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Some applications and problems of the seismic refraction technique in civil engineering projects in Malaysia

B.K LIM & S.J. JONES
(EG & G International Inc.; formerly of Geomex Surveys)

Abstract: The seismic refraction technique has been used worldwide to assist in site investigations for general earthworks associated with high-rise construction, quarrying, hydro-electric power schemes, rail, road and tunnelling projects.

General limitations inherent in the application of seismic refraction theory to "real-world" conditions have been well-documented, as have the theoretical refinements intended to overcome these problems.

The tropical weathering environment encountered in Malaysia imposes additional subtle constraints. This paper discusses the important influence of tropical weathering processes on seismic operations and presents a practical approach to maximise useful data acquisation and interpretation.

INTRODUCTION

Since 1975, Geomex Surveys Sdn. Bhd. have performed shallow seismic refraction surveys in Malaysia. These surveys have been generally for engineering site investigations to provide subsurface information to depth of up to 50 metres. The chief advantage of the technique is that it provides a rapid and economical means of subsurface investigation over vast areas intended for engineering construction.

This paper attempts to describe and illustrate some of the practical problems associated with shallow refraction work undertaken for engineering purposes in Malaysia. The main objective is to acquaint civil engineers and geophysicists with the capabilities of the method which are limited by the local topographical and geological constraints of the survey sites. The treatment is by no means complete. Secondly, it attempts to illustrate that with due consideration to the factors relating to the local ground conditions, terrain and subsurface geology, a more reliable and less ambiguous interpretation is possible.

SHALLOW REFRACTION INVESTIGATION

In shallow refraction studies, energy is introduced into the ground by exploding a small charge of gelignite or by striking the surface with a weight. The artificial shock generated is detected by a line of regularly spaced geophones which are planted on to the ground. Alternatively, a single seismometer can be used to monitor seismic returns from successive energy points. Both single- and multi- channel techniques are illustrated in Fig. 1.

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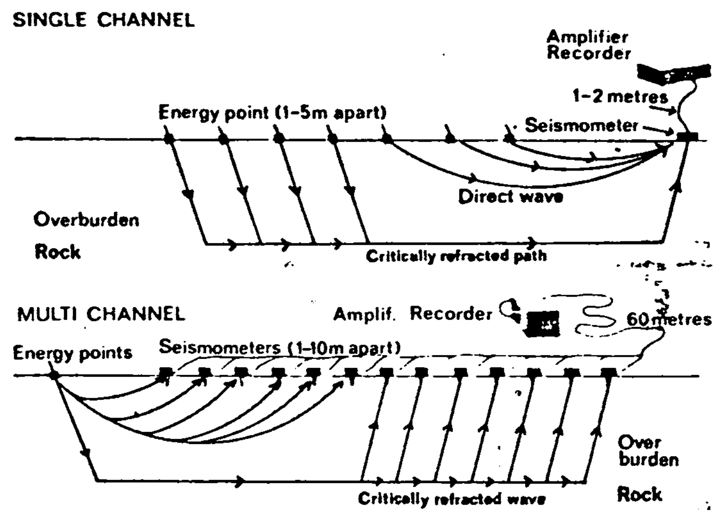


Fig. 1. Multi channel technique requires energy application at two points only to get sufficient data to calculate accurate depths-to-bedrock. A single-channel system needs at last 24 points to get same amount of information. (ABEM Publicity Materials).

Contrasts in the physical properties of the overburden* and bedrock such as the density and elasticity, cause refraction of the seismic waves to occur at the interface. Velocities and depths to the bedrock can be calculated either graphically or by use of formulae from the first arrivals recorded at the geophones (Fig. 2). The recorded times of the first arrivals of the refracted waves from a given seismic interface are a function of the geophone—source distance, the velocity and dip of each overlying layer. The velocity of a given layer is a function of its dynamic elastic constants which are in turn mainly dependent on its textural composition and to a lesser extent, on porosity and depth of burial.

For the seismic refraction method to be applicable, certain physical requirements need to be satisfied within the area investigated:-

(a) The geological conditions may be approximated by homogeneous layers of constant seismic velocity.

(b) These layers are separated by plane interfaces of constant slope.

(c) Successively deeper layers have increasing seismic velocities.

(d) The thickness of each refracting layer is small compared to the length of the refraction spread, that is the distance from the shot point to the most distant detector.

*The term 'overburden' is taken to mean unconsolidated materials overlying the sound bedrock and hence encompasses the weathered bedrock materials also. Soil overburden when used in the text refers to the mechanically loose residual soil layer.

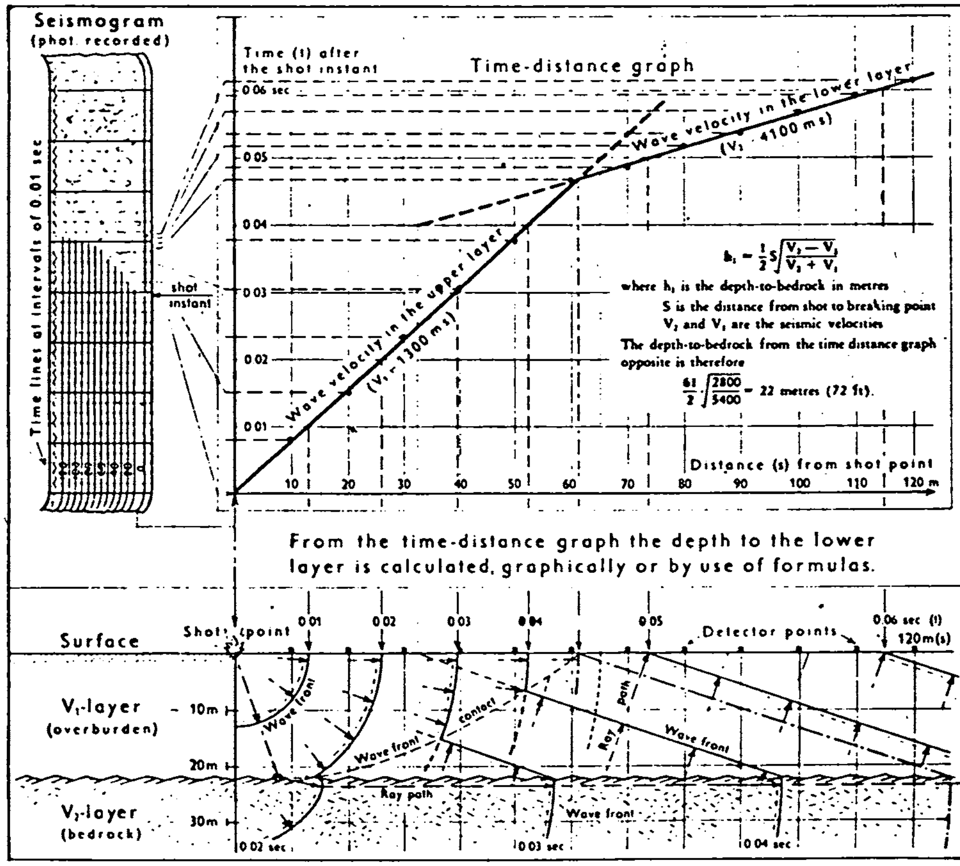


Fig. 2. Time-distance graphs for a theoretical single-layer problem, with parallel interface. With non-parallel interfaces, both forward and reverse profiles must be surveyed. (ABEM Publicity Materials).

(e) Where gradation from completely weathered to unweathered rock is gradual and the seismic velocity increases with depth within the bedrock, the velocity increase is taken to occur smoothly and continuously at right angles to the upper surface of the bedrock layer.

APPLICATIONS OF SHALLOW SEISMIC REFRACTION

Despite its wide potential, it is only in the engineering field that shallow refraction investigations have been applied on a significant scale. For a rapidly developing country, it is not surprising that the major percentage of refraction work undertaken has been for housing and land development schemes, road, highway and dam constructions and quarry operations. The main aims in the application to the engineering projects are;

(i) the determination of the depth to the bedrock and,
(ii) rippability of the subsurface materials.

Such information has been very useful in planning large scale excavation and earthworks for housing and land development schemes. For proposed road and highway constructions and quarry operations, the refraction method offers a rapid and economical means of estimating the overburden thickness over large proposed sites. In the past, insufficient knowledge of the subsurface has often been the chief cause of costly and unnecessary delays during construction stages when unsuspected rock formations were encountered.

In soil investigations intended for foundation design, refraction surveys may be use to complement drilling results. The elastic discontinuities within the soil profile may not always be coincident with lithological changes evident in the borehole data. Consequently, in limited site investigation programme, shallow refraction studies could be conducted to supplement and provide subsurface information and correlation between widely spaced boreholes.

The construction sites for these engineering projects are predominantly in undeveloped and hilly terrain. Problems encountered in the application of the shallow refraction method for such engineering purposes are primarily due to the difficult survey conditions of the construction sites.

LIMITATIONS AND ERRORS

There are several limitations to the application of the refraction method due to various geological and subsurface conditions. The presence of 'hidden' layers and 'blind' zones is a common problem in engineering surveys. Green (1962) showed that even if the velocity of each layer increases with depth, the intermediate layer would be hidden if the thickness of the overlying layer exceeded a critical thickness given by the expression;

$$Z_1 \text{ (min)} = (t_{13} - X_{13}/V_2)V_1/(2 \text{ Cos } i_{13}) \qquad \text{(see Fig. 3)}$$

Blind zone problems are frequently caused by presence of a high velocity layer overlying a low velocity medium. The formation of low-speed can be caused by several factors, which may be independent of each other. Among them are moisture conditions, frost and ice layers elsewhere and in urban areas, concrete layers.

In shallow refraction work, some of the common difficulties encountered in the interpretation are due to the near-surface inhomogeneities and variations in the overburden. Examples of horizontal and vertical variations of the velocity of the overburden have been well documented by Koefoed (1954) and Evison (1952). Poor data quality and, consequently, experimental errors can be caused by various factors relating to the topography, geology and ground conditions. Domzalski (1956) demonstrated that substantial errors may be introduced due to the location of the geophone spread in relation to the topography and influence of the ground conditions in the immediate vicinity of the geophone.

It should be stressed that though some of the errors involved may be relatively small, their significance becomes overbearing and correct treatment vital when dealing with relatively short travel times and shallow depths. In most of the engineering

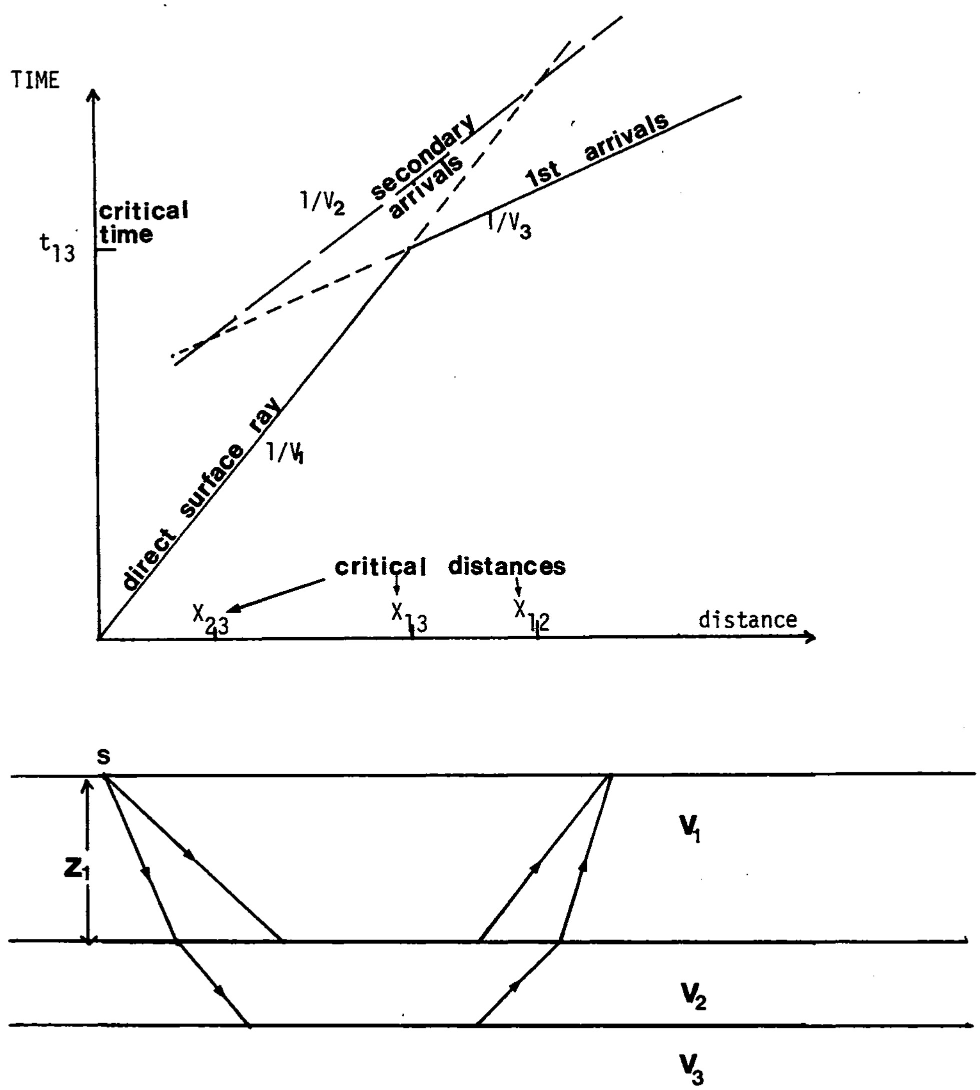


Fig. 3. The structure which can lead to a hidden layer and the time-distance plot illustrating the refracted arrivals from the intermediate layer, in all cases a secondary arrival (Green, 1962). For the intermediate layer to be hidden, thickness of the V_1 layer must exceed a critical thickness Z_1 where

$$Z_1\ (\min) = (t_{13} - X_{13}/V_2)V_1/(2 \cos i_{13})$$

surveys conducted in Malaysia, the depth of investigation seldom exceed depths of 50 m. For such investigations, the nature and variations in the overburden bear considerable significance in the final analysis of the seismic data. In addition, for refraction surveys over tropical terrain, the interpreter has to consider the nature and effects of tropical weathering on the subsurface conditions. Difficulties and errors in the interpretation have been primarily due to deviation of actual conditions from theoretical assumptions made.

DIFFERENTIAL WEATHERING

The nature and thickness of the overburden is dependent on two major factors viz. the weathering conditions and bedrock geology. Weathering under tropical conditions does not always strictly follow the stratigraphic succession downwards. In jointed, bedded or highly fractured bedrock, weathering elements persist deep into the bedrock through these lines of weakness. A preferential pattern of weathering proceeding initially from these zones (Plate 1) eventually results in the formation of highly inhomogeneous overburden and irregular bedrock topography (Plates 2 & 3). This is especially true of granites and other igneous rocks. Plate 4 shows a typical excavated site exposing the highly irregular bedrock. While basic refraction principles assume a distinct and contrasting change in elastic properties from the overburden to the bedrock, the transition in reality is a gradational one.

Time—distance plots of the first arrivals of the refracted waves usually show a gradual curve as in Fig. 4. The problem thus lies in correlating the refractors constructed from seismic data with some definite depth in the soil profile. Lithological changes evident from borehole data may not always be coincident with velocity discontinuities which are dependent on elastic contrasts. Exact correlations of seismic results with drilling under such conditions are fortuitious. Fig. 4 illustrates the discrepancies between engineering interpretation of the borehole data and geophysical interpretation of the refraction data. The misconception that the interpreted seismic refractors represent distinct boundaries separating homogeneous layers of increasing elastic properties within the soil profile could prove disastrous in earthwork planning. Where the bedrock topography is highly irregular and occurrence of core boulders is widespread within the overburden layer, no definite depth estimate to the bedrock material is possible. The 'seismic refractors' nevertheless serve to indicate approximate depths within the soil profile where certain proportions of the rock to soil materials may be expected. The estimated seismic velocity of each layer normally relates to their rippability characteristics and can thus be considered as qualitative measurement of the ratio of rock to soil materials. Consequently, for the 'refracted layer' whose velocity is close to the true velocity of the underlying bedrock, the effect of weathered materials can be expected to be very minor.

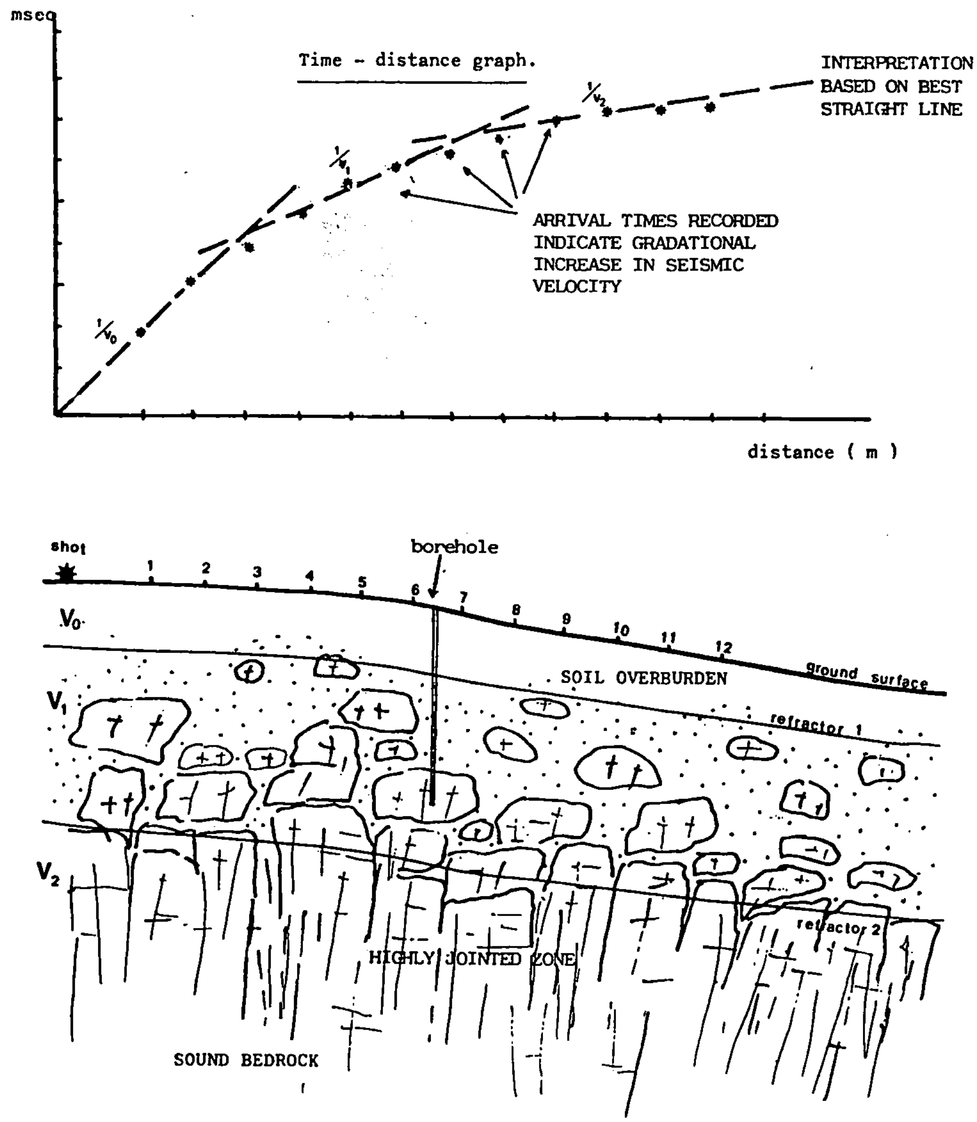
Fig. 5 shows an interpreted seismic section with some boreholes results. Generally, 3 layers are apparent from the refraction data. The first refracted layer is composed of predominantly clayey residual soil with only occasional rock materials present as boulders. Layer 2 represents a transition zone between the residual soil layer and the underlying bedrock (layer 3). Borehole data for layer 2 indicates presence of varying degrees of weathering grades of granite, though the occurrence of less weathered grades becomes more predominant towards the granite bedrock.

Plate 1. Preferential weathering along the joint planes present in the bedrock.
(Off Jalan Duta, Kuala Lumpur)

Plate 2. Inhomogeneous overburden due to differential pattern of weathering. Unweathered bedrock materials enveloped by highly weathered residual soil.
(Taman Tun Abdul Razak, Ampang, Kuala Lumpur)

Plate 3. Excavated granite hill exposing presence of core boulders. Abrupt changes in elevation and slopes of ground terrain are fair indication of such subsurface irregularities.
(Batu Ferringhi, Penang).

Plate 4. Excavated site showing highly irregular bedrock topography typical in tropical terrain. No well-defined plane interface exists between the overburden and the sound bedrock.
(Taman Tun Dr. Ismail, Kuala Lumpur).



GRANITE

NB. Illustration drawn not to scale. It illustrates the discrepancies between engineering interpretation of borehole data and geophysical interpretation of refraction data.

Fig. 4. Theoretical illustration of borehole and seismic refraction interpretation where the change in the elastic characteristics of the subsurface is gradational.

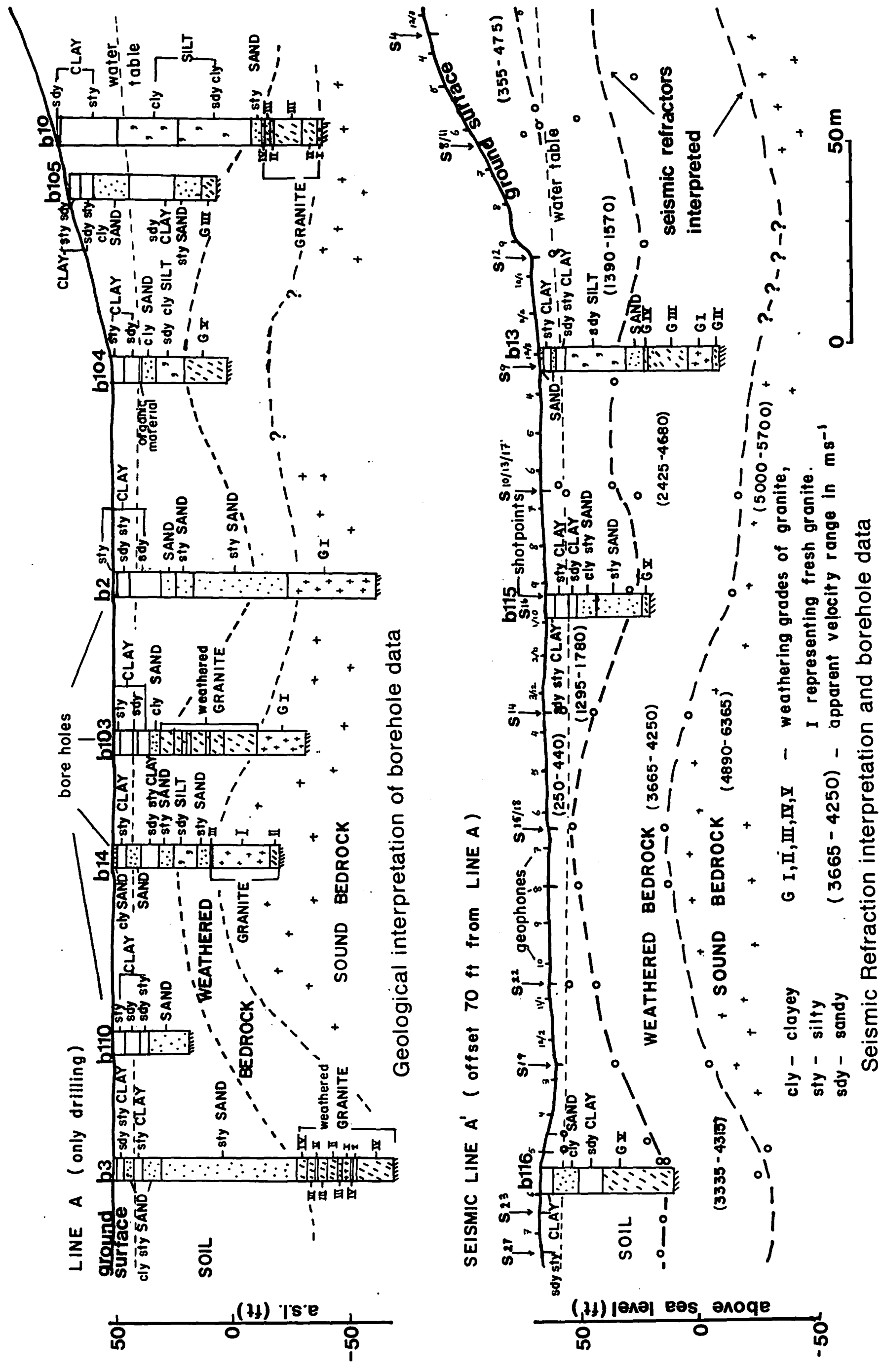


Fig. 5. Comparison between refraction and borehole results.

(NB. The Weathered Bedrock Layer is composed of various weathering grades of granite due to differential weathering)

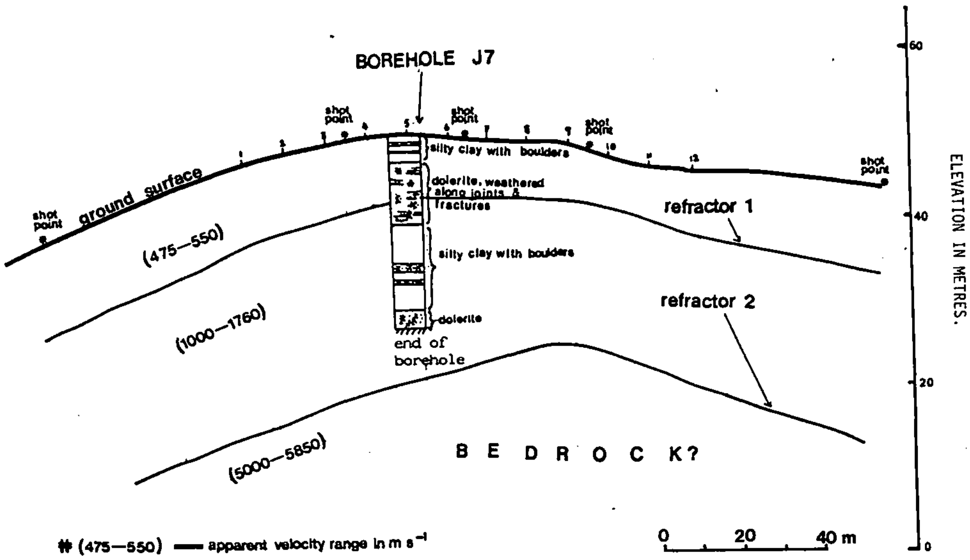


Fig. 6. Errors in interpretation due to differential weathering.

Where planes of weakness in the bedrock are horizontally inclined, a differential weathering pattern could result in alternate layering of weathered and unweathered bedrock materials. Borehole data in Fig. 6 suggests occurrence of preferential weathering along the horizontally inclined sheet joints present in the doleritic bedrock. The interpreted seismic interfaces shown were calculated without considering the errors caused by the presence of these weathered zones within the bedrock.

In general, seismic returns from the bedrock are poor when the bedrock refractor is poorly defined and highly irregular and in such cases it presents a major problem during field survey to obtain interpretable seismic data.

IRREGULAR AND STEEP TOPOGRAPHY

Due to the deep and intense nature of weathering, a highly weathered residual soil layer is prevalent over tropical terrain. The presence of this thick low velocity layer has significant consequences on shallow refraction investigations. The thickness of this layer which varies from 5 to over 15 m is relatively large compared to the total depth of investigation. Due to its low velocity range of about 350 to 500 ms^{-1}, a change of 1 m in thickness alone could cause a time difference of 2 msec. The importance of accurate and correct timing of the first arrivals of the refracted waves need no emphasis. Accurate and reliable interpretations are dependent on correct determination of the fundamental quantities such as velocity, cross-over distances, intercept times and others. Estimation of these quantities are based on surface measurement of distances and times.

In practice, ground conditions rarely approximate closely as parallel or uniformly dipping layers. Nevertheless, in terrain of moderate topography, errors due to slight

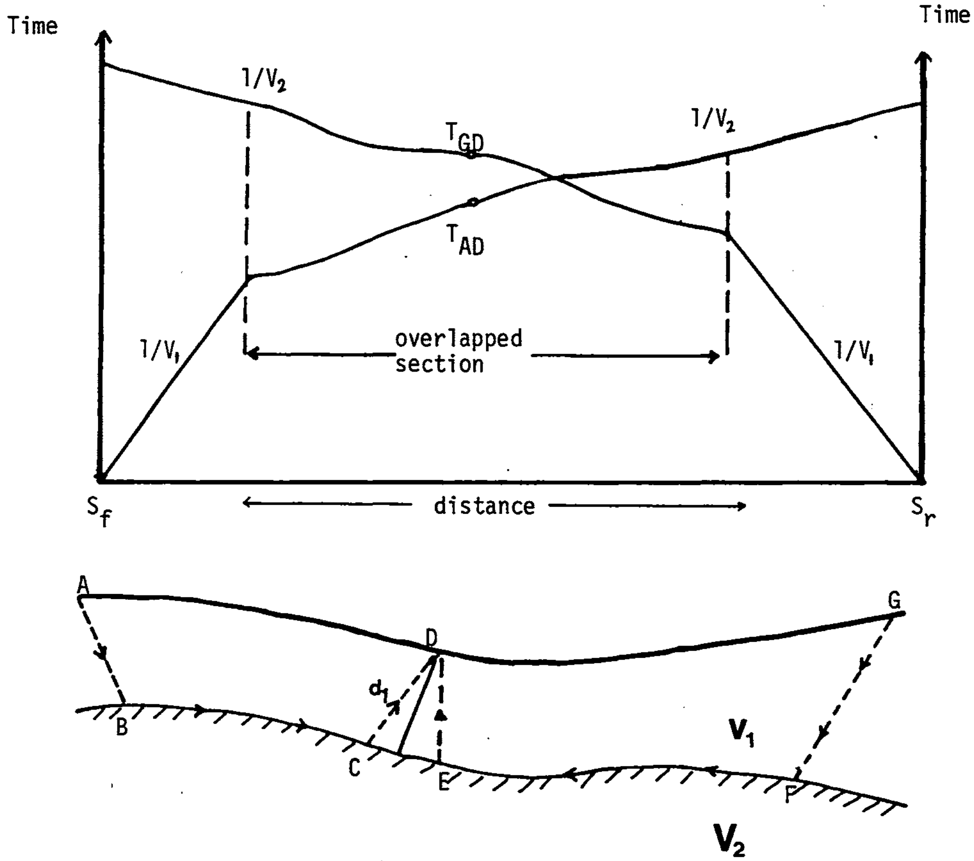


Fig. 7. Time-distance plot for use with the Hawkins' method. Depth can be determined at any point within the overlapped section.

$$d_1 = T . V_1 (\text{Cos } i_{12}) \qquad \text{where } T = \tfrac{1}{2}(T_{AD} + T_{GD} - T_{end})$$

differences in elevation and thickness of the low velocity layer are tolerable and may be corrected using normal reduction procedures. Where the refractors are undulating, interpretation procedures such as the Hawkins' Reciprocal Time Method (Hawkins, 1961) and Hagedoorn's Plus-Minus Method (Hagedoorn, 1959) allow fairly accurate mapping of these refractors. Successful application, however, requires adequate overlapping of the travel-time curves of the same refracting interface from reciprocal shots as illustrated in Fig. 7.

Such requirements are however difficult to achieve in survey sites where surface topography is both irregular and steep. Considerable variations in both the thickness and nature of the soil materials occur with sudden changes in ground elevation and terrain. This variation in the overburden over hilly tropical terrain is generalised in Fig. 8. Such variations are subject to strong influence by structural trends in the bedrock.

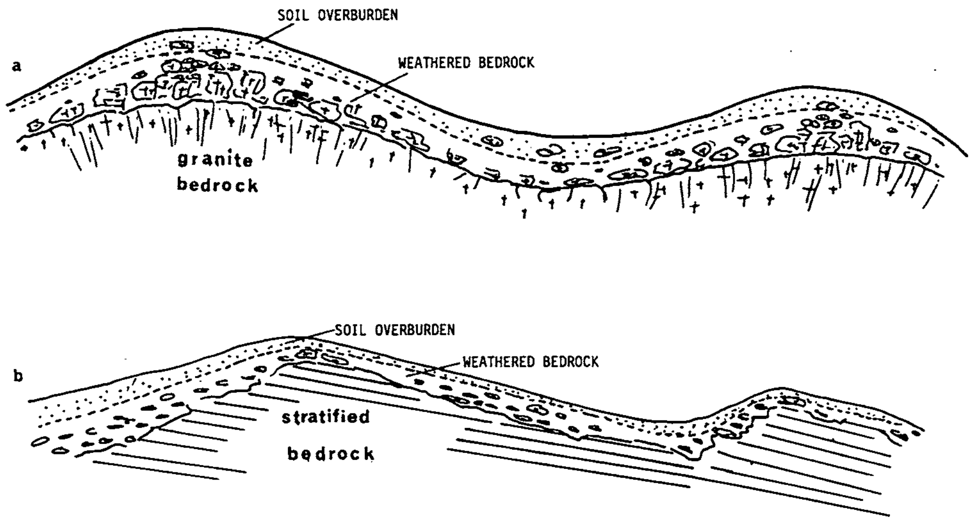


Fig. 8. Generalised variation in the overburden over hilly terrain underlain by (a) granitic and (b) stratified bedrock. The overburden is subdivided into (i) the soil overburden layer of low velocity and (ii) the weathered bedrock layer.

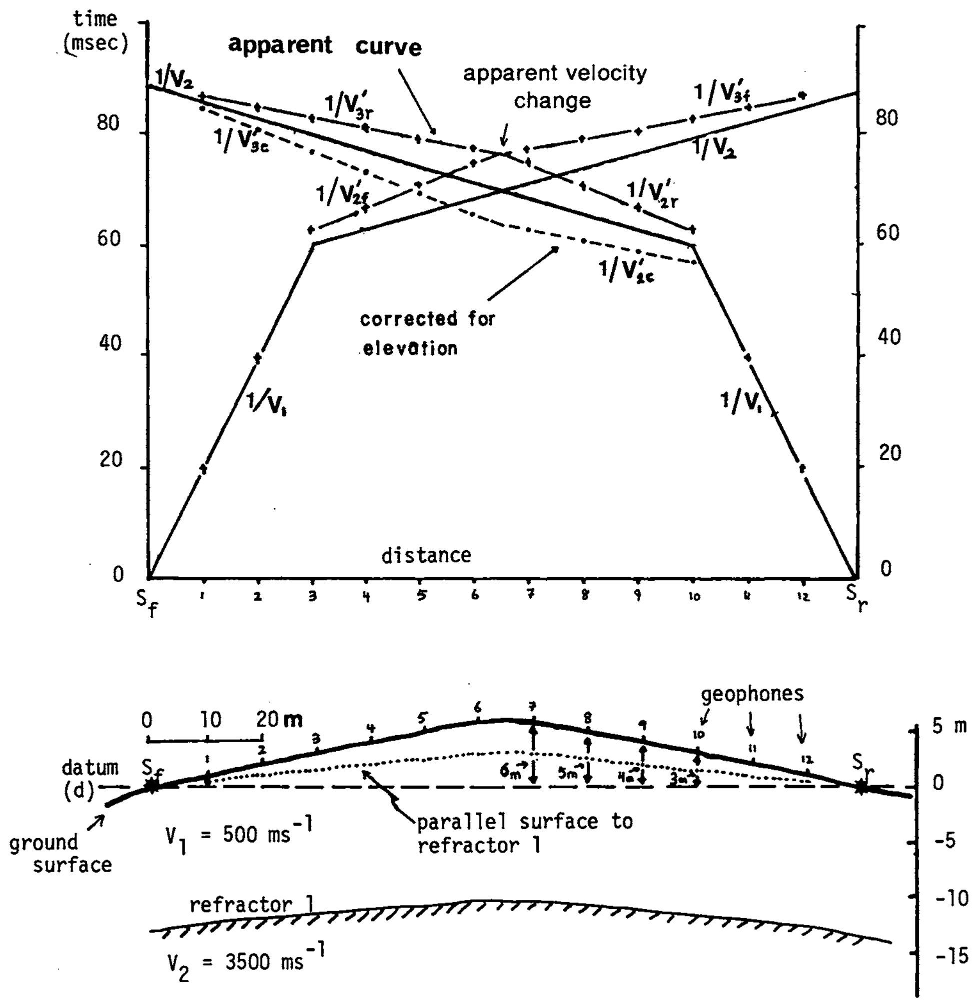
Of particular significance is the variation in thickness of the low velocity layer. Considerable variation occur across topographic features like the top of the hill, ridges and valleys. As illustrated in Fig. 9 and 10, such changes are sufficient to cause apparent velocity changes in the travel-time curve of the first arrivals of the refracted waves. In Fig. 9, the thickness of the soil layer is computed to decrease symmetrically by 0.5 m per 10 m horizontal distance from the centre of the spread. The resulting travel-time curves from shots S_f and S_r show apparently 3 velocities which are indicative of a 3-layer case. The apparent velocities of approximately 2500 and 5000 ms^{-1} for the apparent V_2 and V_3 layers respectively, are fairly representative of weathered and sound granite bedrock velocities. Reduction of the recorded times to an assumed datum using the normal expression;

$$\triangle t = (E_s + E_g - h - t - 2d) \text{Cos } i_{12}/V_1$$

where

$\triangle t$ — correction in msec.,
E_s — elevation of shot point,
E_g — elevation at geophone position,
h — depth of shot below ground surface,
t — thickness of low velocity layer beneath the geophone (not applicable in this case as the datum is within the layer.)
d — datum
i_{12} — the critical angle.

does not yield a truer picture. Unless sufficient borehole data is available, normal corrections applied would be just as erroneous. In truth, variations in the overburden



V_1, V_2—true vel. of 1st and 2nd layers respectively.
V'_{2r}, V'_{2f}—apparent V_2 vel. from shots S_r and S_f respectively. (approx. 2 500 ms^{-1})
V'_{3r}, V'_{3f}—apparent V_3 vel. from shots S_r and S_f respectively. (approx. 5000 ms^{-1})
V'_{2c}, V'_{3c}—apparent V_2 and V_3 velocities corrected for elevation.

Fig. 9. Theoretical consideration of effect of variation in thickness of the low velocity layer on interpretation of refraction data.

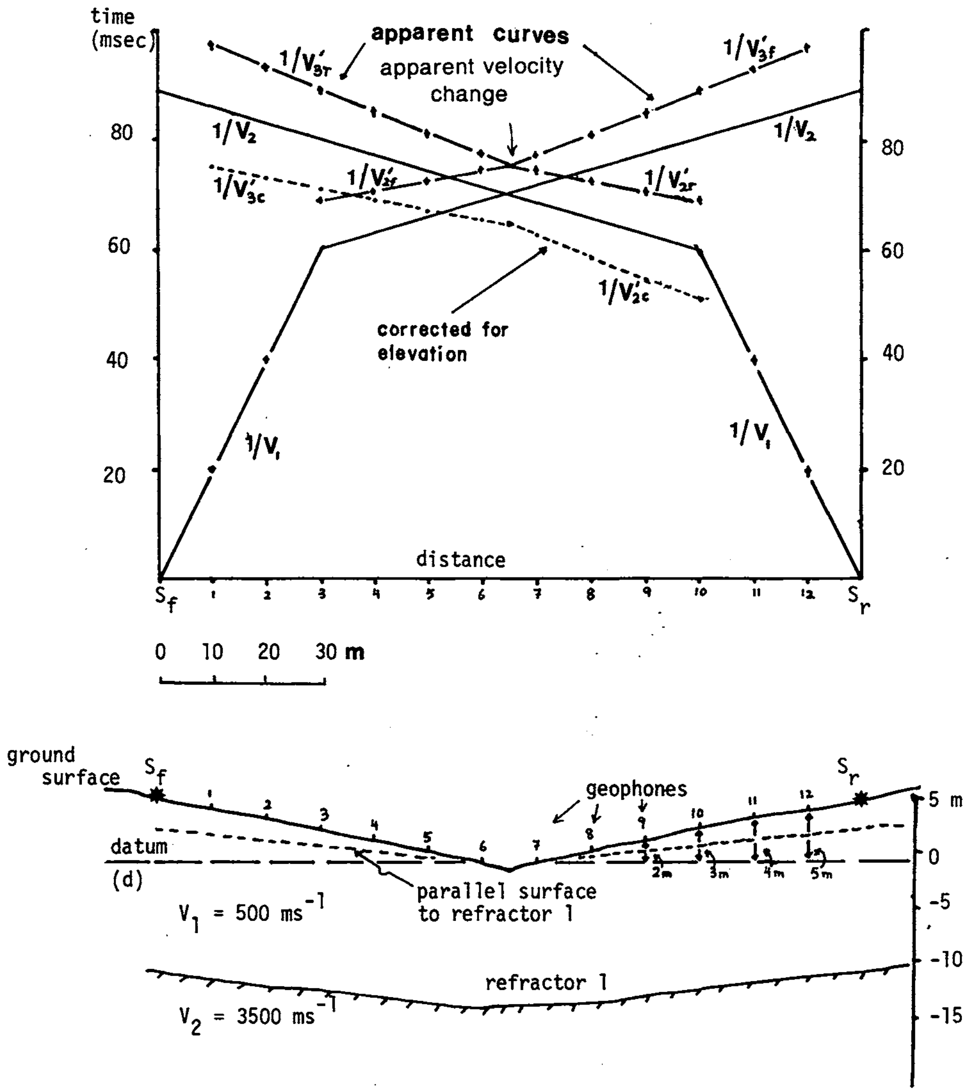
are difficult to predict and impracticable to predict them. Correction procedures in rugged terrain are further complicated by the fact that the average vertical velocity of the overburden changes rapidly along the line of traverse across abrupt changes in slopes and ground elevations.

Fig. 10 illustrates equally ambiguous travel-time curves for a 2-layer case where the overburden is assumed to increase symmetrically from the centre of the refraction spread.

While the reciprocal time interpretation methods such as the Hawkins' method allow for depth estimation beneath each geophone within the overlapped section, such calculations are made with the assumption that the overlapped parts of the velocity curves are from the same refractor. Just as the technique suffers from errors resulting from the inability of the refraction method to detect velocity inversions and layering within a blind-zone above a refractor, there are errors due to apparent velocity changes which may equally introduce bias into the calculated depths.

Fig. 11 illustrates a 3-layer model where the low velocity layer increase in thickness uniformly downslope, corresponding with the change in the gradient of the slope. Cross-section (a) shows the actual computed model, while the section interpreted from the apparent travel-time curves is given in (b). The second velocity change is not apparent from the apparent travel-time curves from both up-slope and down-slope shots. The resulting interpretation in (b) shows only 2 layers with the 'true velocity' computed to be 4440 ms^{-1}. Nevertheless, both time intercept and the Hawkins' methods yield fairly accurate depth estimates to the first refractor. While the error in the computed 'true velocity' does introduce a bias in the depth calculations, the error involved is small. The significant term is the depth estimation of the first refractor for both methods is the velocity of the first layer which is unaffected by the dips of the interface. The errors are, however cummulative and become significantly large when the major term in the depth calculation of the second refractor is the V_2 velocity. For shallow investigations intended for excavation purposes, the error in the determination of the true velocity would consequently lead to misjudgement of the rippability of the underlying rock materials. In reality, interpretation of such seismic data is further complicated by pronounced near-surface inhomogeneities and curvatures in the rock surfaces that normally accompany abrupt changes in the ground terrain. Diffraction or scattering of energy occurs when the curvature of the refractor is large compared to the curvature of the incident wave front. This effect frequently results in very noisy data.

Fig. 12 and 13 illustrate the complexity of the travel-time curves from refraction spreads shot over hilly terrain. In Fig. 12, the variation in the thickness of the residual soil layer is strongly influenced by stratification in the metasedimentary bedrock. Example shown in Fig. 13 is typical of seismic data shot over granite terrain. In both examples, the actual conditions do not approximate to any simple layered models required by refraction theory. Though the travel-time curves normally 'reflect' the variation in the thickness of the soil layer, actual estimation of the thickness is unreliable due to several undeterminable factors involved. In Fig. 12, no first arrivals were recorded at geophone 12 from the up-slope shots S_3, S_4, S_5. This was probably due



V_1, V_2—true vel. of 1st and 2nd layers respectively.
V'_{2r}, V'_{2f}—apparent V_2 vel. from shots S_{r} $_f$ respectively. ($\simeq$5500 ms^{-1})
V'_{3r}, V'_{3f}—apparent V_3 vel. from shots S_{r} $_f$ respectively. ($\simeq$2350 ms^{-1})
V'_{2c}, V'_{3c}—apparent V_2 and V_3 vel. corrected for elevation.

Fig. 10. Theoretical consideration of the effect of variation in thickness of the low velocity layer on interpretation of refraction data.

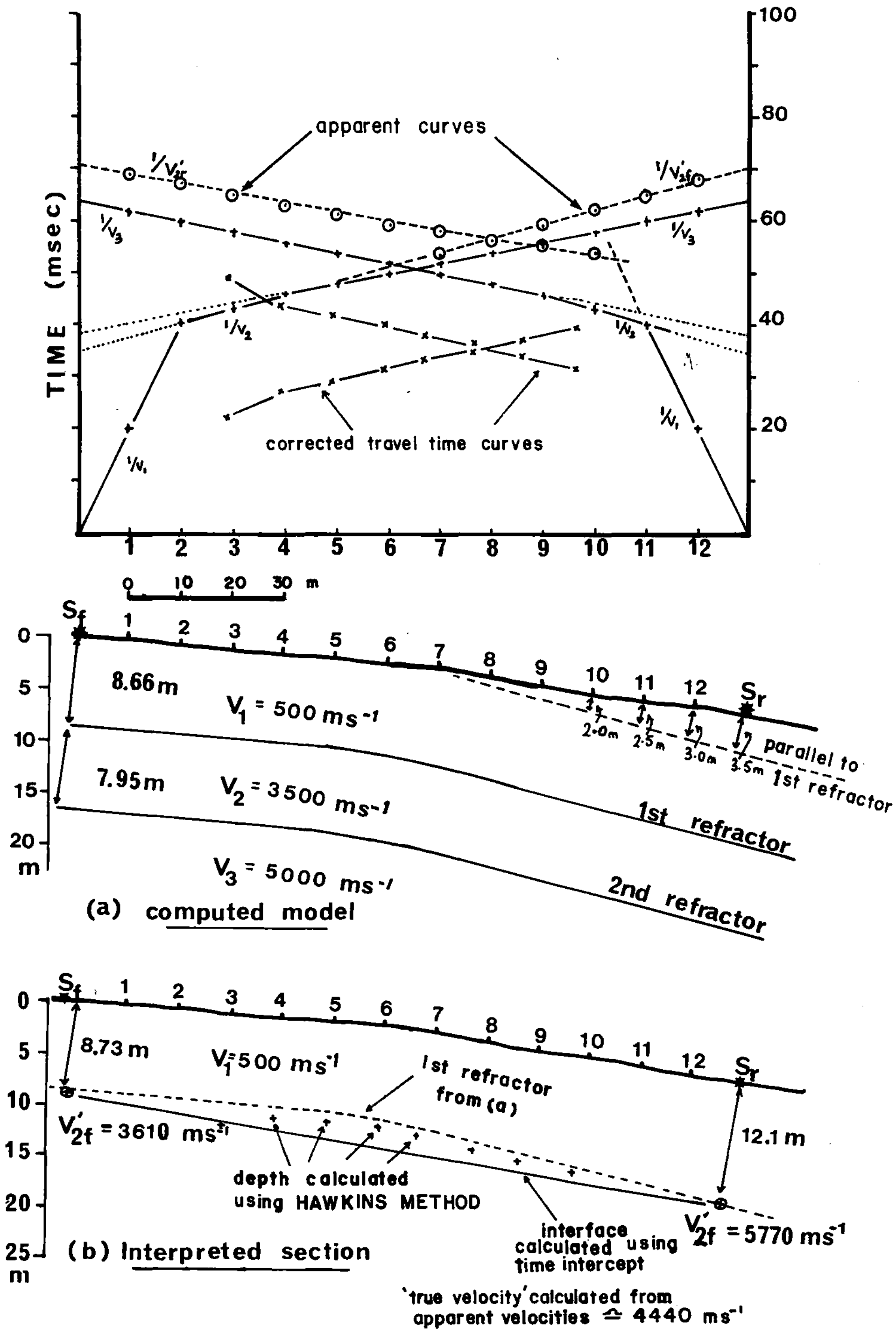


Fig. 11. Errors in interpretation due to variation in thickness of soil layer

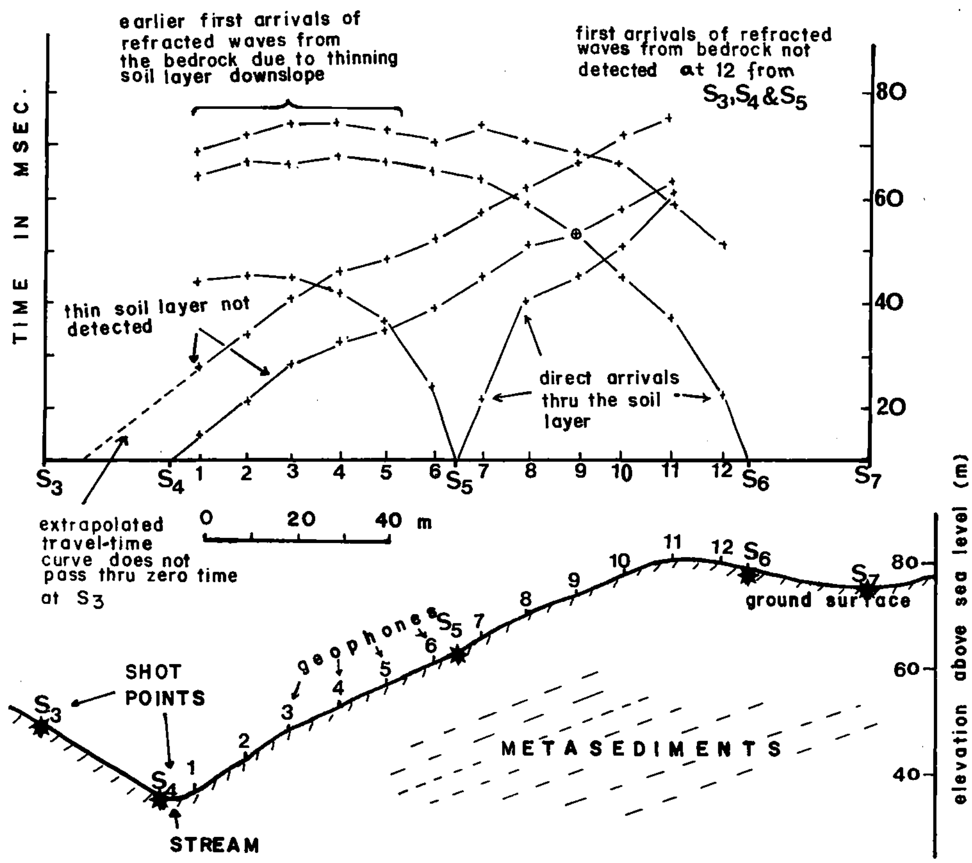


Fig. 12. Example of seismic results over hilly terrain underlain by stratified bedrock.

to adverse scattering of energy from suspected curvature of the rock surface at geophone positions 9 to 12. In the absence of sufficient borehole data, interpretation of refraction data of this nature tends to be very speculative.

THICK OVERBURDEN

In survey sites where the overburden is very thick, it might be necessary to increase the length of the refraction spread so that the first arrivals refracted from the bedrock may be detected. There are however, several factors limiting the use of very long refraction spread in shallow investigation under tropical conditions. Among them are the nature of the terrain, overburden, local ground conditions and probably instrumental capabilities.

In survey sites of irregular and steep topography, sub-geological conditions are unlikely to be laterally uniform over long distances. The difficulties involved in the

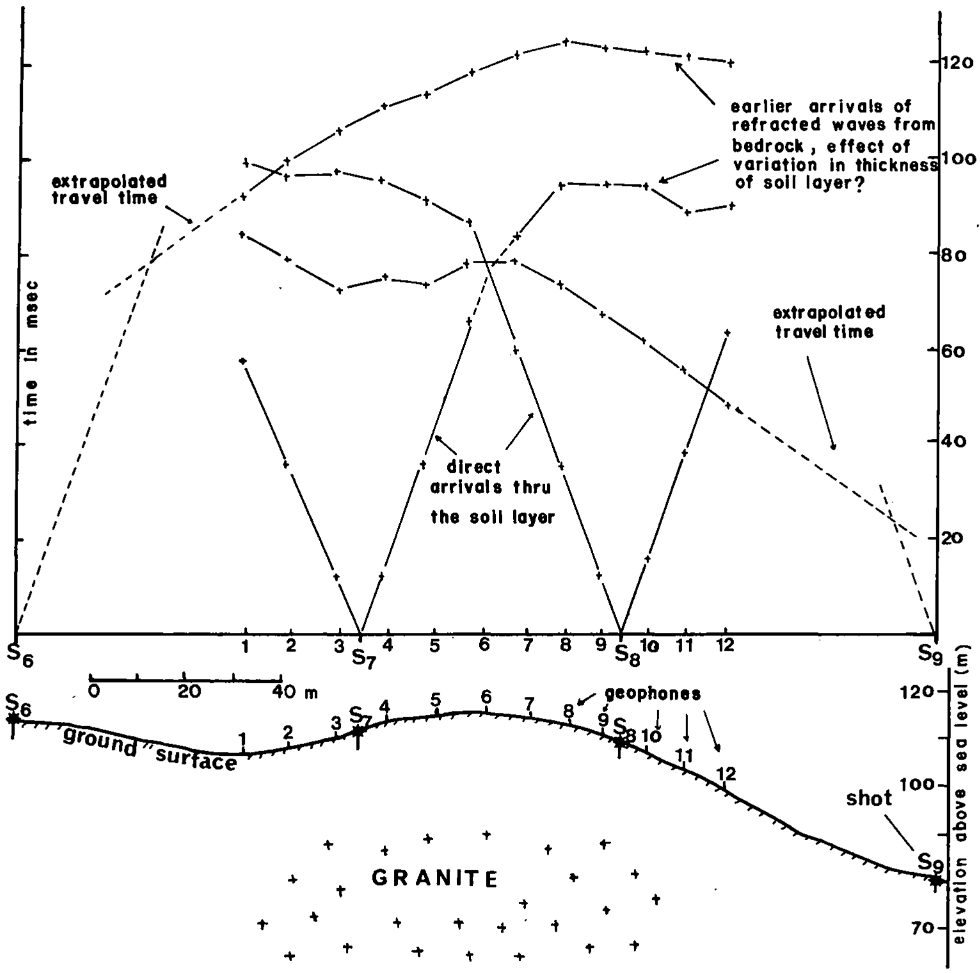


Fig. 13. Example of seismic refraction results over hilly terrain underlain by granites.

interpretation due to irregular topography become more pronounced when long spreads cross topographic features like hills and valleys where the gradient of the slope changes rapidly. Lateral variations in both the nature and thickness of the overburden are difficult and impracticable to predict. In general, the problem is more tolerable in less rugged terrain. Even then, with long spreads we are faced with the problem of low energy penetration and rapid attenuation rate of the high frequency components in the thick and highly weathered overburden layer.

The general form of the seismic spectrum is shown in Fig. 14. The spectrum is however profoundly modified by several factors (O'Doherty & Anstey, 1971). By increasing the charge used, the amount of energy released increases with corresponding

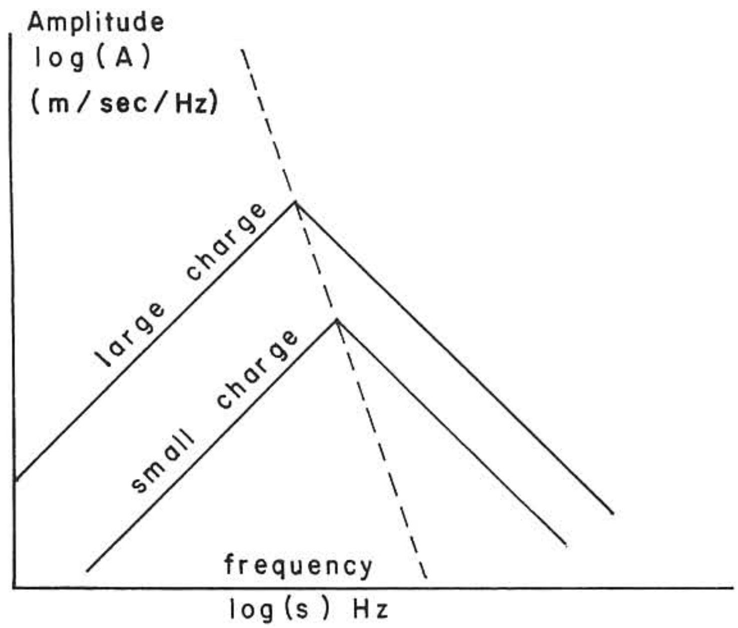


Fig. 14. The seismic spectrum showing the effect of increased charge size (after Green, 1974).

shift in the dominant frequency towards the lower part of the spectrum (Nicholls, 1962). Lower frequencies are however, more strongly attenuated (Hamilton, 1972). This is confirmed by survey work carried out where increase in the charges used appeared to make no significant difference in producing better data quality other than creating a bigger crater and more explosion noise. Deeper shot holes up to about 2 m appear to make some slight improvements and undoubtably deeper shot holes would produce better results. However, the use of a power drill capable of boring deeper holes in hilly and poorly accessible terrain would not be justified for shallow refraction work where the depth of investigation may be less than 30 m. Preparation of deeper shot holes by hand is both inconvenient and time consuming especially where near-surface boulders are present.

Poorly consolidated and highly inhomogeneous soil overburden have a high rate of attenuation, largely brought about by scattering of the seismic energy. Consequently, as the distance from the shot point increases, higher frequencies are selectivity attenuated resulting in rounded "breaks" of the first arrivals. With present day equipment, reading accuracy of up to 0.5 msec may be obtainable, though with very rounded "breaks", possible error may amount to 2.0 msec or more.

Similarly, when wide occurrence of boulders was noted in the survey sites, sharp breaks in the seismic returns were difficult to obtain for long refraction spreads due to much scattering of the energy. Much of the 'noise' showed up in the seismic traces of the further geophones.

The injection of energy and attenuation of the seismic waves appear to be dependent on local ground conditions also. It is a common experience to obtain better 'breaks' in the records when the shots are located in waterlogged soil than in drier ground. Similarly, for the same geophone spread along the slope of a granite hill, sharper breaks were obtained from shots placed at the foot of the hill than at the summit. This could probably be due to drier ground conditions and curvature of the rock refractor at the top of the hill.

The detection of good arrival signals requires firm coupling of the geophones with the ground. In one particular survey site where the low velocity layer consists of highly weathered, loose and dry lateritic soil, very poor signal is obtained even at distances as near as 40 m. Similar problems were encountered where the top soil is highly leached and composed of loose sandy soil. Thick surface vegetation and near-surface roots in secondary jungle areas may also contribute to the problem. Both Koefoed (1954) and Domzalski (1956) demonstrated that arrival times are greatly influenced by the elastic transmitting characteristics of the material immediately underneath the geophone. Changes in ground conditions, thus need to be considered when planning long refraction spreads.

The instrumental capability is of course, an important factor when deciding on very long spreads. Detailed discussion on instrumentation is beyond the scope of this paper. The difficult terrain and poor accessibility of most survey sites for engineering projects do not favour the use of heavy and sophisticated equipment. Use of explosives as the energy source has the advantage of convenient and speedy shooting procedures. Use of an enhanced signal recording system might help to increase the signal to noise ratio*, especially over long distances though one has to consider the repeatability of the seismic signal. In terrain where the soil layer is very soft, experiments with repeated shots at the same point resulted in slightly differing arrival times recorded at the same geophone spreads. The later shots normally showed faster arrival times though the difference is variable. The general shape of the travel-time curves however does not change. This could probably be due to a change in the elastic characteristics of the soil materials in the immediate vicinity of the shot point. In addition, differing condition of the shot hole after the first shot might have a contributing factor.

PLANNING

It is thus apparent that the practical capabilities of the shallow refraction technique are limited under difficult survey conditions. In engineering surveys, the limitations have been primarily due to tropical weathering conditions and rugged topography. For the technique to be an effective and routine investigation tool, the following requirements would be necessary;

(a) speed—Any investigation work has to be completed within limited time as most engineering projects have fairly short term schedules.

*The signal-to-noise ratio is defined as the energy of desired events divided by all remaining energy (noise) at that time.

(b) economy—For the technique to be an economical proposition to the engineers, any boring done to aid interpretation must be kept to a minimum. Often, due to limited funds, detailed coverage of the seismic lines may not be feasible. Coupled with difficult survey conditions and lack of borehole information, interpretation could be very speculative.

(c) applicability—To suit major engineering requirements, the technique needs to be applicable in areas of hilly terrain and poor accessibility which may not be ideal for refraction work. While it is not essential for detailed and academic type of subsurface investigation, the technique should nevertheless be able to yield general information regarding the depths, rippability characteristics and nature of the subsurface layers.

For the geophysicists and engineers involved, planning of the shallow refraction investigation prior to actual field work is essential. In planning the layout of the refraction spreads, it may be worthwhile to consider the topography of the site. Over hilly terrain, it would be necessary to lay the refraction spreads according to certain topographic trends. The rationale for adopting this approach rather than a grid or regular pattern of the seismic lines is that the seismic traverses can follow slopes of constant gradient and avoid major topographic irregularities which could present interpretation problems such as those discussed in section 6. Subsurface conditions along the top of ridges and slopes of constant gradient bear closer approximation to the theoretical assumptions of the refraction method than say across the ridge (Fig. 15). Thus in highly irregular and steep terrain, it may be advisable to plan for shorter spreads. Abrupt or major changes in the slope of the ground surface could be indicative

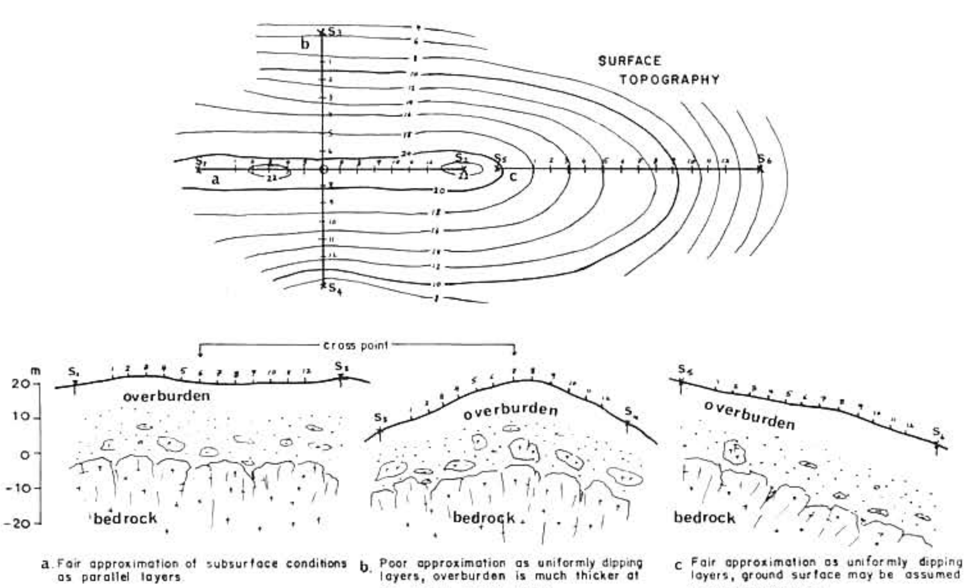


Fig. 15. Generalised subsurface conditions in relation to the surface topography.

of near-surface irregularities or curvatures in the rock refractors. Closer geophone spacing and overlapping spreads should be used to map such features. In the absence of detailed topographic information, it would be preferable to conduct a topographic survey of the site prior to such planning.

In addition, geological information of the site would be helpful indeed during planning and interpretation stages. The nature of the overburden to a certain extent is dependent on the local geology. In site investigation for quarrying purposes, preliminary geological survey would certainly be useful in delineating areas of different geology and feasible quarry sites. In any case, preliminary inspection of the site is most helpful in minimising some of the practical problems.

It ought to be pointed out that regardless of the amount of planning, the minimum number of refraction spreads required to obtain the necessary subsurface information cannot be predetermined. Nevertheless, where funds are lacking, a practical approach in planning the survey minimises the possibilities of costly and time consuming resurvey programmes.

INTERPRETATION

Due to the varying nature of the subsurface underlying tropical terrain, no routine interpretation procedure is possible. For each survey site, due consideration of the factors relating to the local ground conditions, topography and geology is essential.

Under tropical weathering conditions, transition from overburden to bedrock is predominantly of gradational nature. Hence, it is important to relate the refractors constructed from seismic data to actual ground conditions. In areas underlain by granites, such refractors may be rather arbitrary as discussed earlier. Where sediments form the underlying bedrock, care should be exercised in discriminating between refractions from bedrock surface and resistant beds. In low-lying ground, the water table may show up as a typically uniform refractor as in Fig. 5.

Velocities estimated from travel-time curves may be equally misleading. The refractors are seldom of constant dip with respect to the ground surface. Curvatures in the rock refractor and rapidly thinning low velocity layer could lead to errors in velocity estimation. Analysis of velocities in the refractors using subtraction of the time-depths from the recorded travel times at the geophone stations would remove the effect of varying thickness in the overburden (Fig. 11). Caution should nevertheless be exercised in discriminating true velocity inversions due to vertical changes in elastic properties from those associated with lateral variation.

Under difficult survey conditions, refraction data can be rather noisy and at times ambiguous. Diffraction due to near-surface inhomogeneities and irregularities often obscure the true first arrivals of the refracted waves. Use of multiple shots and overlapping spreads such as the example shown in Fig. 16, has been fairly useful in eliminating certain probabilities in interpretation especially when data quality is poor. In highly irregular and steep terrain where the usefulness of the Hawkins' method is limited by lack of overlapped sections from short refraction spreads, it is possible to

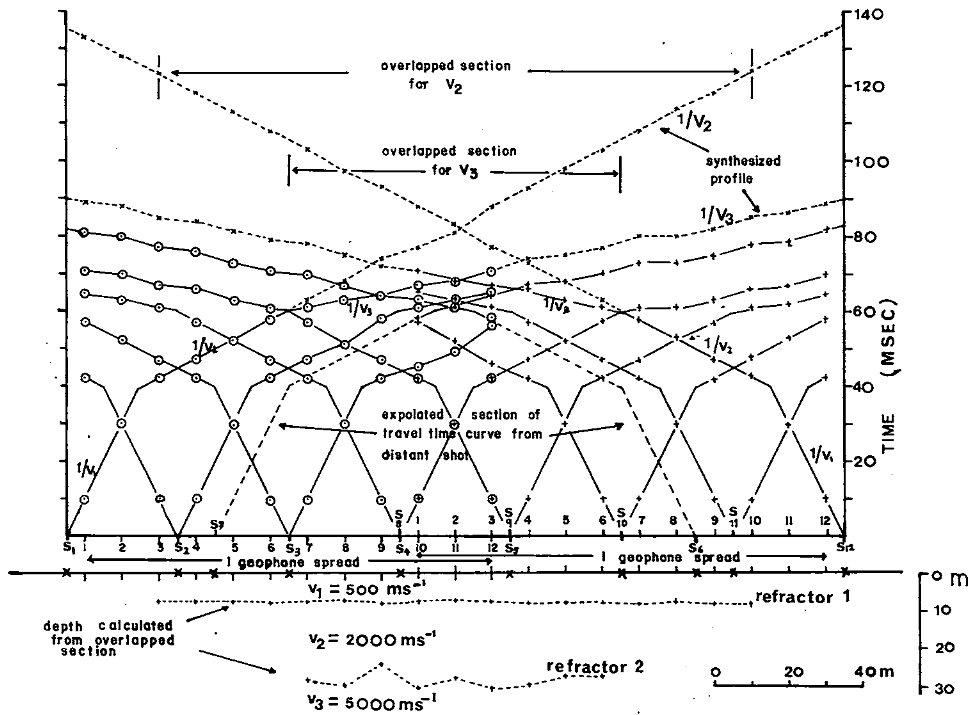


Fig. 16. Use of overlapping spreads for continuous profiling.

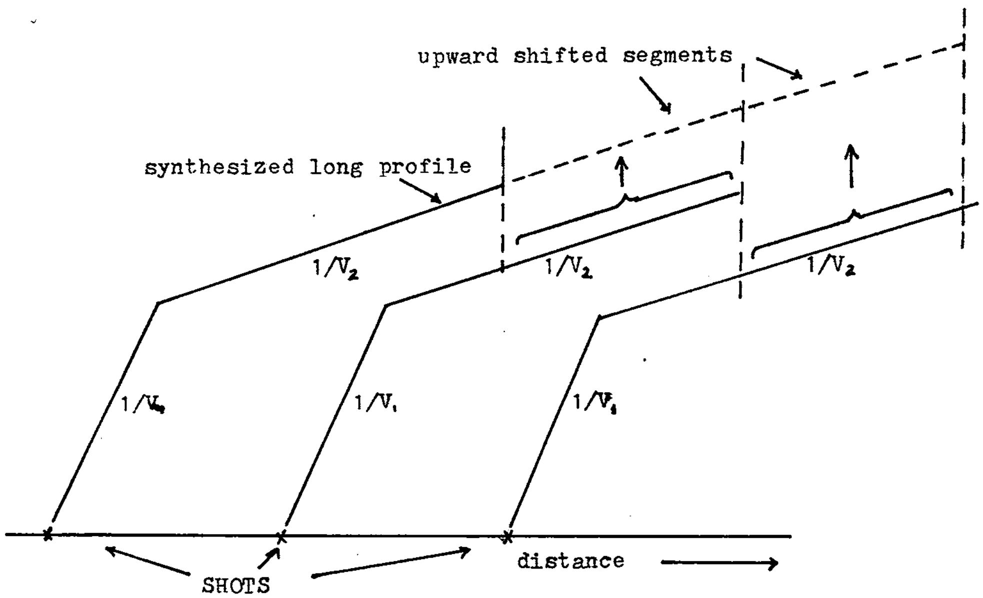


Fig. 17. Method of synthesizing a long profile. By shifting upward overlapping second velocity, it is possible to construct a long synthetic profile, amenable to interpretation by Hawkins' method. (source unknown).

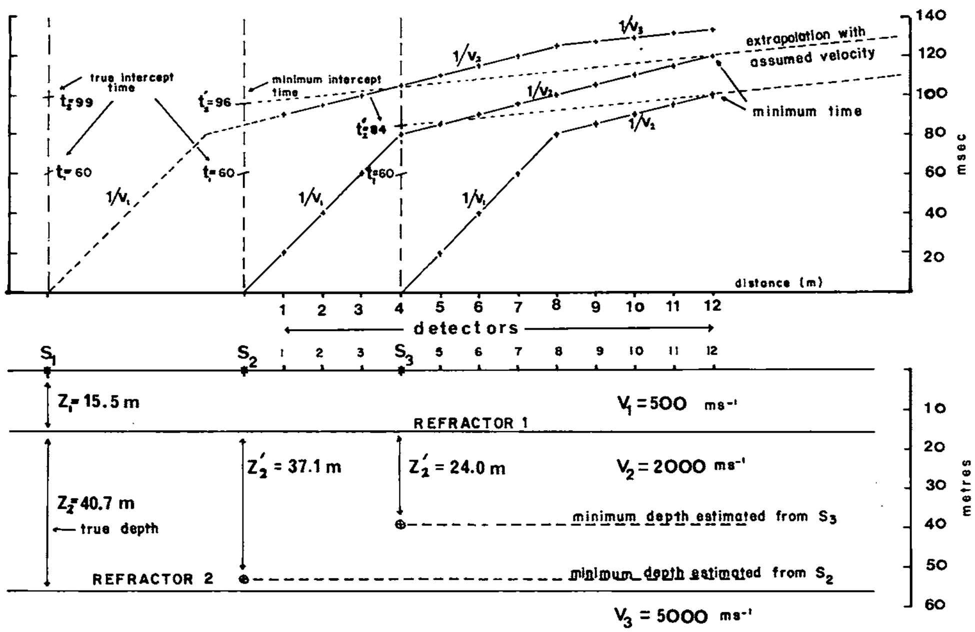


Fig. 18. Minimum time—minimum depth estimation

synthesize longer overlapping sections by such field procedures. The technique of synthesizing a long profile of the desired refractor from short refraction spreads is illustrated in Fig. 17.

Where the refraction spreads have not been long enough to detect the first arrivals of the refracted waves from the bedrock, a minimum time-minimum depth concept can be invoked to provide useful minimum depth estimates. The concept considers that no return from the bedrock was detected due to inadequate length of the refraction spread, but assumes that the earliest time at which a return would have been detected is the last time recorded for the previous layer. This 'earliest' time is then used with that value of seismic velocity for the given layer (measured elsewhere in the immediate vicinity) to calculate a ***minimum depth*** to that refracting horizon. The ***actual depth*** to the refracting layer may of course be greater than the 'calculated minimum depth'. Fig. 18 illustrates the minimum time-minimum depth concept. When the bedrock refractor is highly irregular, returns from the bedrock may be very noisy and the first arrivals indeterminable. In such cases, the minimum time-minimum depth concept may be applied to obtain a 'minimum depth' to the bedrock as shown in Fig. 19.

CONCLUSION

The shallow refraction technique can be utilised as an economical and routine investigation tool for civil engineers. There are however, several limitations to the application of the technique in tropical terrain. Problems commonly encountered in the application to Malaysian engineering projects have been primarily due to tropical

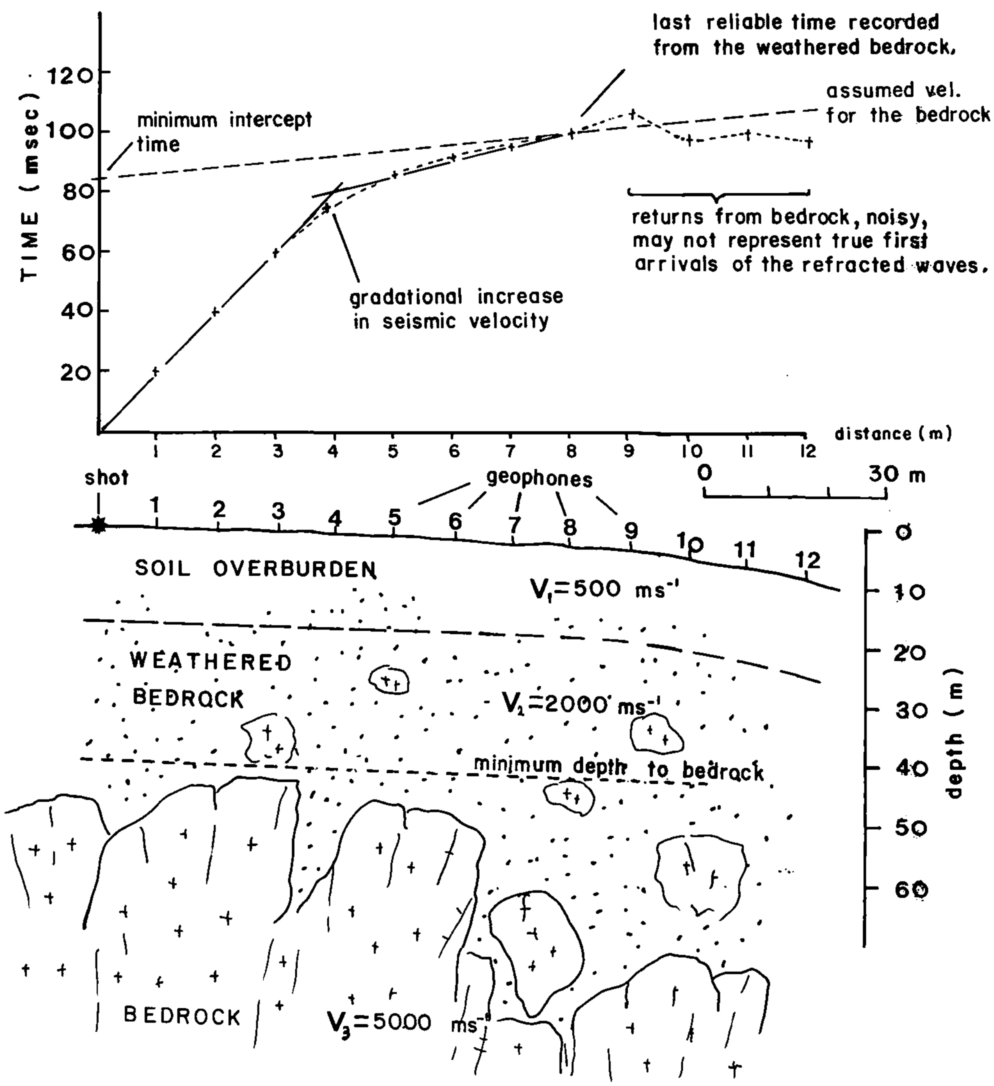


Fig. 19. Use of minimum time-minimum depth concept where the rock refractor is highly irregular. Interpretation is based on best straight lines constructed on time-distance plot of first arrivals.

weathering conditions and highly irregular topography. Some of the important factors considered are the differential weathering pattern in the bedrock, the nature of overburden with respect to the topography and local geology and ground conditions. Practical experience has shown that errors due to such factors may be quite substantial especially when dealing with relatively thick soil overburden compared to the depth of investigation. Computed examples illustrate that some of the errors involved may not be evident given the number of indeterminable factors present under difficult survey conditions. Some of the ambiguities and near-surface disturbances can be eliminated by careful planning of the refraction spreads such that the actual conditions bear closer approximation to the theoretical assumptions made. Such a practical approach in the application of the refraction method is essential in minimising time, cost and ambiguity in interpretation.

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