GL 1966-5

Shallow Seismic Refraction
1960?

by

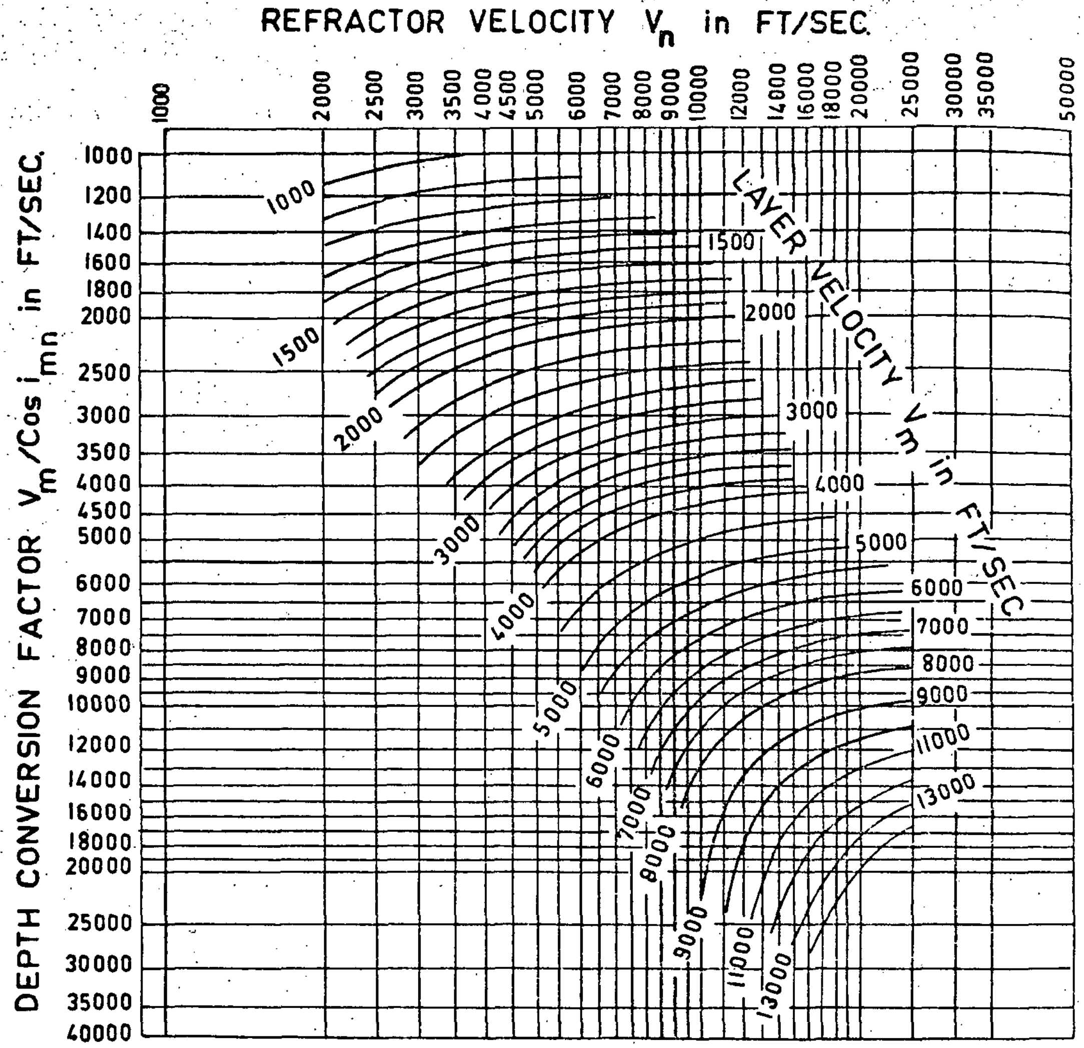
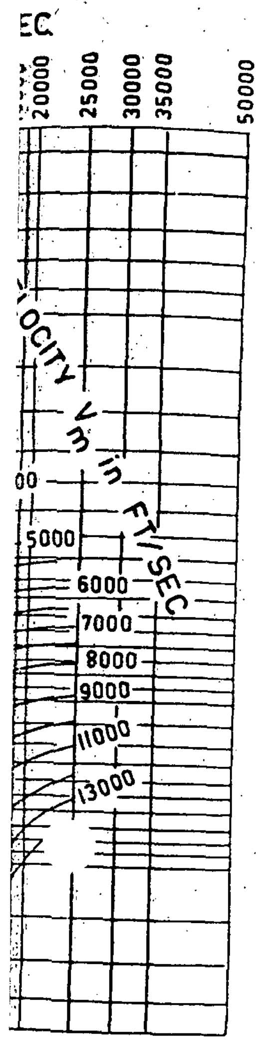


FIG. 3. Nomogram of depth conversion factor for layer of velocity V_m and underlying refractor of velocity V_n.

Where a refractor of velocity V_n is overlain by two or more layers of different velocity, the velocity term $V_m/\text{Cos } i_{mn}$ will vary for each layer as the layer velocity V_m varies. This is due to both the different layer velocity and the different inclination of the ray path. Consequently, either the thickness of each layer must be determined separately in a manner similar to intercept time determinations, or a composite depth conversion factor must be calculated for the refractor. The method adopted will depend on the detail required from the survey.

Where the depths to all recorded refractors are required at all geophone stations, the time-depths for each refractor must be computed at each geophone station. The computation then follows the procedure of determining the thickness of each successive layer from the time-depth of the immediately underlying refracting layer and is identical to that for half-intercept time computations. For this purpose it is assumed that the interfaces are parallel in the region below the geophone station.

In the general form, the equation for determining the thickness of the mth layer, Z_m, from the time-depth (or half-intercept time) t_n to the



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$$Z_m = \left(t_n - \sum_{a=0}^{m-1} Z_a \cdot \text{Cos } i_{an}/V_a\right) \cdot V_m/\text{Cos } i_{mn} \tag{4}$$

where the term,

$$\sum_{a=0}^{m-1} Z_a \cdot \text{Cos } i_{an}/V_a,$$

represents the sum of the "time-thicknesses" of all the layers overlying the mth layer; the time-thickness of a layer being the time delay through that layer for the critical ray from the refractor. Hence, the bracketed terms represent the time-thickness of the mth layer. This is multiplied by the simple depth conversion factor between the V_m and V_n velocities to yield the thickness of the mth layer. Equation 4 may be solved by use of the nomogram in Figure 3 and the values of Z_0, $Z_1 \cdots Z_{m-1}$ which have been previously determined in a similar manner.

Where only the depth to a particular, important refractor is required at all geophone stations, the thicknesses of the layers overlying the important refractor are determined mainly for evaluating the composite depth conversion factor for the important refractor. These thicknesses are determined as above from the half-intercept times of shotpoints in or near normal geophone spreads and from special "weathering spreads." The weathering spreads have a short geophone interval and give more detailed information on the near surface layers.

Where such thicknesses are determined, the composite depth conversion factor may be calculated by summing the thicknesses (Z_a) to obtain the depth of the important refractor and dividing this depth by the time-depth or half-intercept time to the important refractor (t_n). Thus, the composite depth conversion factor, $\overline{V}$, to an nth layer refractor is

$$\overline{V} = \sum_{a=0}^{n-1} Z_a/t_n. \tag{5}$$

In this manner, the composite depth conversion factor is determined at regular intervals along the traverse and interpolated at each geophone station.

The depth to the important refractor at a geophone station G, Z_G, is calculated from the equation,

$$Z_G = t_G \cdot \overline{V}_G \tag{6}$$

where t_G is the time-depth to the important refractor (i.e. the value of t_n at G) and $\overline{V}_G$ is the corresponding composite depth conversion factor.

ANALYSIS OF VELOCITIES IN REFRACTORS

The slope of the time-distance curve beyond the critical distance determines the apparent velocity of seismic waves in the refractor in the direction of shooting along the traverse. In the classical method the apparent velocities from opposite directions are used to determine the true velocity in the refractor. Where the refractor depth and/or the velocity distribution in the material overlying the refractor are irregular, the plotted time-distance curve will scatter about the line of the apparent velocity of the refractor. Here, the apparent velocities may still be determined by drawing lines of best fit to the scattered points. However, this will obscure rapid variations of the refractor velocity which may be of considerable importance, particularly in surveys for the investigation of foundation conditions.

Use of the Time-depth

By the simple procedure of subtracting the time-depths from the recorded travel times at geophone stations, the effect of any irregularities both in the refractor depth and in the velocity distribution in the material overlying the refractor is removed.

This may be illustrated with the two-layer case shown in Figure 2. The corrected travel time from the shotpoint S' for the geophone station at G, $t'_{S'G}$, is

$$t'_{S'G} = t_{S'G} - t_G \tag{7}$$

where $t_{S'G}$ is the recorded travel time and t_G the time-depth. By use of segment travel times and the definition of the time-depth, this equation reduces to

$$t'_{S'G} = S'L/V_0 + LP/V_1 \tag{7a}$$

which is the travel time from the shotpoint S' to the point P on the refractor from which the normal to the refractor passes through the geophone placing at G. As before, the travel times and the time-depths must be from the same refractor.

Since the corrected travel times refer to points on the refractor from which the normals pass through the geophone placings, the corrected time-distance curves are plotted after the depth profile of the refractor has been constructed. The slope of the corrected curves should be the same for both directions of shooting, and the true velocities in the refractor may be determined directly from the slope of the curves.

The velocities are measured parallel to the refracting interface and in the direction of the traverse and, of course, may vary with direction for anisotropic rocks. Also, a small transition zone will occur above a velocity change in the refractor due to differences in the inclination of the ray paths above the refractor. The width of the transition zone will depend on the horizontal displacements between the recording geophone and the points at which the recorded rays leave the refractor.

For the overlying less important refractors for which time-depths have not been calculated, the velocities in the refractors may be determined in the classical manner, using the apparent velocities from reverse shooting. A sufficiently close approximation to these velocities may usually be obtained from the equation,

$$V_m = 2\cdot V_{m'} \cdot V_{m''}/(V_{m'} + V_{m''}) \text{ (approximately)}, \quad (8)$$

(Heiland, 1940, p. 523) in which V_m is the true velocity and $V_{m'}$ and $V_{m''}$ the apparent velocities in the refractor from reverse shooting.

CORRECTIONS

A shot correction is required since a surface to surface subtractor (the reciprocal time) is used in the calculation of the time-depth. The shot correction in effect places the shot at the surface of the ground and is approximately equal to the ratio D_s/V_s where D_s is the distance of the shot from the surface and V_s is the velocity in the material between the shot and the surface. The correction is positive for buried shots, negative for air shots, and is applied during the reading of the records.

Elevation and weathering corrections are generally unnecessary since the topographic surface is taken as the datum and the weathered or surface layer is treated as a layer in the multilayered problem. However, if a differential displacement of some of the travel time irregularities is apparent with reverse shooting, it may be possible to distinguish between variations in the thickness of surface and intermediate layers and apply a standard correction procedure for the surface layer. This follows from considerations of the inclination of the ray paths and the horizontal displacement between the recording geophone and the points at which the recorded rays leave the refractor.

ROUTINE SURVEY PROCEDURE

In most problems for investigation, it is possible to select from the refractors present one important refractor. This refractor is generally overlain by several layers of differing seismic velocity. Such investigations are suitable for a basic or routine survey procedure in which use is made of composite velocity terms but which may be modified as required.

Ambiguities Concerning the Important Refractor

The routine survey procedure must yield time-depths to the important refractor at all geophone stations. Hence, the travel times used in the time-depth calculation must be shown to be of critical rays from the important refractor. This may be done by resolving ambiguities in the time-distance curve prior to commencing computations.

The ambiguities which must be resolved occur when there is a change in slope of the time-distance curve showing an increase in apparent velocity with an increase in distance from the shotpoint. Such a change in slope may be caused either by a change in the dip and/or the velocity in the same refractor, or by the recording of a deeper, higher velocity refractor.

Reverse shooting, which is necessary from other considerations, does not resolve this ambiguity when the change in slope occurs in a similar position from both directions of shooting. However, from considerations of critical distance this may be simply resolved by recording from two shotpoint-to-spread distances for each direction. The point of change of slope in the time-distance curve will be displaced towards the more distant shotpoint if a deeper, higher velocity refractor has been recorded; but no displacement will occur with a change of dip or velocity in the same refractor. The differentiation between a dip or a velocity change in the refractor presents no

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difficulties and is resolved in the method itself. A comparison between the slopes of the time-distance curves for the shots from the same direction is rapidly effected with a parallel rule using two large set-squares.

By this procedure it is readily apparent which geophones have recorded the critical rays from the important refractor. To show that the reciprocal time is also of a critical ray from the same refractor, this travel time is checked against continuous travel time profiles which are obtained by tying adjacent spreads by means of one or two common geophones. The time-depths to the important refractor are then calculated from the travel times of the more distant shotpoints and are checked against those calculated from the closer shotpoints where the important refractor has been recorded. This serves as a further check on the reciprocal times as well as the individual travel times.

In most shallow investigations the important refractor has a relatively high velocity and can be recorded over the distance of the spread and the reciprocal geophone without difficulty. However, if the refractor can be recorded over only part of this distance, additional shotpoints will have to be used. If necessary, the reciprocal times can be determined from the continuous travel time profiles.

The Composite Depth Conversion Factor

The velocities and half-intercept times or time-depths of the near surface and intermediate layers are obtained at the special weathering spreads which are recorded at the alternate junctions of normal spreads on a continuous traverse. Further, without losing the above resultion of ambiguities in the time-distance curves of the normal spreads, it is usually possible to record from the intermediate layers with the first few geophones near the closer shotpoints. Thus, intercept times and apparent velocities for the intermediate layers are obtained near the ends of the normal spreads. Additional values are obtained from a fifth shotpoint placed at the center of the normal spreads.

Hence, the composite depth conversion factor is calculated at the locations of the weathering spreads. The lateral variation of this factor is controlled by similar calculations for the shotpoints near the ends and within the normal spreads. The depth to the important refractor at each geophone station is computed by multiplying the calculated time-depth by the corresponding composite depth conversion factor.

Field Practice

For continuous profiling, the recording equipment is placed near the junction of two normal spreads which are tied by one or two common geophones. Each normal spread is recorded using the above five-shot pattern unless more shotpoints are required to record fully the important refractor. A weathering spread is also recorded. The equipment is then moved two spread lengths along the traverse, and the procedure repeated.

For the weathering spreads, a geophone interval of 10 ft is used with shotpoints recorded from distances of 10 ft and successively increasing distances which give an adequate shotpoint-to-geophone overlap. Usually, a total of six or eight shotpoints are required. A separate geophone cable with the appropriate takeouts is used.

The geophone interval used for the normal spreads will depend on the detail required by the problem, but for most problems an interval of about 40 or 50 ft has been found suitable. With an interval of 40 ft, conventional equipment of twelve channels (of which one is used for the reciprocal geophone) yields a spread length of four hundred feet. Weathering spreads occur every eight hundred feet along the traverse and close shotpoints every two hundred feet.

The shots are usually placed in auger holes at a depth of a few feet, but may be placed deeper in well populated areas. The cables used as shot firing lines are also used to transmit the signal from the reciprical geophone. When geophones are placed near previous shotpoints, care is taken to plant the geophone away from the disturbed zone of the shot. In general the shotpoint is located a little to one side of the traverse and the geophone to the opposite side.

Reduction Procedure

The recorded travel times of each spread are plotted as time-distance curves, and the lines of best fit drawn for the apparent velocities. A comparison of the time-distance curves for the reverse directions and a direct comparison for the two shotpoint-to-spread distances for each direction are made. The reciprocal time is checked against the extended travel time profile. The time-depths to the important refractor are then computed on tabulated result sheets, and the recorded travel times corrected by the subtraction of the corresponding time-depths.

The composite depth conversion factor is evaluated along the traverse and the depths to the important refractor computed. The depths are plotted on vertical sections along traverse lines by striking arcs of scaled radius beneath each geophone station, and the refractor profile is drawn in. The new time-distance curves are then plotted, the true refractor velocities determined and indicated on the section. The known thicknesses and velocities of the overlying layers are also indicated. It is important to note that initial reductions should be carried out during the time of the field survey to ensure that satisfactory results are obtained in the field.

ERRORS

Errors in Depth Determinations

The results of a survey should be accompanied by a statement of the expected errors in the depth determinations. Where sufficient empirical control is available from the results of check drilling, the expected errors may be calculated by establishing a direct correlation between the seismic and drilling results. The mean error in the seismic depth determinations may be taken as an estimate of any bias in the seismic results and the standard deviation from the mean taken as the equivalent random error in the seismic results. By way of example, the six drill-holes shown in Table 1 for the Commonwealth Avenue bridge site are all within 20 ft of geophone stations. The calculation of errors reveals a zero mean error indicating the results are without bias. The equivalent random error indicated by the standard deviation from the mean is plus or minus nine percent. This represents a typical example of the errors obtained for check drilled surveys.

If empirical control is absent or insufficient, a qualified statement on the errors expected under similar survey conditions may be given as a guide to those reading the survey report. The error estimate will be based on experience and on considerations of the sources of possible error in both the time term and the velocity term of the depth computation.

Errors in the time term may result from reading errors and from a smoothing of the profile of an irregular refractor which is inherent in both the recorded travel times and in the calculation of the time-depth. Further errors may result from the recorded rays following minimum time and not necessarily critical ray paths. This leads to errors from variations in the travel paths through the refracting layer for the rays recorded by the various spread and the reciprocal geophones. The variations in travel paths result from either an increase in refractor velocity with depth or a raised irregularity in the refractor profile under a spread geophone.

Errors in the velocity term may result from the discrete and not continuous sampling of both the time-distance curve and the calculated velocity term along the traverse. In the case of the surface velocity continuously increasing with depth, the velocity distribution is approximated with a number of discrete velocity layers. Further errors may result from the inability of the refraction method to detect velocity inversions, layering within a blind-zone above a refractor, or velocities in directions other than parallel to a refract-

Table I. Comparison of Measured Seismic Velocities with the Type and Condition of the Bedrock Refractor

Drill-hole	Dept in ft	Location	Type and Condition of Bedrock	Seismic Velocity in ft/sec
5	188	10 ft from stn. A840	Soft decomposed shale or mudstone.	6,500
1	80	Stn. A160	Weathered mudstone with pockets of soft decomposed mudstone.	6,500
3	90	Stn. A640	Weathered mudstone (less weathered than in hole 1) with pockets of soft decomposed mudstone.	7,200
6	82	Stn. C00 (not shown)	Broken, partly weathered siltstone.	8,000
2	75	Stn. A400	Partly weathered mudstone with appreciable strength.	9,500
4	60	20 ft from stns. A760 and A720	Partly weathered mudstone with appreciable strength.	9,500

ing interface. Such errors may readily introduce a bias into the calculated depths.

From considerations of the magnitude of possible errors in the depth computation, it appears that the greatest uncertainties are present in the determination of the velocity through the material overlying the refractor. However, the availability of drillholes at the time of the survey for both vertical velocity measurements and direct correlation will minimize the possible errors from the deficiencies in the refraction method.

For surveys under "normal" conditions and without drilling control, the errors usually expected may reasonably be stated as having an equivalent random error within ±10 to 15 percent with a possible bias within 10 percent of the calculated depths. This estimate would be applied to the example survey of the Acton weir site.

Errors in Velocity Determinations

Errors in the measured velocities are due to the time errors and to distance errors which occur in the plotting of the corrected time-distance curves. The transition zones in the velocity profile, which occur above velocity changes in the refractor, must also be considered. However, where the velocity in the refractor is constant over more than three geophone stations, the measured velocity should be determined with good accuracy.

COMMENTS

Seismic refraction methods which aim to extract detailed information on the refractor profile are the graphical methods of Thornburgh (1930, p. 185–200) and others, and the analytical methods based on isolating time terms at geophone stations. The graphical methods of Thornburgh involve less assumptions than the analytical methods and should therefore obtain a higher accuracy. However, the main uncertainties still remain in the determination of the velocity distribution in the material overlying the refractor. In view of the additional time involved in the construction of wave-front diagrams, it is only in the exceptional cases where the analytical approximations are unacceptable that the graphical methods may be used with real advantage. Such cases arise where deep, irregular refractors with steep dips and low velocity contrasts with the overlying material are present.

The analytical methods of isolating the time term at geophone stations are based on the concept of either the time-depth or the delay-time. The assumptions and procedures used differ in each case, but the accuracy of the results obtained, appear comparable.

For the time-depth, the refractor is assumed to be plane in the limited region below the geophone station between the points from which the recorded rays leave the refractor. This follows from the calculation of the mean value of the time-depths from opposite directions of shooting. No additional assumptions are made for the dip of or the velocity in the refractor. Critical ray paths are assumed for both the time-depth and the delay-time.

For the delay-time, the refractor is assumed to be horizontal at the points where the recorded rays leave the refractor. Also, the velocity in the refractor is assumed to be constant. However, if changes in the refractor velocity extend over a considerable distance, they are readily corrected in the calculation of the delay-time differences.

In the determination of the delay-time differences, the delay-time curves are migrated towards their respective shotpoints by the approximate horizontal displacement between the recording geophone and the points at which the critical rays leave the refractor. This procedure reduces the errors from the slight smoothing inherent in the calculation of the time-depth. However, additional errors introduced due to variations in elevation and surface conditions between the recording and the migrated position offset the advantage from this procedure.

In the reduction of results, the time-depths have the advantage of involving only simple numerical computation and yield the absolute depth profile of the refractor directly. Delay-time analysis usually involves a somewhat more lengthy procedure with a number of graphical steps. This yields a relative delay-time profile which may be tied to half-intercept times to obtain the absolute depth profile of the refractor.

The use of the time-depth in the analysis of the refractor velocity is related to a method sometimes used in seismic reflection surveys as a check on the geophone placing and on serious errors in the measured subweathering velocity along the geophone spread (Vale, 1957). In this method, if G' and G'' are two successive geophone stations which record from shotpoints S' and S'' on respective ends of the geophone spread, the recorded travel times are grouped as

$(t_{S'G''} - t_{S'G'})$ and $(t_{S''G'} - t_{S''G''})$. The Mean of the Sum of these groups yields the approximate travel time in the refractor between the geophone stations. The Mean of the Difference of the groups yields the delay-time difference between the two stations.

Finally, the Plus-Minus method of Hagedoorn (1959, p. 158–182) may be seen to be basically similar to the Reciprocal Method. Hagedoorn's Plus values are identical to the time-depths, and his Minus values give a refractor velocity analysis in a similar manner to the Mean Sum method.

EXAMPLES

Two examples are included. The first is an example of a completed survey of a weir site at Acton, Canberra, Australia. The second is a specific example illustrating the technique of velocity analysis for a seismic traverse of the Commonwealth Avenue bridge site, Canberra, chosen because of subsequent check drilling of the refractor velocities.

Both surveys were carried out in June, 1956, for the Department of Works, Canberra, by a geophysical party of the Bureau of Mineral Resources, Melbourne, Australia. The geophysical party consisted of the author as party leader-geophysicist, an observer-shooter, and an assisting geophysicist for some of the time. Two to four field hands were supplied by the Department of Works. The surveys were two of a group of nine surveys of dam, weir, bridge, building, and quarry sites carried out between May and August, 1956. As both surveys were conducted in partly populated areas which had considerable traffic, shots were placed in auger holes at a depth of 5 to 10 ft to reduce noise and damage.

Example of a Completed Survey—the Acton Weir Site

The Acton weir site, which has since been abandoned for a more favorable alternative site, formed part of the Canberra Lakes Scheme. The site extended over much of the Royal Canberra golf course and lies across the Molonglo River at Acton, Canberra.

Geology.—The geology of the site is rather complex and is covered by undifferentiated Recent to Pleistocene deposits almost entirely. The main structural feature of the area is the Acton fault which was known to occur somewhere on or near the site. The Acton fault is a major normal fault which strikes north-west and separates folded Ordovician sandstones and shales to the south-west from folded Silurian calcareous shales with limestone bands, shales, sandstones, tuffs, and rhyolites to the north-east (Opik, 1953).

Seismic Results.—The location of the seismic traverses together with the topographic and "unweathered bedrock" contours, zones of low seismic velocity in the bedrock, and possible fault zones are shown in Figure 4. Cross-sections along traverse lines showing the depth profiles of the "weathered bedrock" and the "unweathered bedrock," the measured seismic velocities in the bedrock, and average velocities through the overburden are shown in Figure 5.

In the presentation of the seismic results, a surface layer of 1,200 ft/sec velocity and an underlying layer of 5,000 ft/sec velocity have been grouped together as overburden, and an average velocity calculated for it which ranges between 1,350 and 1,900 ft/sec. This layer ranges between 12 and 47 ft in thickness and is composed mainly of alluvial deposits.

Beneath the overburden is a layer which ranges in velocity from 5,500 to 9,500 ft/sec except at one place on traverse *M* where the velocity is about 12,000 ft/sec. The thickness of this layer varies considerably throughout the area. On the western half of the site the thickness is between 39 and 115 ft, averaging 73 ft. On the eastern half of the site it is much thinner and has been detected at only a limited number of places where it is between 10 and 50 ft in thickness and has a velocity of about 9,000 ft/sec. The general term, "weathered bedrock," is used to denote this layer.

Underlying the "weathered bedrock" layer is a refractor of increased velocity which ranges from 8,000 to 20,000 ft/sec. The low velocities from 8,000 to 9,000 ft/sec are interpreted as occurring in zones of fracturing and partial weathering. Faulting is postulated as the cause. These zones correspond with relatively lower velocities in the overlying "weathered bedrock" layer. The remaining velocities are in the range of relatively unweathered sedimentary rocks, and this refractor is denoted in general terms as the "unweathered bedrock." The use of the above general terms is considered justified because the implications as to the state of the rock is in general correct, although some exceptions occur.

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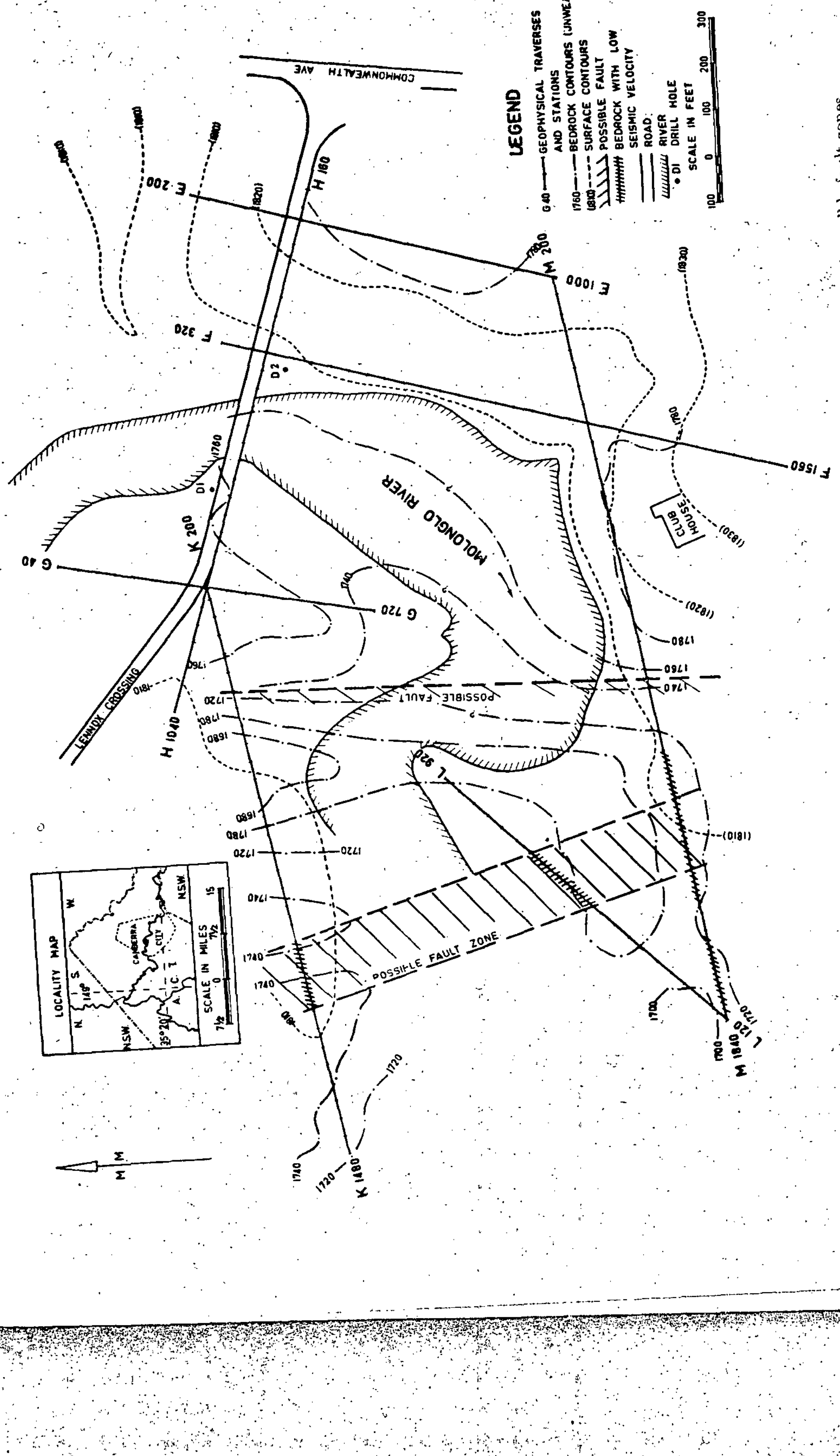


FIG. 4. Traverse plan of survey of Acton weir site showing unweathered bedrock contours and possible fault zones indicated by seismic results, surface contours, and drill locations.

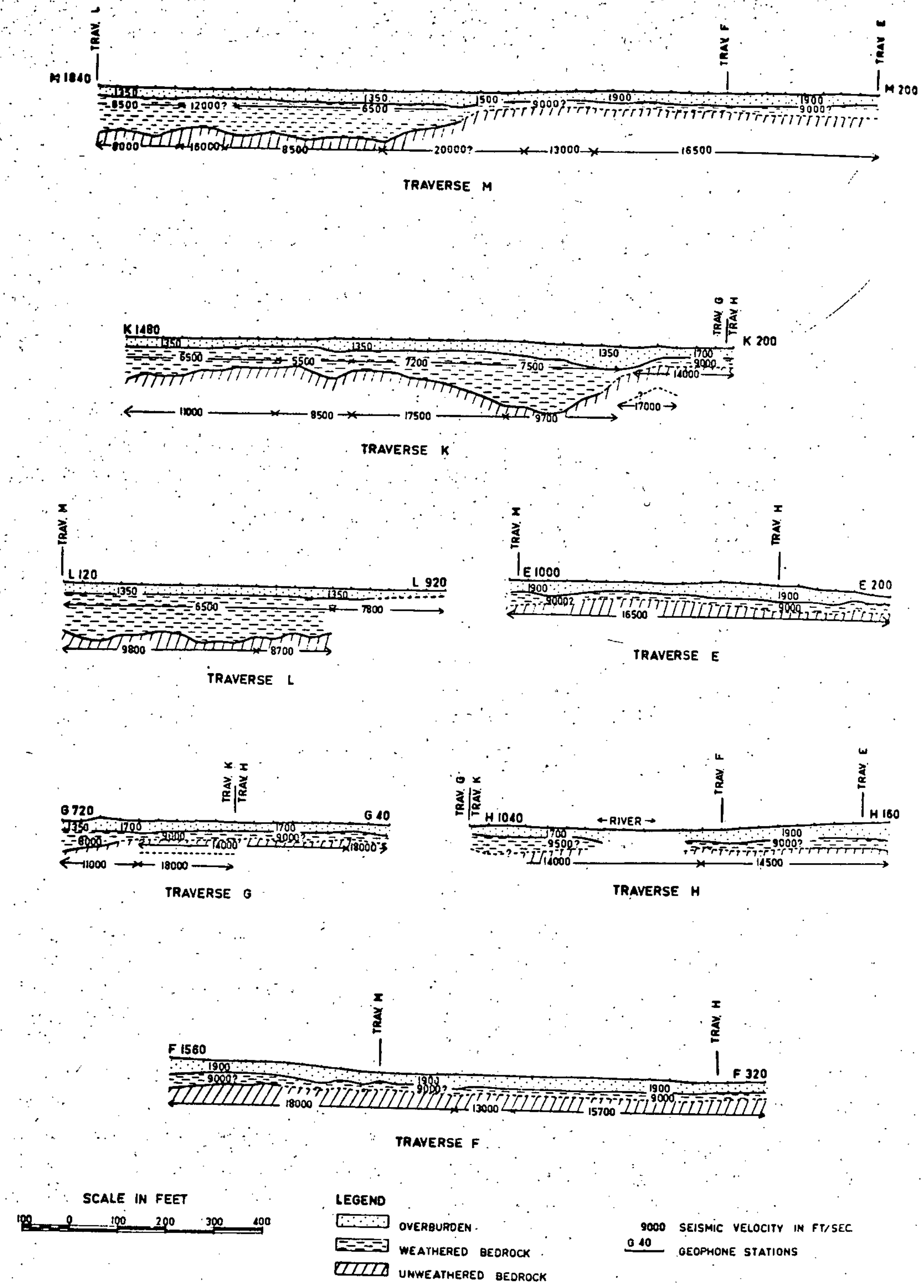
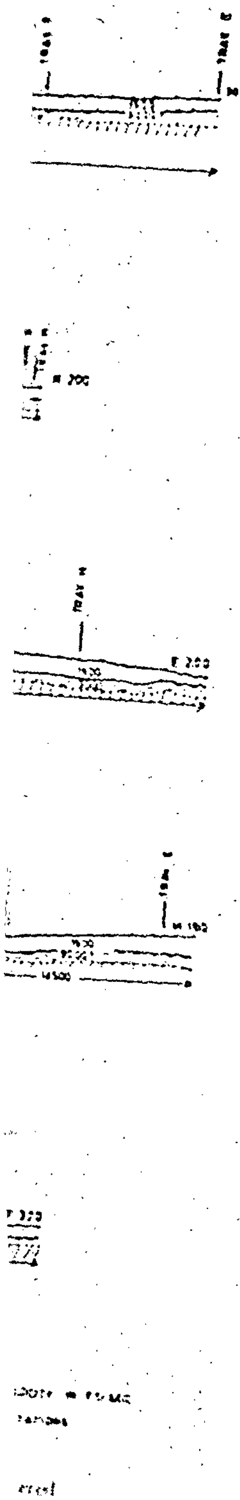


FIG. 5. Cross-sections along traverses showing seismic determinations of weathered and unweathered bedrock and measured seismic velocities.



bedrock" may be from lenses of limestone which could be relatively thin. However, it is reasonable to assume that underlying interbedded sediments, although they may have a somewhat lower velocity, would also be relatively unweathered and have considerable strength. Two cases of higher velocity layers within the "unweathered bedrock" were recorded on traverses *K* and *G*.

Two possible fault zones are marked on Figure 4. The first strikes almost north-south across the middle of the proposed site and is indicated in the seismic results by a substantial increase in the thickness of and decrease in the seismic velocities in the "weathered bedrock" layer to the west of the line shown on Figure 4. This line marks the eastern limit of the supposed fault zone, but the width of the zone is indefinite because the whole area to the west is deeply weathered and crossed by the second supposed fault. The second fault is indicated by low seismic velocities on traverses *K*, *L*, and *M*. This supposed fault has a north-northwesterly trend and is correlated by geologists with the Acton Fault.

A point of interest in the seismic results is the plotting of a thin continuous "weathered bedrock" layer extending over the eastern half of the site. Here, the velocity in the "unweathered bedrock" is between 13,000 and 20,000 ft/sec. The thin overlying layer was recorded only at some weathering spreads and at shotpoints near normal spreads at the southern ends of traverses *F* and *G* where the layer is thicker. The layer was also indicated by later arrivals on some normal and weathering spread records from traverse *F*. This occurred where the first arrivals (of 15,700 ft/sec velocity) were of high frequency but of relatively small amplitude, possibly due to refraction along thin limestone lenses. Where recorded, the layer is generally of the order of 10 to 20 ft thick and may represent partly weathered interbedded sediments overlying the higher velocity beds or lenses. The evidence suggests that the layer may be continuous across this area but that it is masked by the higher velocity "unweathered bedrock."

In the interpretation, the layer was assumed to be continuous, and the depth profiles of both the "weathered" and "unweathered" bedrock were plotted. The time-depths to the top of the "weathered bedrock" were obtained by subtracting the approximate time-thickness of this layer from the calculated time-depths of the "unweathered bedrock." Since the composite depth conversion factor in the calculation of the depth to the "weathered bedrock" is small, the calculated depth is relatively insensitive to the value adopted for the time-thickness of the "weathered" layer. Hence, in this interpretation, the upper surface of the bedrock is estimated fairly closely even in places where the assumed weathered layer may be absent.

Conclusions from the Seismic Results.—It is apparent that the area to the west of the first possible fault is unfavorable for weir foundations. Although the thickness of the overburden here is only slightly greater than to the east, the bedrock appears deeply and extensively weathered and is crossed by two possible faults, one of which is correlated with a major fault between the Ordovician and Silurian strata.

In the area to the east of the first fault much more favorable conditions are present, and the most promising site is in the northern part of the area approximately along traverse *H*. In this area the overburden ranges from 12 to 27 ft and averages 25 ft in thickness. The underlying bedrock appears to consist of a thin "weathered" layer of about 9,000 ft/sec velocity (which probably does not exceed 20 ft in thickness and may be absent), underlain by the "unweathered bedrock" in which the velocity is between 13,000 and 20,000 ft/sec. The velocities in the "unweathered bedrock" are indicative of strong foundation rock even though they may result from lenses of higher velocity rock overlying associated sediments. The "weathered bedrock" layer, if present, may also prove suitable foundation rock.

Subsequent Drilling.—Diamond drilling of the site was carried out in 1958, and the locations of the two drillholes on the site of the survey are shown on Figure 4. The drillholes were located a little away from the geophysical stations, approximately along traverse *H* and near the centerline of the proposed weir. Both holes entered hard calcareous, little weathered mudstone, siltstone, and sandstone immediately below the sandy alluvium. The depths at which this bedrock were intersected were about 17 and 23 ft and are similar to the seismic estimates to the top of the "weathered bedrock" at the closest geophone stations. No appreciable change in weathering was apparent from the drilling, showing that the assumed "weathered bedrock" layer is absent in this particular area.

Example of the Analysis of the Velocity in the Refractor

The part of the centerline traverse of the new Commonwealth Avenue bridge site shown in Figure 6 runs approximately north from the top right hand corner of Figure 4 across the alluvial covered Molonglo valley up to the south bank of the Molonglo River.

In the presentation of the seismic results the surface layers have again been grouped into one layer (the overburden) which has a calculated average velocity between 1,900 and 2,600 ft/sec.

The measured velocities in the bedrock refractor range from 6,500 to 18,000 ft/sec. Figure 6 shows the continuous time-distance curves of both the recorded and the corrected travel times, the measured bedrock velocities, the depth profile of the bedrock refractor, and the average velocities through the overburden.

Eight holes were drilled on the proposed bridge site subsequent to the seismic survey. Five of the drillholes are shown in Figure 6. The sixth was drilled just north of the river into bedrock in which the seismic velocity is 8,000 ft/sec. The

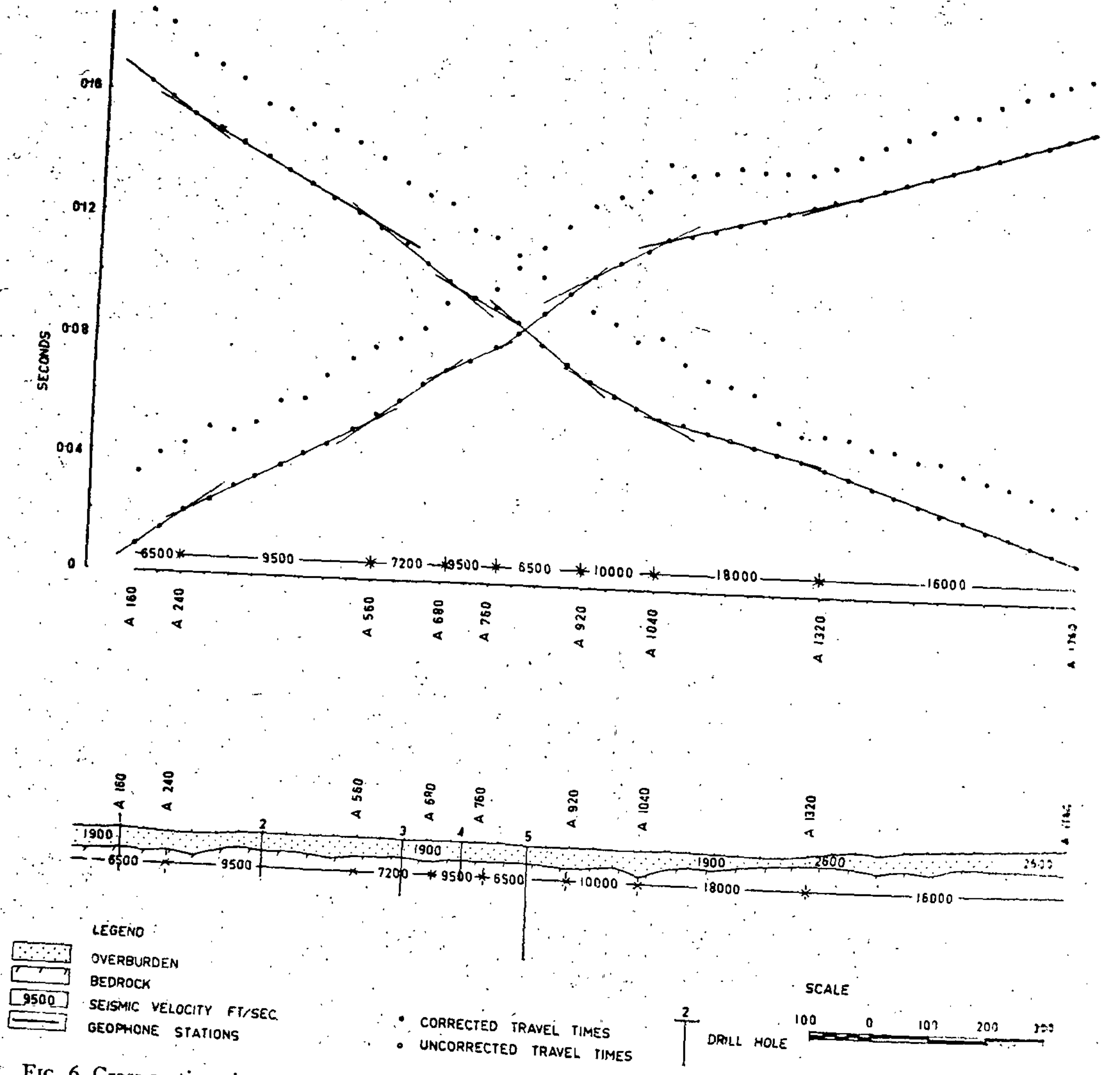


Fig. 6. Cross-section along seismic traverse from survey of Commonwealth Avenue bridge site showing bedrock profile and drill locations together with time-distance curves of recorded and corrected travel times and measured velocities.

two remaining holes were located in the river bed away from the seismic traverses. The results of the drilling are recorded in an unpublished Record of the Bureau of Mineral Resources (Gardner, 1957).

The holes were drilled to check areas of bedrock in which the seismic velocity was in the lower range of 6,500 to 9,500 ft/sec. The bedrock in these areas was shown to be Silurian mudstones and siltstones in which the fracturing and degree of weathering show a direct correlation with the measured seismic velocities. A comparison between the seismic velocities and the type and condition of the bedrock for the six relevant drillholes is shown in Table 1. It is interesting to note that hole No. 4 was drilled into bedrock in which the recorded velocity of 9,500 ft/sec extends approximately 80 ft over only two geophone stations. Holes Nos. 3 and 5 were drilled one hundred feet on each side of hole No. 4 into the lower velocity, more decomposed rock and show that variations of the seismic velocity are delineated fairly precisely within the limits of the geophone spacing used.

The bedrock in which the seismic velocity is 16,000 to 18,000 ft/sec was not checked by drilling on this site. However, the area in which it occurs is just to the northeast of the Acton weir site. It appears probable that the highly calcareous sediments with limestone beds and lenses persist here.

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