$$l_1^{\,2} + n_1^{\,2} = l_o^{\,2} + n_o^{\,2} = 1 \tag{15}$$

where h_o is thickness of upper layer (see Fig. 2),

h_1 is depth of shot below top of lower layer,

l_o, n_o, l_1, n_1 are direction cosines of rays in upper and lower layers ($m_o = m_1 = 0$),

c_o, c_1, are velocities in upper and lower layers in directions (l_o, 0, n_o) and (l_1, 0, n_1) respectively,

x is horizontal distance from shot-point to geophone, and

t is travel time.

Of these, x, t, h_o, and h_1 may be regarded as known, and c_o, c_1, l_o, n_o, l_1, and n_1 as unknown. Thus there are only five equations to determine six unknowns, and the problems cannot be solved by shooting and recording at one point only. Use of equation (11) under these circumstances only substitutes the unknown F_o and F_1 for c_o and c_1. The above theory also assumes that the surface and the boundary between the two layers are horizontal. Corrections can be made for surface elevations, but in practice, variations in travel time occur in the top few feet through unconsolidated soil or weathered material, and this represents an additional unknown which should be included in equation (12).

To solve the problem completely then, it is necessary to shoot at different depths and record at different distances. One obvious proposal would be to shoot at or just above the boundary to determine c_o and hence F from equation (11) for the upper layer.

Another method would be to shoot at two different depths in the lower layer, and record the times of rays travelling at the same angle to the vertical. This should give the same travel time through the upper layer, and the same value for c_1 in the lower layer; thus c_1 could be calculated from the difference in times. Thus equations (14) and (15) above would be unchanged, as would the last terms of equations (12) and (13). This would give :

$$c_1 \Delta t = \Delta x / l_1 = \Delta h / n_1 \tag{16}$$

where refers to differences between the two shots; or for 45 degrees

$$\left. \begin{aligned} c_1 &= \sqrt{2}\,\Delta h / \Delta t \\ \Delta x &= \Delta h \end{aligned} \right\} \tag{17}$$

It remains to determine the appropriate geophone positions for a given angle, i.e. x_o in Fig. 3 should be known; in practice this could be estimated with sufficient accuracy. However, if unknown surface corrections exist, this method is not sufficient.

To eliminate the surface corrections it is necessary to record at the same geophone position, paths from shots at different depths. In the near-surface low-velocity material the ray path would be almost vertical and the travel-time through it may be taken as constant. However, this involves paths at different angles through the layers, and hence new values for the six unknowns, while adding only five equations similar to (12) to (15). We have therefore to add two (or more) further equations similar to (8), which replace the four (or more) unknown velocities by two unknown values of F.

In the present problem, where time intervals of only a few milliseconds (msec) were measured with an accuracy of $\pm$ 1 msec, it is clear that the algebra and subsequent calculations involved in getting an exact theoretical solution would not be justified. In fact, as will be seen, it was not possible to determine a value for F for the lower layer with any certainty. However, the theory has been set out in some detail above for future reference, and as a background to the present approach.

Another approach is to detonate a series of explosions at two or more depths, and record the waves from each explosion at several geophone locations. Theoretical travel-time curves for each explosion could be calculated from equations (8) and (12) to (15), i.e. values of x and t could be obtained for various assumed values of F and l_1. These could be matched against the observed travel-time curves, and the value of F chosen which gives the best fit for all curves.

To transform the constants A, C, F, L, and N into Young's moduli, equation (18) from Love (1927, p.161) may be used :

$$\frac{1}{E_1} = \frac{BC - F^2}{\begin{vmatrix} A & H & G \\ H & B & F \\ G & F & C \end{vmatrix}}$$

For a transversely isotropic medium F = G, A = B, L = M, and H = (A - 2N); $E_1 = E_2$ is Young's modulus in the horizontal plane. Hence :

$$E_1 = E_2 = \frac{\begin{vmatrix} A & A-2N & F \\ A-2N & A & F \\ F & F & C \end{vmatrix}}{AC - F^2} = \frac{4ND}{AC - F^2} \quad (18)$$

where $D = AC - F^2 - CN$ (19)

Young's modulus in the vertical direction is :

$$E_3 = D/(A-N) = C - F^2/(A-N) \quad (20)$$

The three Poisson's ratios are represented by:

σ_1 - effect of horizontal strain on horizontal strain.

σ_2 - effect of horizontal strain on vertical strain.

σ_3 - effect of vertical strain on horizontal strain.

The formulae given by Love (op. cit. p.162, equation 20), with appropriate substitutions, reduce to :

$$\sigma_1 = 1 - 2NC/(AC - F^2) = E_1/2N - 1 \quad (21)$$

$$\sigma_2 = 2FN/(AC - F^2) = F(1 - \sigma_1)/C \quad (22)$$

$$\sigma_3 = F/2(A - N) = E_1/\sigma_2 E_3 \quad (23)$$

There are certain restrictions on the values of the constants, as given by Barden (1963, p.201). His two inequalities (13) and the three unnumbered preceding ones may be shown to be equivalent (with positive elastic constants), and may be expressed as :

$$1 > \sigma_1 + 2\sigma_2\sigma_3 \quad (24)$$

or $C(A - N) > F^2$ (25)

Further restrictions given by Barden '...on the assumption that the dilatation has the same sign as the applied stress, which may be true for perfectly elastic materials, but which is not necessarily true for soil...' are:

$$1 > \sigma_1 + \sigma_2 \quad (26)$$

$$0.5 > \sigma_3 \quad (27)$$

By substituting from (21), (22), and (23) above, these are equivalent to :

$$2N(C - F)/(AC - F^2) > 0 \tag{28}$$

$$A - N > F \tag{29}$$

As $AC - F^2$ is positive from (25), (28) becomes

$$C > F \tag{30}$$

It should be noted that σ_1 or σ_2 may be greater than 0.5, contrary to the usual restriction for isotropic media.

Taking σ_1 as positive gives us the additional restriction from (21) :

$$1 > 2NC/(AC - F^2)$$

$$\text{or} \quad N < (AC - F^2)/2C \tag{31}$$

5. RESULTS

The seismic refraction results are shown in Plate 1. Three layers are indicated :

(1) A thin 3 ft to 7 ft thick surface layer in which the seismic velocity is about 3000 ft/sec,

(2) An upper layer in which the horizontal longitudinal seismic velocity is 7200 ft/sec representing the mudstone of 'Bed 1' (see Geology),

(3) A lower layer in which the horizontal longitudinal seismic velocity is 11,500 ft/sec, representing the sandstone below the mudstone ('Bed 1').

The depth of the 11,500-ft/sec layer is about 20 ft at the north-western end of the seismic spread (near 'Calyx' drill hole No. 318) and about 9 ft at the south-eastern end. The average depth is about 16 ft, with a slight north-westerly dip in the direction of the traverse.

The seismic velocities were also measured perpendicular to the bedding in 'Calyx' drill hole No. 318, a hole about 4 ft in diameter drilled at the same locations as DH322. The collar of this drill hole is about 20 ft higher than the excavated surface where the main seismic traverse was laid out. The geophones for recording the vertical waves were laid out on the natural surface adjacent to drill hole No. 318. Shots were fired at depths of 45, 53, 70, and 85 ft. The vertical longitudinal velocity in the mudstone (Bed 1) above 45-ft depth appeared to be about 4700 ft/sec or slightly less, and in the sandstone and siltstone layers below 'Bed 1' about 8300 ft/sec. These measurements can be accurate only within about 25 percent because of the short travel times involved. However, it appears that there is some velocity anisotropy.

The transverse wave velocities measured in the borehole are about 3600 ft/sec between 45 and 70-ft, depth in the sandstone and siltstone, and 2500 ft/sec or slightly less in the mudstone between the surface and 45-ft depth.

The velocity of the horizontally polarised transverse wave in the X direction, measured from seismic refraction shots in two opposite directions, is about 4400 ft/sec in the sandstone and siltstone. This determination is not very accurate. The oblique path from the shot at 45-ft depth to the geophone at 40-ft distance gives a velocity of about 5500 ft/sec.

The specific gravity of the sandstone and siltstone was taken as about 2.47 and of the mudstone about 2.4 (Mather, 1961).

The elastic constants A, C, L, and N were calculated from equations (4), (5), (6), (7), and (10). The results are shown in Table 1. The velocity of the horizontally polarised wave travelling horizontally in Bed 1 could not be measured, and therefore N could not be determined.

TABLE 1

Elastic Constants	Sandstone and siltstone		Mudstone Bed 1	
	in units of 10^9 dyne/cm^2	in units of 10^6 lb/in^2	in units of 10^9 dyne/cm^2	in units of 10^6 lb/in^2
C	160	2.3	48	0.69
A	300	4.4	116	1.68
L	30	0.43	14-	0.20-
F	?	?	16	0.23
N	45 $\pm$	0.65 $\pm$	?	?

Using these values of A, C, and L for the lower layer, velocities have been calculated for various values of F. These are plotted as a function of inclination to the vertical in Figure 4. From the restriction (30), F must be less than 160 x 10^9 dyne/cm^2; the velocities have been calculated for 0, 50, 100, or 150 x 10^9 dyne/cm^2. The maximum variation in velocity for a given angle occurs between 30 and 45 degrees and is about 1500 ft/sec; the corresponding difference in travel time for a path of 50 ft is about 1 msec. As the times can only be estimated to 1 msec and they show a scatter of 1 or 2 msec about a smooth curve, it is therefore impossible to make an estimate of F for the lower layer with any certainty.

It is interesting to note that for low values of F and for inclinations to the vertical less than about 40 degrees the velocity may be lower than in the vertical direction. An assumption is commonly made, that the velocity for cross-anisotropic media in the vertical plane plotted in polar co-ordinates describes an ellipse. Figure 4 shows that this is not true in general, and may not be even roughly true.

From restriction (31), N for the upper layer must be less than 55 $dyne/cm^2$.

Tables 2 and 3 show values of the principal Young's moduli and Poisson's ratios for the two media, calculated for various values of the unknown elastic constants, using equations (18) to (23).

TABLE 2

Elastic constants of sandstone and siltstone

F (10^9 $dyne/cm^2$)		25	50	75	100	125	150
E_1	10^9 $dyne/cm^2$	153	152	149	146	140	129
	10^6 lb/in^2	2.22	2.20	2.16	2.12	2.03	1.87
E_3	10^9 $dyne/cm^2$	158	150	138	121	99	72
	10^6 lb/in^2	2.29	2.18	2.00	1.76	1.44	1.04
	σ_1	0.70	0.68	0.66	0.62	0.56	0.44
	σ_2	0.05	0.10	0.16	0.24	0.31	0.53
	σ_3	0.05	0.10	0.15	0.20	0.24	0.29

TABLE 3

Elastic constants of mudstone (Bed 1)

N (10^9 $dyne/cm^2$)		10	20	30	40	50
E_1	10^9 $dyne/cm^2$	36	66	88	102	110
	10^6 lb/in^2	0.52	0.96	1.28	1.48	1.60
E_3	10^9 $dyne/cm^2$	46	45	45	45	44
	10^6 lb/in^2	0.67	0.65	0.65	0.65	0.64
	σ_1	0.82	0.64	0.46	0.28	0.10
	σ_2	0.06	0.12	0.18	0.24	0.30
	σ_3	0.08	0.08	0.09	0.11	0.12

From Table 2, it can be seen that variations in F near the middle of its range (say 50 to 100) do not effect E_1, E_3, or σ_1 greatly. Table 3 shows that variations in N do not effect E_3 or σ_3 greatly, but E_1, σ_1, and σ_2 are sensitive to these variations. E_1 probably has a value between 50 and 100 x 10^9 $dyne/cm^2$ for the mudstone.

Wiebenga and Manganwidjoyo (1960) give an empirical relation between longitudinal seismic velocity and rock strength, measured as compressive strength in a standard compression test. Taking the lowest seismic velocities in the anisotropic rock as a measure, the compressive strength of the sandstone or siltstone is estimated at 11,000 lb/in^2 or 4.9 ton/in^2, and of mudstone (Bed 1) at 7500 lb/in^2 or 3.3 ton/in^2.

Wiebenga and Manganwidjoyo (1960) give also an empirical relation between porosity and compressive strength. Based on specific gravity measurements made by the Commission (Mather, 1961) the porosity of the sandstones and siltstones is estimated at about 15 percent. By using the empirical relation, the compressive strength is estimated at about 12,000 lb/in^2 or 5.4 ton/in^2. This agrees closely with the estimate based on seismic velocity.

For comparison Mather (1961) gives the compressive strength of a fresh sandstone from $DH_2 254$ (measured in the laboratory) as between 3.18 and 5.77 ton/in^2, and of a mudstone between 1.72 and 1.93 ton/in^2.

6. CONCLUSIONS

The most important elastic constants to be considered are the constants L and N in relation to horizontal shear stresses in a horizontally layered medium. L for the mudstone of Bed 1 is considerably lower than for the underlying sandstone and siltstone. Although N for mudstone was not determined it is probably comparable to L, and also considerably lower than N for the underlying sandstone and siltstone.

The mudstone of Bed 1 is not recommended as a suitable foundation rock for a dam. The underlying sandstone or siltstone may be strong enough for certain types of dam.

The accuracy of determination of the elastic constants was severely limited by the accuracy or time measurements over short distances in the vertical or oblique directions. For future problems of this type, it would be desirable to investigate more-accurate methods of time recording, perhaps such as those used with the continuous velocity logger, or those used by White and Sengbush (1953).

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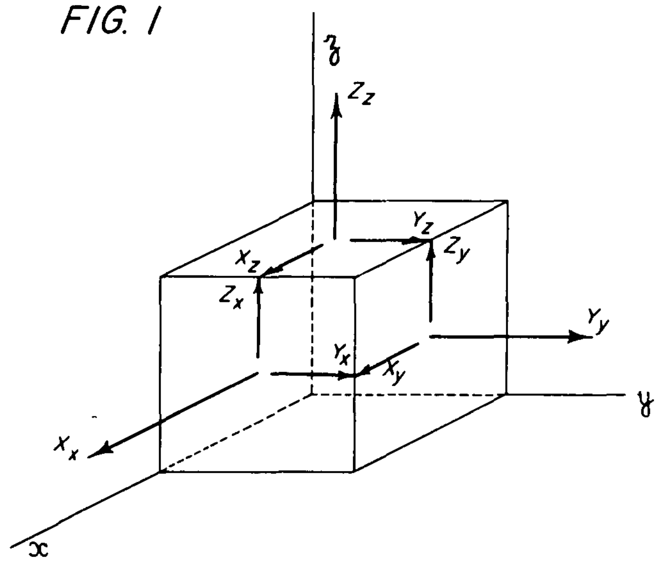
APPENDIX

Velocity measurements on core samples

For comparison with the geophysical work the transmission time or velocity of pulsed ultrasonic waves (frequency 125 kc/s) in unwaxed and waxed core samples of drill hole DH 322 was measured in the Bureau's Footscray laboratories using an ultrasonic material tester (type UCT2) manufactured by Cawkell. The results are shown below :

Sample No.	Length of sample (in)	Depth of sample (ft)	Velocity (ft/sec)	Description	
1	15.1	9	10,980	Unwaxed,	sandstone
2	15.2	18	10,950	"	"
3	1.8	32	5480	"	mudstone
4	2.4	32½	6370	"	"
6C	2.4	46	6100	"	"
5	2.2	47	7420	"	"
8	2.2	61½	7650	"	sandstone
7	1.7	63½	9950	"	"
10	2.2	75½	8350	"	mudstone
9	2.3	76½	8800	"	"
92D	4.6	81	11,580	Waxed,	siltstone
92E	4.2	81	13,300	"	"
92F	4.2	81	9400	"	"
93A	4.1	84	12,650	"	sandstone
93B	4.1	84	12,350	"	"
94	4.1	85	13,080	"	"
95A	4.1	87	13,180	"	"
95B	4.0	87	13,080	"	"
96A	4.1	88	13,080	"	"
96B	4.1	88	14,500	"	"
231	17.7	92	10,150	"	siltstone

FIG. 1



DIRECTIONS OF STRESS COMPONENTS

FIG. 2

OBLIQUE RAY PATH

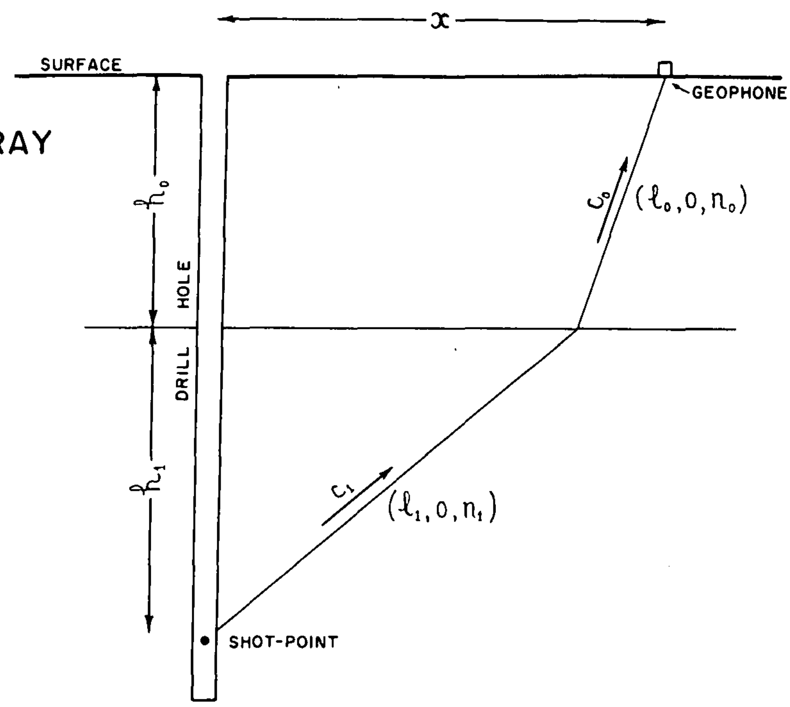
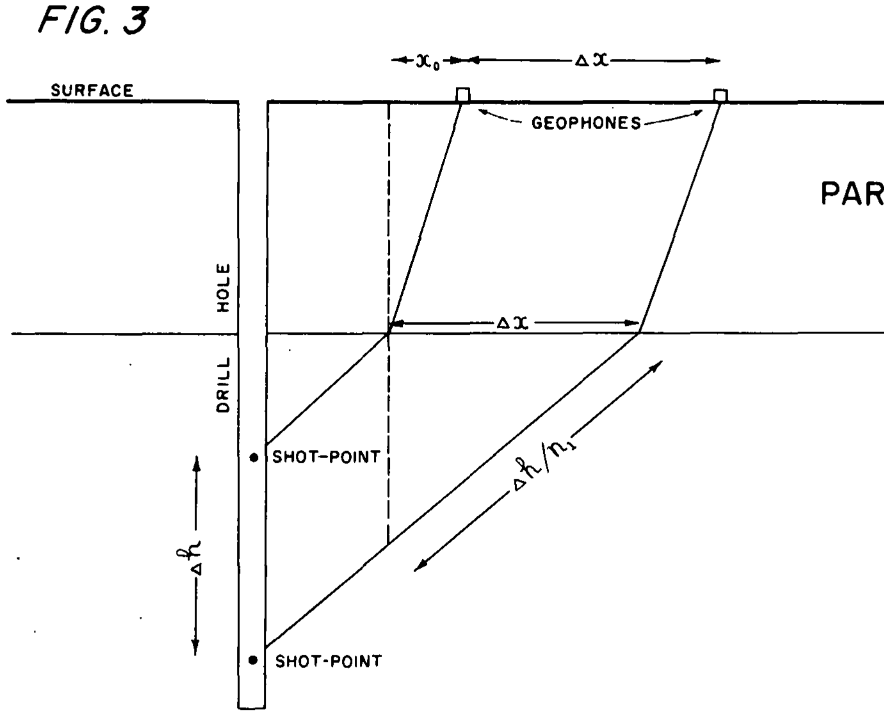


FIG. 3



PARALLEL RAY PATHS

FIG. 4

SEISMIC VELOCITY FOR OBLIQUE PATH IN LOWER MEDIUM

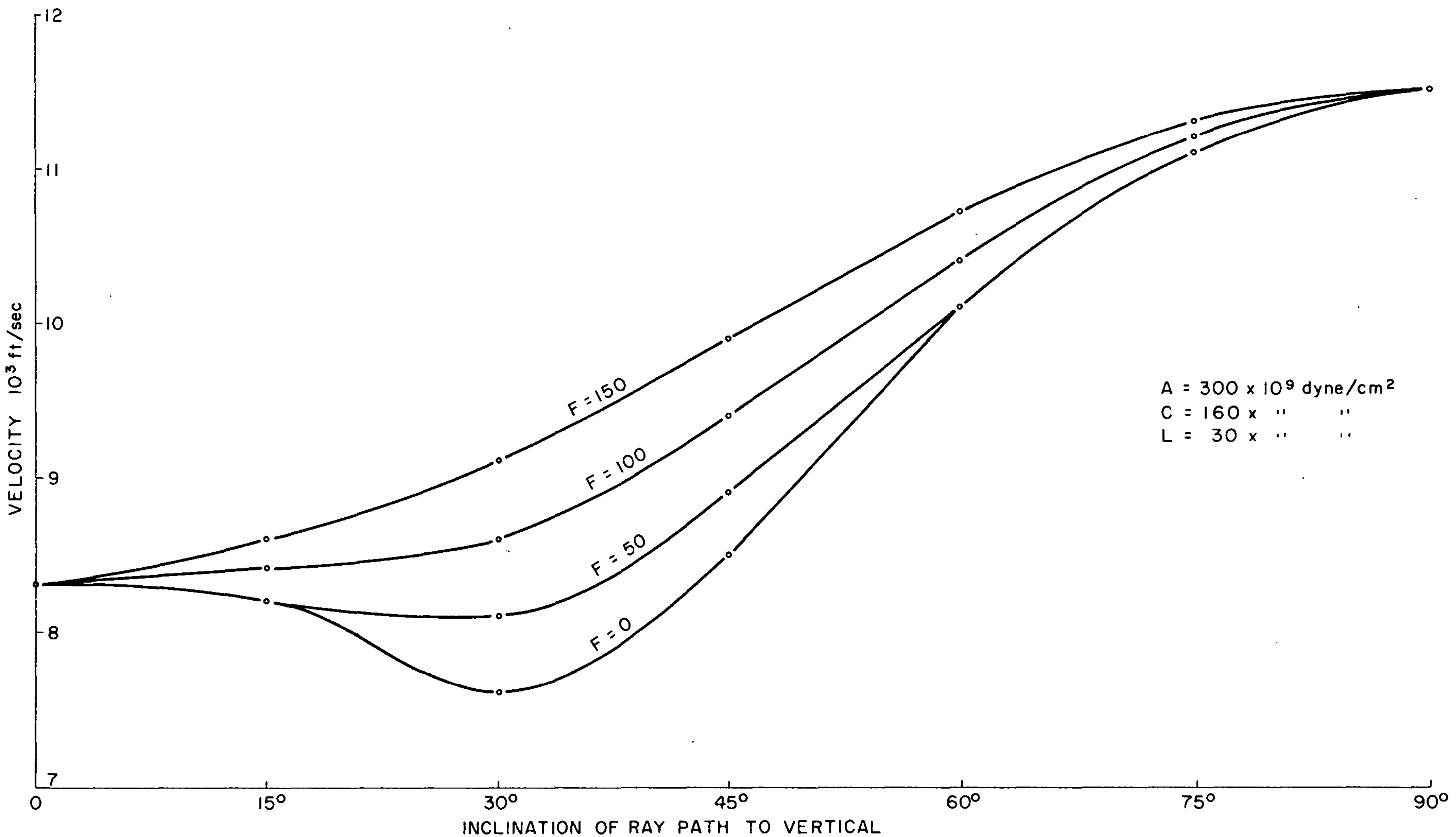


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FIG. 4

MEADOWBANKS DAM SITE, TASMANIA, 1963

SEISMIC DETERMINATION OF ROCK CONSTANTS

TO ACCOMPANY RECORD No. 1964/114

Geophysical Branch, Bureau of Mineral Resources, Geology and Geophysics

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