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1957 No. 31



# GEOPHYSICAL SURVEY OF THE ACTON WEIR SITE,
# CANBERRA, A.C.T.

by

L. V. HAWKINS.

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ILLUSTRATIONS

## ABSTRACT

A geophysical survey was carried out by the Geophysical Section of the Bureau of Mineral Resources to investigate the depths to rock suitable for the foundations of a proposed weir across the Molonglo river at a site near Acton, Canberra.

A detailed description of the seismic refraction method as used by the Bureau for investigating foundation problems is given, together with a graph for determining the Young's Modulus of rocks from the seismic velocity of the recorded compressional waves.

The results of the survey show the weir site to be divided into two distinct areas by an approximate north-south line just west of Lennox Crossing. East of this line the depths to rock suitable for foundations appears to be relatively shallow; the weathered bedrock which generally appears to have a Young's Modulus of $1.3 \times 10^{11}$ dynes/cm$^2$ or higher might prove adequate for foundations and ranges from 12 to 37 feet in depth, the average depth being 25 feet. Unweathered bedrock with a substantially higher Young's Modulus is from 10 to 20 feet deeper. West of the line, the weathered layer is much thicker and may be unsuitable for foundations; the depth to unweathered bed-rock is considerably greater than to the east of the line, ranging from 54 to 147 feet and averaging about 94 feet. Also the bedrock appears to be intersected by a number of fault zones in which the seismic velocity and Young's Modulus are relatively low.

From considerations of depth and velocity of the unweathered and weathered bedrock, the best prospects for obtaining suitable foundations appears to be near the bridge at Lennox Crossing.

## INTRODUCTION

The Department of Works, Canberra, proposes constructing a weir across the Molonglo River as part of the Canberra Lakes scheme. Two alternative weir sites have been proposed, one at Acton, and the other at Yarralumla. The present report describes a geophysical survey of the Acton weir site which was conducted by the Geophysical Section of the Bureau of Mineral Resources during June, 1956, in response to a request from the Department of Works, Canberra. A similar survey was carried out at the Yarralumla site, and is described in a report by Hawkins and Stocklin (1957). The Department of Works supplied the explosives for the seismic survey and four field hands, and also repaired minor damage caused by the shot holes during the survey.

In this report the term "overburden" is used to signify Recent and Pleistocene deposits in which the seismic velocity is relatively low. The term "bedrock" is used for the rock underlying the overburden.

Seismic refraction and resistivity methods were used to determine the depth to unweathered and weathered bedrock at the proposed site. From the seismic velocities estimates of Young's Modulus have been made.

The Acton weir site is located on the Molonglo River near Lennox Crossing and extends over part of the Royal Canberra Golf Course. The topographic survey was done by the Department of the Interior, which also supplied traverse plans and sections. The plan of the geophysical traverses is shown on Plate 1.

The geophysical party consisted of L.V. Hawkins, party leader and J.P. Pigott, field assistant.

## 2. GEOLOGY

The geology of the Canberra City district has been described by Öpik (1955) and is shown on the geological map of Canberra (Öpik, 1953).

The geophysical traverses, with the exception of parts of Traverses K, G and H, are located on undifferentiated Recent to Pleistocene deposits. The parts of traverses K, G and H not included in the above are located on the City Hill Shale which crops out north-west of Lennox Crossing.

The main structural feature at the site is the Acton Fault, which is a normal fault striking north-west across the proposed weir site; the position of the fault is known only approximately from the surface geology.

The downthrown side of the Acton Fault is to the north-east, where the Lower Silurian rocks of the City Hill Shale and the Riverside Formation are folded into the Lennox Syncline. The axis of the Lennox Syncline trends north-north-west and passes approximately through the centre of traverse K.

South-west of the fault, Ordovician rocks (Black Mountain Sandstone, Pittman Formation and Acton Shale) and Lower Silurian rocks (Camp Hill Sandstone and State Circle Shale) crop out just off the weir site, which is covered by undifferentiated Recent to Pleistocene deposits. The State Circle Shale occurs within the State Circle Rift, which is covered by Recent to Pleistocene deposits about half-a-mile south of the weir site.

There is no geological evidence as to which formations underlie the undifferentiated Recent to Pleistocene deposits at the weir site. Shot holes, which were dug to a depth of 5 feet, showed the surface layers to be sandy alluvium.

The formations to the south-west of the Acton fault consist of sandstones, shales and mudstones, but do not contain either limestone bands or volcanic rocks. However, the formations to the north-east of the fault contain calcareous shales with limestone bands or lenses (the City Hill shale), or sandstones, shales, limestone bands and lenses, tuffs and rhyolites (the Riverside Formation).

## 3. METHODS AND EQUIPMENT

Seismic refraction and electrical resistivity methods were used during the survey.

### A. SEISMIC REFRACTION METHOD.

#### (i) General.

As this is the principal report on geophysical surveys of weir, bridge and building sites in the City of Canberra, the seismic refraction method and computing techniques as used by the Bureau in shallow seismic refraction surveys, are described in detail.

The seismic refraction method depends on the contrast between the seismic velocities of different zones of rock. The seismic velocity of a rock depends on its elastic properties and density; the velocity increases with increase in the elasticity, but decreases with increase in density. In practice, an increase in density of a rock is generally accompanied by a greater increase in elasticity and, hence, an increase in seismic velocity. Elastic waves propagated through the ground are reflected and/or refracted at velocity discontinuities. The waves which are refracted at the critical angle, travel along the discontinuity and are refracted back to the surface, are used in the seismic refraction method. Elastic waves can be refracted at the critical angle only when they pass from a lower to a higher velocity at a discontinuity; hence only those layers for which the seismic velocity is higher than that of the overlying rock can be investigated by the refraction method.

The principles on which the understanding of the propagation of elastic waves is based are:-

(i) Huygen's Principle, which states that each point on a wave front acts as the source of new spherical waves, and

(ii) Fermat's Principle, which states that the recorded ray takes the path of minimum travel time.

Also from either of these principles we have

(iii) Snell's Law, which states that the angles of incidence, i, and refraction, r, when travelling from a medium of velocity $V_1$ to a medium of velocity $V_2$ is controlled by the relation

$$\frac{\sin i}{\sin r} = \frac{V_1}{V_2}$$

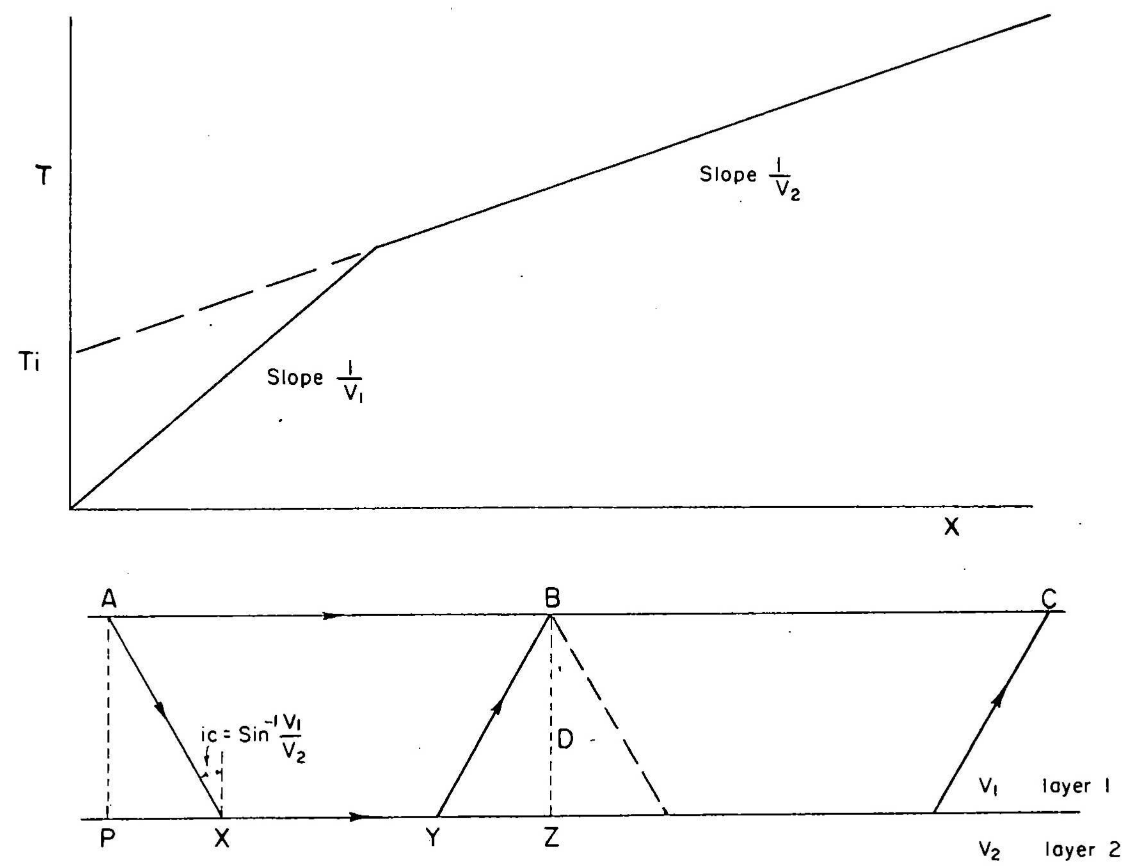


Fig. 1. Ray paths and time distance curve for two horizontal layers ($V_2 > V_1$)

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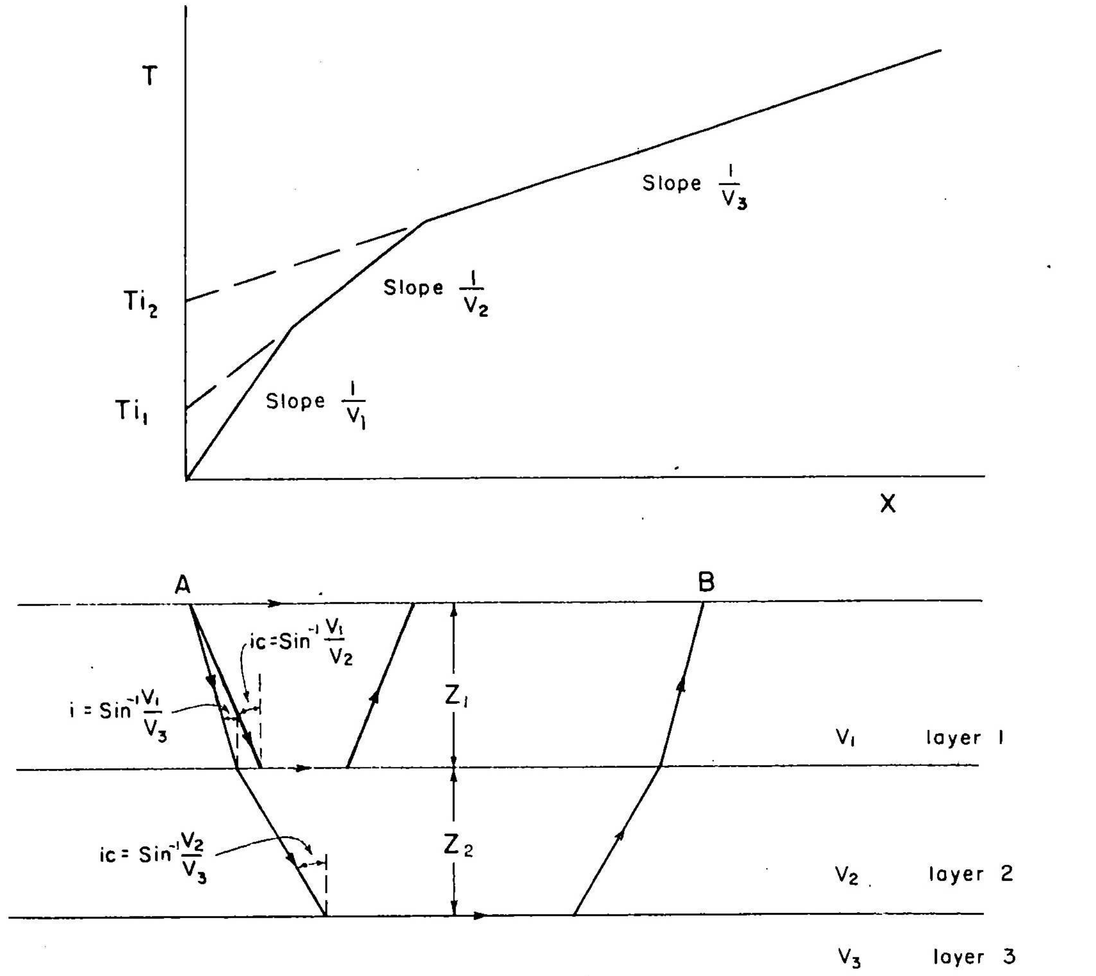



Fig. 2. Ray paths and time distance curve for three horizontal layers. ($V_3 > V_2 > V_1$)

At the critical angle, $\text{Sin } i_c = \frac{V_1}{V_2}$

An explosive charge is used as the source of the elastic waves. In the normal refraction method the charge is in line with a series of detectors (geophones) spaced at equal intervals on the surface of the ground and known as a "spread". The first arrival times of the elastic waves are recorded at each geophone. A graph of the first arrival times against the distance from the shot point is called a time-distance curve. The velocity of elastic waves in the refracting layer is determined directly from the slope of this curve if the layers are horizontal.

Referring to Figure 1, A is a shot point at one end of a spread about B, and the time distance curve for shot A is shown above the line AB. Layers 1 and 2 have velocities $V_1$ and $V_2$ respectively. The time Ti is known as the intercept time for layer 2.

Now Ti equals the Travel Time $T_{AB} - \frac{AB}{V_2}$

$$= \frac{AX}{V_1} + \frac{XY}{V_2} + \frac{YB}{V_1} - \frac{AB}{V_2}$$

$$= \frac{AX}{V_1} + \frac{YB}{V_1} - \frac{PX}{V_2} - \frac{YZ}{V_2}$$

or for horizontal layers

$$T_i - 2 \left( \frac{AX}{V_1} - \frac{PX}{V_2} \right)$$

As the vertical depth (D) is required, use is made of the following relations:-

$$AX = \frac{D}{\cos i_c}$$

$$PX = D \text{ Tan } i_c$$

$$\text{Sin } i_c = \frac{V_1}{V_2}$$

and consequently $\text{Cos } i_c = \sqrt{\frac{V_2^2 - V_1^2}{V_2^2}}$

to give $$Ti = \frac{2D}{V_1} \cdot \sqrt{\frac{V_2^2 \quad V_1^2}{V_2}}$$

or $$D = \frac{T_i}{2} \cdot \frac{V_2}{\sqrt{V_2^2 - V_1^2}} \cdot V_1 \ldots\ldots\ldots\ldots\ldots (1)$$

where $\frac{V_2}{(V_2^2 - V_1^2)^{\frac{1}{2}}}$ may be considered as a "correction factor" for the inclined travel path through layer 1.

Equation (1) may be written as $D = \frac{Ti}{2} \cdot V_{1,2}$ in which $V_{1,2}$ represents $\frac{V_2}{(V_2^2 - V_1^2)^{\frac{1}{2}}} \cdot V_1$, and is known as the "depth conversion factor". A nomogram showing the depth conversion factor for different values of $V_1$ and $V_2$ is used to shorten computations.

Equation (1) is also true for uniformly dipping layers if the depths are plotted on the normal to the refractor which passes through the shot point.

A technique known as the "method of differences" was introduced by Edge and Laby (1931, P.339). Referring again to Figure 1, a "reciprocal" geophone is placed at point C with the shot point at A and the geophones spread about B. The shot point and "reciprocal" geophones are then reversed. The "reciprocal time" $T_{AC}$ is equal to $T_{CA}$.

The time-depth, $T_B$ at B is defined as:-

$$T_B = \tfrac{1}{2} (T_{AB} + T_{CB} - T_{AC}) \quad \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

which for horizontal or uniformly dipping layers

$$= \frac{BY}{V_1} - \frac{YZ}{V_2} \quad \ldots\ldots\ldots\ldots\ldots\ldots(3)$$

This is similar to the expression for an intercept time for horizontal or uniformly dipping layers if a shot were placed at B; the time-depth $T_B$ is equal to half the intercept time for a shot at B.

It may be shown by a reduction similar to that above that

$$T_B = D \cdot \sqrt{\frac{V_2^2 - V_1^2}{V_2 V_1}}$$

or

$$D = T_B \cdot \frac{V_2}{\sqrt{V_2^2 - V_1^2}} \cdot V_1$$

which as before may be written as $T_B \cdot V_{1,2}$

By this method the depths to the refractor (plotted along the normal to the refractor) may be found at each geophone station.

(ii) Velocity in the refractor.

In horizontal beds, the elastic wave velocity in the refractor is equal to the reciprocal of the slope of the time-distance curve. For very irregular or dipping layers the velocity in the refractor may be accurately determined if a correction for the time of travel in the layers above the refractor is applied.

In the two-layer case (Fig. 1), if the time-depth $T_B$ is subtracted from the total travel time $T_{AB}$ (or $T_{CB}$) at each geophone station, then, using equation (3), we have:-

$$T_{AB} - T_B = T_{AB} - \frac{BY}{V_1} + \frac{YZ}{V_2} \quad \ldots\ldots\ldots\ldots\ldots(4)$$

From Figure 1, $T_{AB} = \frac{AX}{V_1} + \frac{XY}{V_2} + \frac{BY}{V_1}$ ..............(5)

and substituting equation (5) in equation (4), we have:-

$$T_{AB} - T_B = \frac{AX}{V_1} + \frac{XY}{V_2} + \frac{YZ}{V_2} = \frac{AX}{V_1} + \frac{XZ}{V_2}$$

$$= T_{AZ} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

which is the travel time from the shot point A to the point Z which is the point on the refractor at which the normal from the refractor passes through the geophone placing at B.

The travel times $T_{AZ}$ and $T_{CZ}$ are plotted as new time-distance curves thereby giving true refractor velocities.

This method is particularly valuable for determining changes of velocity in the refractor, and also for determining the velocity in the refractor where the thickness and/or velocity of the overlying material is very irregular.

The errors involved in the determination of the refractor velocity are due mainly to timing errors and partly to small variations in travel paths, etc. Determinations of refractor velocity over horizontal distances greater than 150 feet are estimated to have a maximum error of ± 10 per cent.

(iii) Solution for Multiple Layers.

To determine the depth conversion factor to a refractor with more than one overlying layer the thickness of individual layers must be determined. The thickness of individual layers may best be determined from the corresponding intercept times at a shot point since under normal operating conditions only the first arrival energy waves are recorded.

The following discussion applies to a three-layer problem, and may be expanded to include problems involving more than three layers.

Figure 2 shows the ray paths and the time-distance curve for three horizontal layers of velocities $V_1$, $V_2$ and $V_3$ ($V_3$ $V_2$ $V_1$). The thickness of the upper layer, $Z_1$, is determined as for two layers. The thickness of the middle layer, $Z_2$, is determined from the intercept time $Ti_2$, which is the intercept time of the layer with velocity $V_3$.

Now, $Ti_2 = T_{AB} - \frac{AB}{V_3}$ ..............................(7)

and the total travel time from A to B, $T_{AB}$ may be shown to be

$$T_{AB} = \frac{AB}{V_3} + \frac{2Z_1}{V_{1,3}} + \frac{2Z_2}{V_{2,3}} \quad \text{...................(8)}$$

where $V_{1,3}$ is the depth conversion factor between $V_1$ and $V_3$ and $V_{2,3}$ the depth conversion factor between $V_2$ and $V_3$. Both are determined from the nomogram. Solving equations (7) and (8) for $Z_2$, we have

$$Z_2 = \tfrac{1}{2} \left\{ Ti_2 - 2Z_1 \quad V_{1,3} \right\} \cdot V_{2,3} \quad \text{.........................(9)}$$

(Dobrin 1952, p224)

In the general case of (n+1) layers, the thickness of the nth layer, $Z_n$ , becomes:-

$$Z_n = \tfrac{1}{2} \left[ T_{in} - \frac{2\ Z_1}{V_{1,n+1}} - \frac{2\ Z_2}{V_{2,n+1}} \text{ .... } - \frac{2\ Zn-1}{V_{n-1,n+1}} \right] Vn,n+1 \quad \text{......(10)}$$

This can be solved using the nomogram previously referred to.

To convert the time-depths along the spread to actual depths, the former are multiplied by $\frac{2 \sum^{n} Zn}{Ti_n}$ in which $Ti_n$ is the intercept time of the lowest refractor considered (i.e. the (n+1) th layer), Zn is computed as shown above.

The conversion factor can be determined at shot points and applied to the time-depths at geophone stations. The solution is also mathematically correct for uniformly dipping layers if the computed depths are plotted normal to the refracting surface, instead of vertically below the geophone stations.

(iv) Source and Magnitude of Errors in Seismic Depth Determinations.

Seismic depth determinations are a function of time (time-depth) and velocity (depth conversion factor), hence the sources of error are:-

(a) timing errors, and
(b) velocity errors.

Timing errors are introduced in instrumentation and in record reading. Both these errors are small and the total error due to timing under average operating conditions is estimated at ± 5 per cent.

Errors in the velocity determinations of the near surface layers may be introduced by the following:-

(i) Lack of precise information on the velocity and thickness of the near surface layers which are not determined by weathering spreads at every geophone station used for depth determinations but only at discrete intervals along the traverses. The information obtained from the weathering spreads is augmented by that obtained at the ends of normal geophone spreads from a "close" or "short" shot and from the vicinity of any shot position within the spread (a centre shot is commonly used). Lateral variations in the velocity of the near surface layers may not be precisely delineated by this method. Average values of velocity and thickness are used and local departures from these averages will cause errors in determining the depths to the deeper refractors.

(ii) Undetected vertical inhomogeneity within each layer identified. This may be caused by:-

(a) Low velocity layers underlying layers with a higher velocity. As explained earlier refracted energy on which the measurement of velocities is based only returns to the surface if the elastic wave is refracted at a critical angle when passing downwards from one medium to another of higher velocity.

(b) Layers may exist which for technical reasons are too thin to give refracted energy that can be recognised in the time-distance curves even though their velocity is higher than in the layers above.

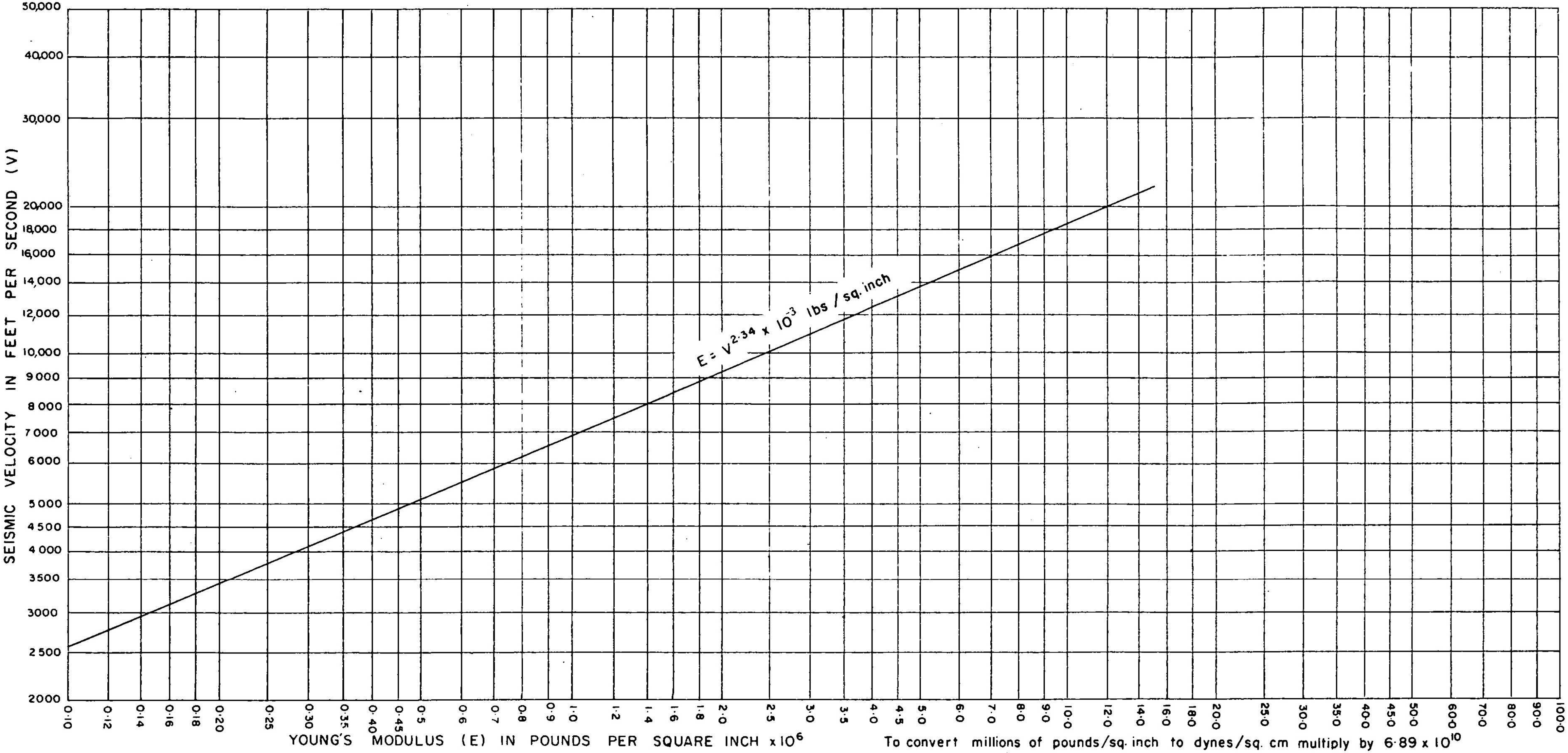
The minimum thickness for a subsurface layer which can be detected decreases as the velocity contrast with the overlying material increases, and increases as the depth to the layer increases and the velocity contrast with the next deeper indicated layer increases (Leet. 1938, pp.145-149).

(c) Continuous changes of velocity with depth: This results in curved ray paths through the layer and is indicated by a curved segment on the time-distance curve. However, as points on the time-distance curve are only determined at geophone stations this curvature may not be apparent on the plotted time-distance curve.

(iii) Anisotropic velocities in the individual layers. Only "horizontal" seismic velocities are recorded and these are used in making vertical depth determinations. Almost invariably, a "horizontal" velocity will differ from the "vertical" velocity in the same material.

If drill holes are available errors in the near surface velocities may be reduced considerably by -

(a) Measuring the vertical velocities by uphole or downhole shooting in the drill holes. This method may give misleading results if the velocity in the individual layers have been affected by the drilling (Dix, 1952, p.98).




To convert millions of pounds/sq. inch to dynes/sq. cm multiply by $6{\cdot}89 \times 10^{10}$

*The values of Young's Modulus may be considered to have a maximum error of ± 30 %*
*The above relationship is approximately correct for most rock types, other than salts*

FIGURE 3. EMPIRICAL RELATION BETWEEN YOUNG'S MODULUS AND THE COMPRESSIONAL WAVE VELOCITY IN ROCKS

*Geophysical Section, Bureau of Mineral Resources, Geology and Geophysics.* G 263 - 16

(b) By correlating the geology as indicated by the drill hole with the seismic results. For example, a drill hole may indicate clearly the depth to a hard unweathered bedrock which is the undoubted source of a high velocity refraction observed in seismic tests over the site. A vertical velocity based on the measured travel times and the known depth to the refraction is used in interpreting the seismic results in nearby areas.

Under normal conditions and in the absence of drilling, the maximum error in depth determination due to incorrect velocity assumptions is estimated at $\pm$ 10 to 15 per cent.

Hence the maximum total error under normal operating conditions and without drilling information is estimated at $\pm$ 15 to 20 per cent. Velocity information from drill holes may substantially reduce this figure.

In general field practice, shots are fired at a short distance from either end of the spread, in addition to longer shot distances which are used to record events from the deeper refractors. The short shot distances give intercepts and velocities of the intermediate layers and also remove some ambiguities in the interpretation of the time-distance curve. "Weathering" spreads, with geophone intervals much closer than those used for normal spreads, are used to obtain further information on intermediate and near-surface layers. A geophone interval of 40 feet was used for normal spreads and 10 feet for weathering spreads in this survey.

When geophones are placed near previous shot points, care should be taken to plant geophones away from the disturbed zone of a shot point. It is advisable to locate the shot point a little to one side of the traverse and the geophone to the opposite side.

(v) <u>Young's Modulus of rock from velocity of seismic compressional waves.</u>

The elastic moduli of rocks are related to their seismic compressional and transverse wave velocities by several standard equations (Dobrin, 1952, p.p. 180-182). In the seismic refraction method it is usual to record only compressional wave velocities, and the equation relating Young's Modulus (E) to the compressional wave velocity (V) is:-

$$E = \frac{V^2 p(1 - 2\sigma)\ (1 + \sigma)}{(1 - \sigma)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

where p is the rock density and $\sigma$ the Poisson's ratio. Both of these must be estimated or measured, or $\sigma$ can be computed from compressional and transverse wave velocities.

The party was not equipped to measure transverse wave velocities for the computing of Poisson's ratio.

Brown and Robertshaw (1953) presented a graphical relation between E and V from data obtained by Reich (1930). This relation is shown on Figure 3 and the formula derived from this figure is:-

$$E = V^{2.34} \times 10^{-3} \text{ lbs/inch}^2 \qquad \text{.......................(12)}$$

$$\text{or} \quad E = 68.9\ V^{2.34} \text{ dynes/cm}^2 \qquad \text{.......................(12a)}$$

in which V is the velocity of the compressional wave in ft/sec. Evison (1956) shows that Reich's data are of questionable origin. However, a test of formula (12), using data from Birch, Schairer and Spicer (1942) and Heiland (1946) gives reasonable values of E for a fair range of V, with an estimated accuracy of $\pm$ 30 per cent. For this reason, formula (12) is used to estimate Young's Modulus from compressional velocities until such time as more accurate data can be obtained.

The data from which this relation was derived were from competent rocks and the reliability of the relationship with respect to incompetent materials, such as overburden and incompetent weathered rock, is questionable.

The Young's Modulus of elasticity is defined as the ratio of longitudinal stress to strain. This is not a linear function and different Young's Moduli are defined which correspond to different parts of the stress-strain curves. Figure 4 shows the stress-strain curve for a brittle material in which the following types of Young's Moduli are illustrated:-

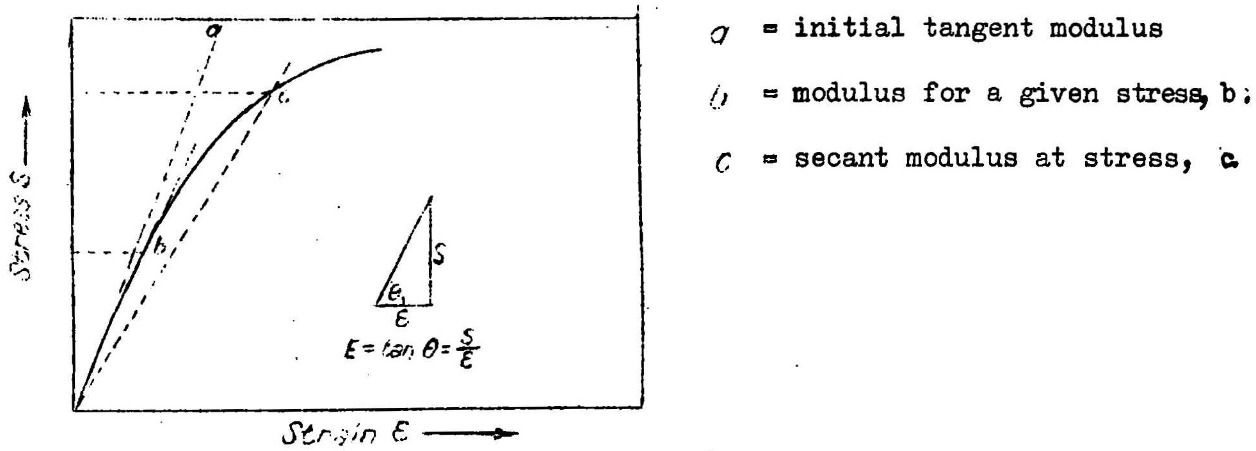



FIG. 4. The stress-strain curve of a brittle material. Various moduli of elasticity. (After Wuerker, 1953).

(a) the "initial tangent modulus",
(b) the modulus for a given stress, and
(c) the "secant modulus" at a given stress.

The "apparent modulus" is also sometimes used and corresponds to the straight line part of the stress-strain curve.

The Young's Modulus determined by seismic wave velocities is the same as that determined by the sonic method and is always the "initial tangent modulus" (a in Figure 4). According to Wuerker (1953), it is always higher than the value obtainable by static testing.

Further in the refraction method the seismic velocity in a horizontal direction is determined and thus the estimated Young's Modulus will correspond only to this direction. Due to the anisotropic character of most rock types the value of the Young's Modulus in a vertical direction will be different.

(vi) Seismic Equipment.

Equipment used on this survey was a Century Geophysical Corporation 12-channel, portable refraction seismograph with T.I.C. geophones of natural frequency 20 c.p.s.

B. RESISTIVITY METHOD.

The resistivity method is described in detail in a report on a survey at Mugga Mugga Quarry, Canberra (Hawkins, 1956).

The Wenner configuration of electrodes was used for the three expanding electrode "depth probes", and for the resistivity traversing with electrode separations of 40 and 120 feet, which was done on traverses F,K,L and M.

A resistivity meter, designed and built by the Bureau, and a Megger earth tester were used in the resistivity survey.

## 4. RESULTS

A. SEISMIC RESULTS.

In general the seismic results showed a succession of layers with increasing velocity in depth. The surface layer composed mostly of alluvium or clay derived from weathering of the rocks has an average velocity of 1200 feet/sec. Underlying this is a layer with a velocity of approximately 5,000 feet/sec. which is probably also alluvium, gravel or clay with a higher moisture content and a greater degree of compaction than the surface material. For the purpose of this report these are considered as a single layer and called the "overburden" and an average velocity which ranges between 1350 and 1900 feet per sec. assigned to it. It varies between 12 and 47 feet in thickness but is mostly between 15 and 30 feet thick. Beneath the "overburden" is a layer which ranges in velocity between 5500 and 9500 feet per sec. Its thickness varies considerably throughout the area. To the east of a line between stations 440 on Traverse K and 1080 on traverse M, shown as line "A" on plate 1 it has been detected at only a limited number of places where it is from 10 to 20 feet thick but it is believed that it exists as a thin layer even where for technical reasons it could not be detected. To the west of line "A" it is much thicker ranging from 39 to 115 feet and averaging 73 feet.

It invariably overlies a layer of indeterminate thickness which has a higher velocity than the layer above and which is assumed to be unweathered (or only slightly weathered) bedrock and is referred to as unweathered bedrock. Consideration of the regional geology suggests the presence in the area surveyed of the City Hill Shale (calcareous shales with limestone bands or lenses) or the Riverside Formation (sandstones, shales, limestone bands and lenses, tuffs and rhyolites). From the geological descriptions it appears that the high velocity refractors in the bedrock (13,000 to 20,000 ft/sec) may represent limestone lenses or rhyolite flows, which may be relatively thin. However, since these high velocities belong to the range of relatively unweathered rocks, it is reasonable to assume that any underlying interbedded sediments, though having a lower velocity and Young's Modulus, are also relatively unweathered; also, that the layer between the "unweathered" bedrock and the overburden is rock weathered in situ to a variable degree and for the purposes of this report is referred to as the 'weathered layer' or weathered bedrock. Bedrock is therefore the upper surface of this layer.

The velocity in the 'unweathered' bedrock varies between 8000 to 20,000 feet per second. It is reasonable to assume that the velocities are related to the rock type and its degree of fracturing and possible minor weathering. The known rocks in the area are hard and compact and in an unfractured and unweathered state might be expected to have velocities of the order of 12,000 to 20,000 feet per second. It is known from the results of surveys in the dolerite areas of Tasmania (Wiebenga, et al, 1956) and from work in other areas (Dyson and O'Connor, 1956) that the velocity in what is normally a high velocity medium, such as massive dolerite, is lowered substantially by fracturing in fault and shear zones. The low velocities, from 8,000 to 9,000 feet per second, recorded in 'unweathered' bedrock are most likely due to fracturing of the bedrock and faulting is postulated as the cause.

It is of interest to note that in general the weathered bedrock overlying these fractured zones has a lower velocity than the average for weathered rock, from which it may be inferred that weathering is more advanced in such places.

(i) <u>General.</u>

The location of the seismic traverses and the surface and 'unweathered' bedrock contours are shown on Plate 1, and profiles showing the thickness of the overburden. The depth to the 'unweathered' bedrock are shown on Plate 2.

The most striking feature in the results is the substantial difference in average thickness of the 'weathered' layer east and west of line 'A'. The results on the individual traverses will be discussed in relation to this line of demarkation.

(ii) <u>West of Line A.</u>

To the west of line A, the 'weathered' layer is relatively thick and the depth to 'unweathered' bedrock is correspondingly large (between 54 and 147 feet at stations 1120 and 560, respectively, on traverse K, with an average depth of 94 feet.

The overburden has an average vertical seismic velocity of 1350 ft/sec. and a thickness of between 14 feet (station 1200, traverse K) and 47 feet (station 440, traverse K).

The weathered layer has a seismic velocity between 5,500 ft/sec. and 7,800 ft/sec., except between stations 1560 and 1680 on traverse M, where the velocity is 12,000 ft/sec. The thickness of the weathered layer ranges between 39 feet (station 1200, traverse K) and 115 feet (station 600, traverse K).

The velocity in unweathered bedrock ranges from 8,000 ft/sec. to 20,000 ft/sec. and is less than 9000 ft/sec. between stations 1560 and 1240 on traverse M, between stations 520 and 680 on traverse L and between stations 1160 and 1000 on traverse K. As mentioned above, these relative low velocities are most likely due to fracturing in rock which normally has a higher velocity and faulting is postulated as the cause. The positions where these low velocities occur on traverses M, L and K are in a line striking north-north-west and indicate a possible fault zone (Plate 1).

The velocity in 'unweathered' bedrock is also less than 9000 ft/sec. west from station 1680 on traverse M.

Table 1 shows the approximate value of Young's Modulus corresponding to the seismic velocities in the weathered and unweathered bedrock west of line A. The values were obtained from the graph on Fig.3. The estimated maximum error of the Young's Modulus values is ± 30 per cent for the competent rocks.

TABLE 1.

| ROCK TYPE | | VELOCITY OF SEISMIC COMPRESSIONAL WAVE (ft/sec.) | YOUNG'S MODULUS | |
|---|---|---|---|---|
| | | | lbs/sq.in. | dynes/sq.cm. |
| Overburden | Overburden | 1350 | $0.02 \times 10^6$ | $0.01 \times 10^{11}$ |
| Bedrock | 'Weathered' 'Bedrock' | 5500 | $0.6 \times 10^6$ | $0.4 \times 10^{11}$ |
| | | 6500 | $0.9 \times 10^6$ | $0.6 \times 10^{11}$ |
| | | 7500 | $1.2 \times 10^6$ | $0.8 \times 10^{11}$ |
| | | 7800 | $1.3 \times 10^6$ | $0.9 \times 10^{11}$ |
| Bedrock | 'Unweathered bedrock' | * 8000 | $1.4 \times 10^6$ | $1.0 \times 10^{11}$ |
| | | * 8500 to 8700 | $1.6 \times 10^6$ to $1.7 \times 10^6$ | $1.1 \times 10^{11}$ to $1.2 \times 10^{11}$ |
| | | 9700 to 11000 | $2.4 \times 10^6$ to $3.0 \times 10^6$ | $1.7 \times 10^{11}$ to $2.1$ $10^{11}$ |
| | | 16000 to 20000 | $7.0 \times 10^6$ to $12.0 \times 10^6$ | $4.8 \times 10^{11}$ to $8.3 \times 10^{11}$ |

* Probably fractured.

(iii) East of Line A.

East of line A, the depth to the top of the weathered layer ranges between 12 feet at station 680 on traverse G and 37 feet at station 400 on traverse K, the average depth being 25 feet.

The overburden is generally the undifferentiated Recent to Pleistocene deposits which have an estimated average vertical seismic velocity of 1,700 ft/sec. west of the Molonglo River at Lennox Crossing, and 1,900 ft/sec. east of the river. The seismic results show this surface layer of Recent to Pleistocene deposits to consist of two parts, namely a top layer with a velocity of 1200 ft/sec., which was shown by the shot holes (dug by a hand auger to a depth of about 5 feet and occasionally 10 feet) to be sandy alluvium, and an underlying layer with a velocity of about 5000 ft/sec. which ranges up to 10 feet in thickness. On the southern end of traverse G and near line A on traverse K the geophone stations are possibly located on the soil covered City Hill Shale. Here the average seismic velocity of the overburden is approximately 1350 ft/sec. The overburden is shown on Plate 2 as a single layer with an average vertical velocity.

The velocity in 'unweathered' bedrock recorded from normal spreads (40-foot geophone interval) ranges from 13,000 to 20,000 ft/sec. However, a thin 'weathered' layer of velocity about 9,000 ft/sec. was recorded from weathering spreads, near the shot points of some normal spreads and, also, as later arrivals (after the 13,000 to 20,000 ft/sec. velocity waves) on some normal spreads. The technique employed in the survey was not sufficiently precise (i.e. continuous recording of later energy arrivals) to determine the thickness of the 9,000 ft/sec. layer where it is thin (about 10 to 20 feet) because it is then less than the minimum thickness for this layer to be recorded on the first arrival time-distance curve. (see earlier). It seems reasonably certain, however, that a weathered layer with a velocity approximately 9,000 feet per second is present throughout the area east of line A, but its thickness was not determined with any certainty except near the southern end of traverse G where it is between 20 and 50 feet thick and the layer has a velocity of 8,000 feet per second, and at the southern end of traverse F where it is 30 feet thick. Such evidence as there is suggests that in general its thickness ranges from 10 to 20 feet. This is in strong contrast to the area west of line A in which the average thickness is 73 feet.

In two places evidence was obtained of layering within the 'unweathered' bedrock. These are between 320 and 440 on traverse K and between 360 and 560 on traverse G. On traverse K the velocity in 'unweathered' bedrock increases at depths of from 90 to 120 feet from 14,000 feet per second to 17,000 feet per second. On traverse G it increases from 14,000 to 18,000 feet per second at a depth of approximately 60 feet.

(iv) <u>Possible fault zones indicated by the seismic results.</u>

The low velocities recorded in fresh bedrock west of line A on traverses K, L and M indicate a possible fault with a north-north-westerly trend; this may correspond to the Acton Fault, which is shown on the geological map of Canberra (Öpik, 1953) to have a north-westerly trend.

The sharp contrast in the average thickness of the weathered layer on either side of line A may be the result of faulting approximately along this line. However, the boundaries of this possible fault zone are uncertain. The increase in the depth of weathering west of line A appears to indicate that the supposed 'fault' closely follows line A, but the velocities in unweathered bedrock indicate that on traverse M the eastern limit of the 'fault' zone is at station 1240 (160 feet west of line A), where the velocity changes from 20,000 to 8,500 ft/sec. The eastern limit of the possible 'fault' zone is shown on Plate 1 as following line A. The width of the 'fault' zone is indefinite because the whole area west of line A is deeply weathered and crossed by another fault described earlier. The width appears to be about 200 feet on traverse K. Correlation of the supposed fault which follows line A with the known geology is not definite; but it may possibly be a northward extension of the eastern fault of the State Circle Rift (see Section 2 of this report).

However, it is not known whether the State Circle Rift extends under the Recent to Pleistocene deposits at the weir site, and the supposed 'fault' could possibly be a separate fault truncated to the south by the Acton Fault.

Explanations other than faulting are possible for the observed difference in bedrock conditions on either side of line A. In general, the increased depth of weathering to the west of line A may be due to one or more of the following: (i) general and widespread fracturing of the rock to the west of line A with consequent increase in intensity and depth of weathering; (ii) different rock types on either side of the line 'A'; those to the west being more susceptible to weathering than those to the east of the line. Such a difference could result from a variety of geological causes other than faulting, for example a pronounced difference in dip east and west of line 'A'. The seismic results show a more or less uniform bedrock velocity east of the line suggesting flatly lying sediments. To the west of the line bedrock velocity changes at relatively short intervals along the traverses and this could be due to the traverse crossing the truncated surface of a succession of relatively steeply dipping beds.

It was shown in an earlier section that the seismic velocity in a rock is related to its elasticity. Table 2 shows the approximate values of Young's Modulus corresponding to the seismic velocities in the overburden and bedrock east of line A. The values are obtained from the graph on Fig.3. The estimated maximum error in Young's Modulus is ± 30 per cent, for the competent rocks.

TABLE 2.

| ROCK TYPE | | VELOCITY OF SEISMIC COMPRESSIONAL WAVES (Ft/sec) | YOUNG'S MODULUS | |
|---|---|---|---|---|
| | | | lbs/sq.in. | dynes/sq.cm. |
| Overburden | Top layer | 1200 | $0.02 \times 10^6$ | $0.01 \times 10^{11}$ |
| | Bottom layer | 5000 | $0.48 \times 10^6$ | $0.3 \times 10^{11}$ |
| | Average | 1700 | $0.04 \times 10^6$ | $0.03 \times 10^{11}$ |
| | | 1900 | $0.05 \times 10^6$ | $0.03 \times 10^{11}$ |
| Bedrock | Weathered and/or Fractured | 8000 | $1.4 \times 10^6$ | $1.0 \times 10^{11}$ |
| | | 9000 | $1.8 \times 10^6$ | $1.3 \times 10^{11}$ |
| | Unweathered | 13000 to 14500 | $4.8 \times 10^6$ to $5.6 \times 10^6$ | $3.3 \times 10^{11}$ to $3.9 \times 10^{11}$ |
| | | 15700 to 20000 | $6.7 \times 10^6$ to $12.0 \times 10^6$ | $4.6 \times 10^{11}$ to $8.3 \times 10^{11}$ |

(v) Discussion of Results.

For the purpose of description, the results of the seismic survey have been considered as a three layer section with 'overburden' ranging in average velocity from 1350 to 1900 feet per sec., a weathered layer, considered to be weathered bedrock, ranging with one exception in velocity from 5500 to 9500 feet per second and unweathered bedrock ranging in velocity from 8000 to 20,000 feet per second.

As the seismic refraction method can only detect layers with successively higher velocities in depth it is possible that intermediate layers with velocities lower than those above and below it may exist and have not been detected. This, however, is improbable and even if present would not substantially alter the relative depths to the various layers from place to place within the area although the absolute values of the depths might be in error through this cause.

There are substantial lateral changes in the velocity in 'unweathered' bedrock throughout the traverses and in two places vertical changes were detected. These changes are no doubt related to the types of rock within the basement but the geology of the area is not known in sufficient detail to attempt any direct correlation.

Low velocities (8000-9000 feet/sec.) within the 'unweathered' bedrock are attributed to fracturing resulting through faulting and on this basis a fault zone striking north-north-west through traverses M, L and K is postulated.

There is a rough correlation between the velocity in the 'weathered' layer and that in the 'unweathered' bedrock immediately beneath it - the velocity in the weathered layer being relatively low or high over unweathered bedrock in which the velocity is respectively low or high. The reduction in velocity in the weathered layer is due mainly to a reduction in the elasticity brought about by weathering which varies with rock type and degree of fracturing. However, the geology is evidently complex in this area and the degree of weathering is necessarily very variable.

Of particular note are -

(1) the weathered layer between 1560 and 1640 on traverse M which has a velocity of 12,000 feet per second and overlies unweathered bedrock with a velocity of 16,000 ft/sec. and

(2) between 1000 and 1160 on traverse K where the weathered layer has a velocity of 5500 feet/sec. overlying unweathered bedrock with a velocity of only 8500 feet per second.

In example (1) bedrock is evidently of a type that weathers little or in which weathering produces a relatively small decrease in elasticity.

In example (2) the low velocity in 'unweathered' bedrock is interpreted as being due to fracturing. The weathering of such a rock would be more complete than in unfractured rock and this is the probable cause of the very low velocity in the overlying weathered rock.

B. RESISTIVITY RESULTS.

The results of the resistivity traversing showed the area east of line A to have a higher apparent resistivity than that west of line A. This confirms the seismic results, which indicate less weathering and shallower unweathered bedrock east of line A. The resistivity results did not yield any additional information, due to the thick weathered layer of low-resistivity west of line A. The resistivity profiles are not reproduced in this report as they add nothing to the information given by the seismic results.

Resistivity depth probes were taken at pegs 400 on traverse M and 800 on traverse F to the east of line A, and at peg 1280 on traverse K to the west of line A.

The results of these depth probes are shown in Figure 5 as histograms of the vertical distribution of specific resistance and seismic velocity, and illustrate the difference between the areas to the east and west of line A. The layer of minimum specific resistance in each histogram may be due to a layer of alluvium with more than average clay content. The resistivity and seismic methods measure different rock properties and correlation between the two is not apparent from the three 'probes' done (see Figure 5).

5. CONCLUSIONS

The object of the survey was to determine the depth to rocks suitable for the foundations of a proposed dam at Acton on the Molonglo River. This involved -

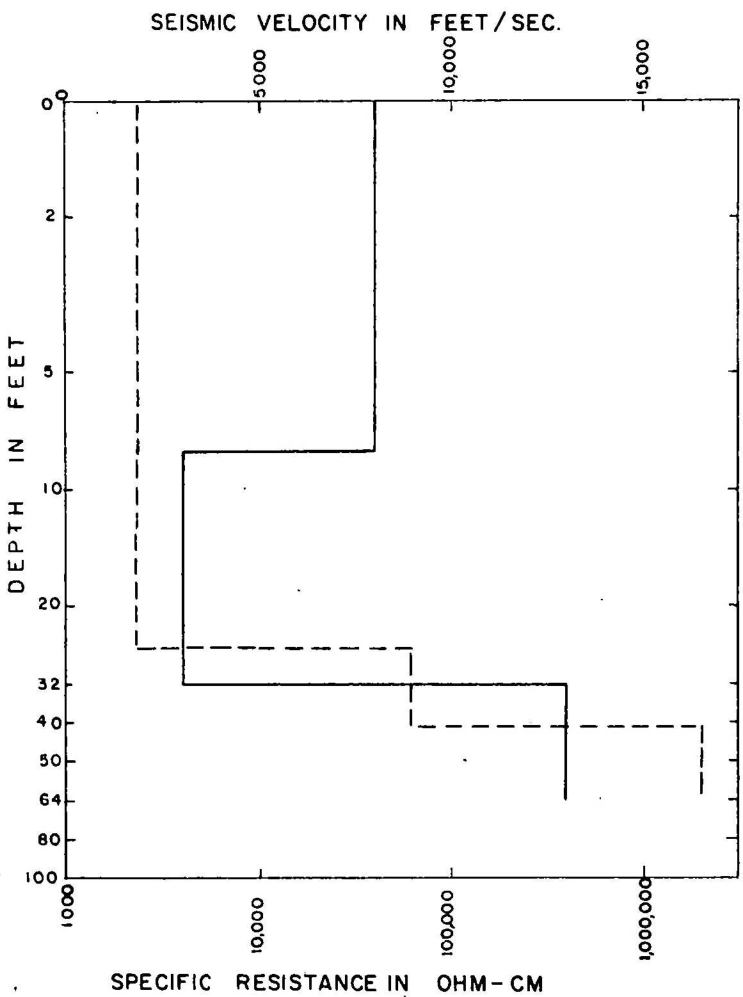
(a) The determination of the thickness and physical properties of the overburden which consists of alluvial and elluvial material.

(b) The depth and extent of weathering in the bedrock and an estimation of the elasticity of the weathered rock.

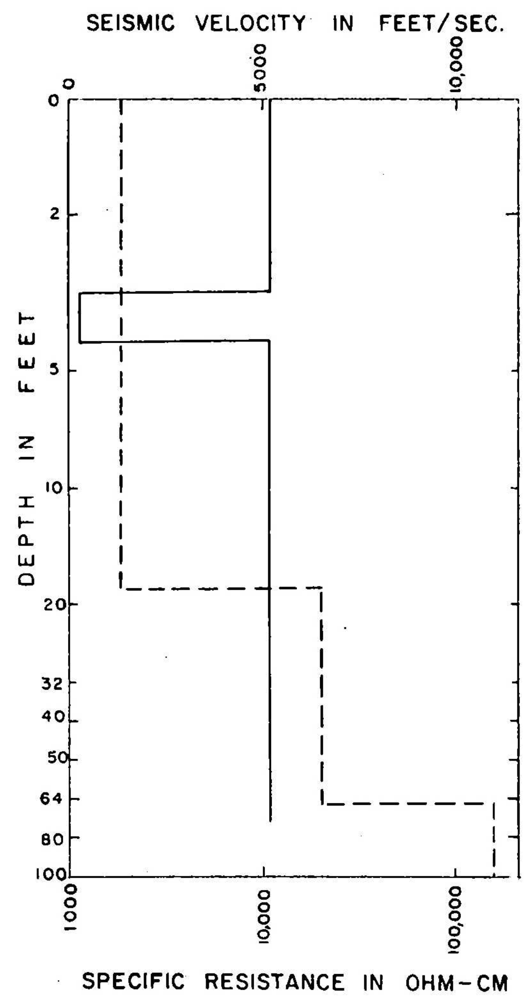
(c) An estimation of the elasticity of the unweathered bedrock.

These objects were in the main achieved. The overburden has a low seismic velocity and a corresponding low Young's Modulus. It is reasonable to assume therefore that it would be unsuitable for a dam foundation and would have to be excavated. Its thickness is in most places between 15 and 30 feet. At the southern end of traverse F it is 30 feet thick and at one place near Lennox Crossing on traverse K it is 47 feet thick. The latter could possibly coincide with a former channel of the river. No measurements were made over the present river channel at Lennox Crossing on traverse H and it is possible that the overburden may thicken beneath the river.

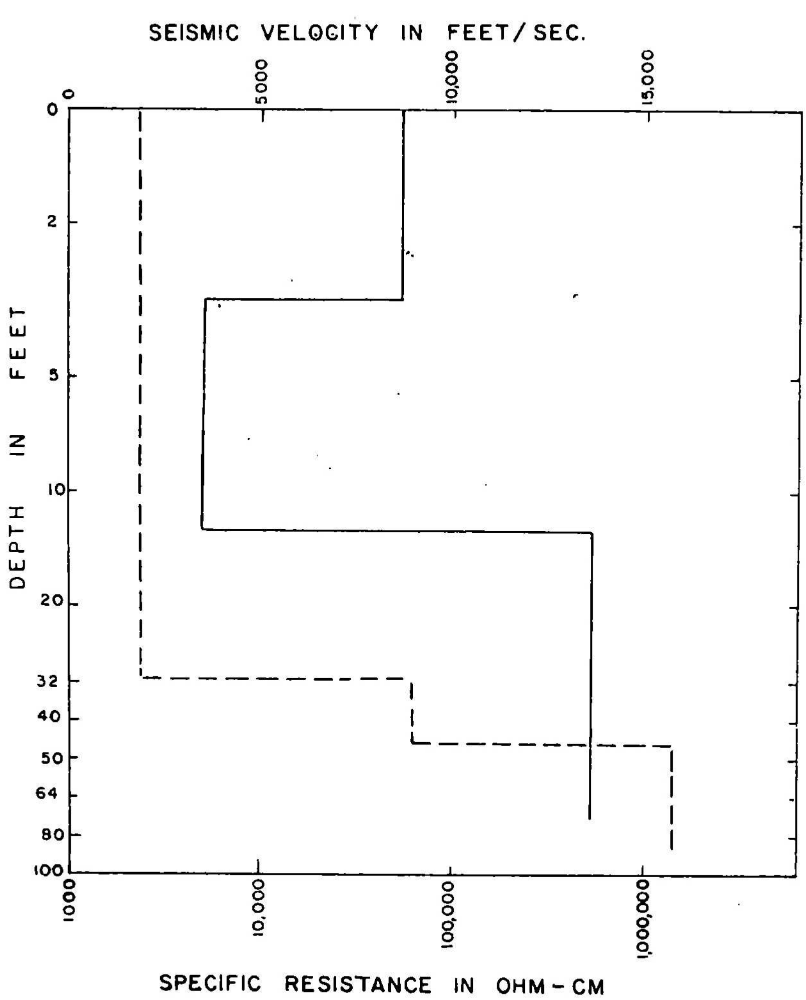
Whether or not the weathered bedrock would be suitable for foundations may only be determined by testing, but in this regard it has been found by experience that its seismic velocity and values of Young's Modulus calculated from them can be accepted as a satisfactory guide. The velocity in the weathered layer ranged in general from 5,500 feet/sec. to 9,000 feet/sec. and Young's Modulus from 0.6 to 2.0 x $10^6$ lbs/square inch. At one place the velocity was 12,000 feet/sec. with Young's Modulus 3.5 x $10^6$ lbs/square inch.




(a) STATION 400 ON TRAVERSE M




(c) STATION 1280 ON TRAVERSE K




(b) STATION 800 ON TRAVERSE F

LEGEND

——— Specific resistance

– – – Seismic velocity

FIGURE 5

HISTOGRAMS OF THE VERTICAL DISTRIBUTION OF SPECIFIC RESISTANCE AND SEISMIC VELOCITY

It is reasonable to assume that weathered rock with a velocity as low as 5,500 feet/sec. would be unsuitable for the foundations of a dam whereas weathered rock with a velocity of 12,000 feet per second would probably be suitable.

The velocity on the unweathered bedrock is in most parts of the area high and it can be assumed that bedrock with relatively high velocity and Young's Modulus would be suitable for foundations. At some places however, the velocity is between 8,000 and 9,000 feet per second due, it is believed, to fracturing in the rock; at such places even the 'unweathered' bedrock might be unsuitable for dam foundations.

A limited amount of testing might establish a satisfactory relationship between the seismic velocities and the foundation quality of the weathered and unweathered bedrock and thus permit the seismic results to be used for a rough assessment of the amount of excavation necessary.

If it is supposed that bedrock with a velocity of 9,000 feet per second or higher is suitable for foundations and rock with a velocity of 7,800 feet/second or less unsuitable, then the area east of line "A" is more favourable than the area to the west of this line.

It is possible that the velocity and hence Young's Modulus within the weathered layer increases progressively in depth within the layer and that the velocities recorded relate to the upper section only. This could result in rock suitable for foundations being encountered at a shallower depth than the depth to 'unweathered' bedrock in places where the velocity of the weathered layer is low but high in the underlying 'unweathered' bedrock.

This however would not affect the relative merits of the areas to the east and west respectively of line "A". East of line "A" the overburden ranges from 12 to 37 feet and averages 25 feet in thickness and overlies weathered and unweathered bedrock with a velocity of 9,000 feet per second or greater. The thickness of the weathered layer has been determined at only a few places but it is evidently thin and probably does not exceed 20 feet in most places. The velocity in the unweathered bedrock is everywhere in excess of 13,000 feet per second and the average depth to unweathered bedrock is probably not greater than 43 feet. Rock suitable for dam foundations may be expected to occur at an average depth not greater than 43 feet and possibly at an average of only 25 feet.

West of line "A" the average thickness of overburden is approximately the same as east of the line but the bedrock is deeply weathered and the velocity in the weathered layer relatively low. The average depth to unweathered bedrock is 94 feet and deep excavations would be needed if the low velocity weathered rock proves unsuitable for foundations.

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PLATE - 1

LOCALITY MAP
Scale in Miles
AREA INVESTIGATED
CANBERRA
CITY
A. C. T.
N. S. W.
DEPT. INTERIOR
LENNOX CROSSING
EMBANKMENT
BITUMEN ROAD
SAND TRAP
WATER HOLE
TRAVERSE "H"
TRAVERSE "G"
TRAVERSE "F"
TRAVERSE "E"
TRAVERSE "K"
TRAVERSE
MOLONGLO RIVER
COMMONWEALTH AVE
Possible Fault Zone
Possible Fault
Line "A"
Golf Club House
LEGEND
Geophysical traverse and stations
Bedrock contour (Elevations to local survey datum)
Surface contour
Possible fault
Unweathered Bedrock with seismic velocity less than 9000 ft./sec. indicated along traverse.
Road
Fence
SEISMIC REFRACTION SURVEY OF THE ACTON WEIR SITE, CANBERRA, A.C.T.
SEISMIC TRAVERSES AND SURFACE AND UNWEATHERED BEDROCK CONTOURS
SCALE IN FEET
100 0 100 200 300
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PLATE 2


SEISMIC REFRACTION SURVEY OF THE ACTON WEIR SITE, CANBERRA, A.C.T.

## VERTICAL SECTIONS SHOWING THICKNESS OF OVERBURDEN AND DEPTH TO UNWEATHERED BEDROCK

SCALE IN FEET

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