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भूकंपीय अपवर्तन विधि द्वारा भूवैज्ञानिक अन्वेषण — रीति संहिता

(IS 15681 *का पहला पुनरीक्षण*)

Draft Indian Standard

GEOLOGICAL EXPLORATION BY SEISMIC REFRACTION METHOD — CODE OF PRACTICE

(*First Revision of* IS 15681)

Geological Investigation and Subsurface Exploration Sectional Committee, WRD 05

Last date for comments: 21 October 2025

FOREWORD (*Formal clauses will be added later*)

Seismic refraction technique is mainly concerned about evaluation of the project site and its stability to man-made structures. The technique plays a crucial role in the design of engineering projects. Seismic refraction surveys, being rapid and economical, are conducted to help select a site amongst a number of alternatives at the reconnaissance stage. It also forms a part of detailed site investigations at the chosen location. It plays a major role in locating fault and shear zones and in determining engineering parameters, for example, P-wave velocity.

It is a reliable tool for determining depth to various subsurface layers, particularly in conjunction with a few exploratory drillings. The accuracy of depth determination has been improved substantially with the availability of multichannel digital enhancement seismographs and new interpretation techniques, using digital computers.

This standard deals with various aspects of seismic reflection technique and its applications to shallow subsurface exploration of engineering sites. The primary purpose of the standard is to provide working knowledge of the method, with relevant references, and with a basis to weigh the applicability of the method to various engineering geological problems. In particular, it seeks to provide an understanding of the proper planning of surveys, so as to obtain adequate and relevant coverage and highlight the most important area of interpretation of seismic data.

This standard was first published in 2006 and the first revision of this standard has been brought out based on the technological advancements taken and experiences gained in the use of this standard. The major changes included in this revision are:

a) Addition of seismic refraction tomography along with detailed procedure in Annex A;
b) Update of figure of ray paths for a critically refracted wave;
c) Update of clause ‘Planning of Survey’; and
d) Addition of schematic presentation of seismic refraction tomography in Annex B.

In the formulation of this standard it is presumed that the execution of its provisions is entrusted to appropriately qualified and experienced people, for whose guidance it has been prepared. This standard gives general Interpretation of the data collected during the seismic refraction survey. However, for in depth details and interpretation of the data, reference should be made to specialized texts.

For the purpose of deciding whether a particular requirement of this standard is complied with, the “final value, observed or calculated, expressing the result of a test or analysis, shall be rounded off in accordance with IS 2: 2022 ‘Rules for rounding off numerical values (*revised*)’. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

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1 SCOPE

1.1 This standard gives guideline for seismic refraction method, a type of geophysical method applicable in mapping subsurface conditions for various uses including geological, geotechnical, hydrological, environmental, mineral and archaeological investigations. The standard also includes guidelines for the equipment, field procedures and interpretation of data for assessment of subsurface materials.

NOTE—The calculated seismic wave velocity is related to the type of rock, degree of weathering, and rippability assessment on the basis of seismic velocity and other geologic information.

2 TERMINOLOGY

For the purposes of this standard, the following terms and definitions shall apply.

2.1 Apparent Velocity — The velocity which a wave front appears to have along a line of geophones. It is the inverse of the slope of a refraction time-distance curve.

2.2 Blind Zone — A layer which cannot be detected by refraction methods, also called hidden layer. The blind zone may have a velocity lower than that of shallower refractors.

2.3 Compressional Wave (P–wave) — An elastic body wave in which particle motion is in the direction of propagation; the type of seismic wave assumed in conventional seismic exploration. Also called as P–wave and longitudinal wave.

2.4 Critical Distance — The offset at which a refracted event becomes the first break, the intersection point for the travel time curves for two refractors.

2.5 Delay Time — The additional time taken for a wave to follow a trajectory, to and along, a buried marker over that which would have been taken to follow the same marker, considered hypothetically to be, at the ground surface or at a reference level.

2.6 Geophone — The instrument used to transform seismic energy into an electrical voltage.

2.7 Geophone Interval —The distance between adjacent geophones within a group.

2.8 Head Wave — A refraction wave or Mintrop wave; a wave characterized by entering and leaving the high velocity medium at critical angle.

2.9 Huygens' Principle — The concept that every point on an advancing wave front can be regarded as the source of a secondary wave and that a later wave front is the envelope tangent to all secondary waves.

2.10 Hydrophone — A pressure detector which is sensitive to variations in pressure. Used when the detector can be placed below a few feet of water as in marine or marsh work, or as a well seismometer.

2.11 Intercept Time — The time obtained by extrapolating the refraction alignment on a refraction time-distance ($t - x$) plot back to zero offset.

2.12 Overburden — The section above a refractor or a reflector.

2.13 Reciprocal Time — The common travel time on reversed refraction profiles. Surface-to-surface time from a shot point at A to a geophone at B must equal that from a shotpoint at B to a geophone at $A.$

2.14 Refraction — The change in direction of a seismic ray upon passing from a rarer to a denser medium or *vice-versa* with a different velocity.

2.15 Refraction Wave — A wave which travels obliquely downward from a source to a high-velocity formation (or marker), then within the formation, and finally, obliquely upward to detectors. The angles of incidence and of emergence at the marker are critical angles.

2.16 Seismic Survey — A programme for mapping geologic structure by creating seismic waves and observing arrival time of the waves reflected from acoustic-impedance contrasts or refracted through high velocity members.

2.17 Seismic Waves — Seismic waves are elastic waves. Energy may be transmitted through the body of an elastic solid by P-waves or S-waves or along boundaries between media of different elastic properties by surface waves.

2.18 Seismograph — A recording system for seismic waves.

2.19 Shear Modulus — The stress-strain ratio for simple shear.

2.20 Shear Wave (S-wave) — A body wave in which the particle motion is perpendicular to the direction of propagation. Also called S-wave.

2.21 Shot/Hammer — To make an impact on ground, or tire an explosive to generate a seismic wave.

2.22 Snell's Law — When a wave crosses a boundary between two isotropic media the wave changes direction so that the sine of the angle of incidence (angle between the wave front and a tangent to the boundary) divided by the velocity in the first medium equals the sine of the angle of refraction divided by the velocity in the second medium. Snell's law applies to both P-wave and S-wave.

2.23 Surface Wave — Energy which travels along or near the surface.

2.24 Time-Distance Curve — A plot of the arrival lime against the shot point-to-geophone distance. Also called a '$t - x$' curve, used in interpreting refracted waves. The slopes of segments of the curve give the reciprocals of the apparent velocities for various refractor beds.

2.25 Time Break — The mark on a seismic record which indicates the shot instant or the time at which the seismic wave was generated.

2.26 Travel Time — The time between time break and the recording of a seismic event.

2.27 Velocity — A vector quantity which indicates time rate of change of displacement, usually refers to the propagation rate of a seismic wave without implying any direction.

2.28 Seismic Refraction Tomography — Seismic refraction tomography is a geophysical method of interpreting seismic refraction data, which uses a gridded, inversion technique to determine the velocity of individual two dimensional blocks (pixels) within a profile. It provides detailed continuous tomograms, which is missing in conventional layer modeling done in seismic refraction technique. It can provide better resolution of detailed velocity structure of the subsurface even under areas of high slopes and complex geology.

3 MEASURED PARAMETER AND REPRESENTATIVE VALUES

The seismic refraction method gives the velocity of compressional waves (P-waves) in subsurface materials. Although the P-wave velocity can be a good indicator of the type of soil or rock, it is not a unique indicator. **Table 1** shows that each type of sediment or rock has a wide range of seismic velocities, and many of these ranges overlap. While the seismic refraction technique measures the seismic velocity of seismic waves in earth materials, it is the interpreter who, based on knowledge of the local conditions or other data, or both, must interpret the seismic refraction data and arrive at a geologically reasonable solution. P-wave velocities are generally greater for:

a) Denser rocks than lighter rocks;
b) Older rocks than younger rocks;
c) Igneous rocks than sedimentary rocks;
d) Solid rocks than rocks with cracks or fractures;
e) Unweathered rocks than weathered rocks;
f) Consolidated sediments than unconsolidated sediments;
g) Water-saturated unconsolidated sediments than dry unconsolidated sediments; and
h) Wet soils than dry soils.

Table 1 Range of Velocities for Compressional Waves in Soil and Rock
(Clause 3*)*

Sl No.	Natural Soil and Rock	Velocity (m/s)
(1)	(2)	(3)
i)	Weathered surface material	240 to 610
ii)	Gravel or dry sand	460 to 915
iii)	Sand (saturated)	1 220 to 1 830
iv)	Clay (saturated)	915 to 2 750
v)	Water	1 430 to 1 665
vi)	Sea water	1 460 to 1 525
vii)	Sandstone	1 830 to 3 960
viii)	Shale	2 750 to 4 270
ix)	Chalk	1 830 to 3 960
x)	Limestone	2 135 to 6 100
xi)	Granite	4 575 to 5 800
xii)	Basalt	6 000 to 6 400
xiii)	Quartizite/Phyllitic quartizite	4 000 to 6 000
xiv)	Quartizite phyllitic/phyllite	2 500 to 3 500
xv)	Gneiss	4 000 to 6 000

P-wave velocity can also be used to get the rock mass quality Q to characterize the rock mass for engineering purposes (*see* IS 13365 - Part 2).

4 PURPOSE OF SEISMIC REFRACITON SURVEY

The seismic refraction survey has application in a variety of geological exploration problems, where information on the depth and strength of subsurface materials is required. These surveys provide subsurface information over large areas at relatively low cost, locate critical areas for more detailed testing by drilling and can readily eliminate less favorable alternative sites. Seismic surveys can also reduce the number of boreholes required to test a particular site and improve correlation between boreholes. The following are the areas, where this method can be used to obtain information:

a) *Problems of engineering geology*

   1) Depth to bedrock (thickness of overburden and/or weathered rock);
   2) Strength of the bedrock (looking for weak zones like fractures, shears and weathering and for faults etc.) for foundation studies;
   3) Rippability/excavability studies for quarries and dynamic elasticity determination;
   4) Location of sink holes and other manmade objects;
   5) Correlation of geological units between boreholes; and
   6) Monitoring of landslides.

b) *Problems in alluvial prospecting*

   1) Indirect search for alluvial deposits;
   2) Location of ancient stream channels; and
   3) Location of thick gravel beds.

c) *Problems in hydrogeology*

   1) Thickness of aquifer overlying impermeable bedrock;
   2) Detection of water table, mainly in alluvial aquifers; and
   3) Location of leakage zones.

d) *Complimentary method* — as a constraint on the ambiguities inherent in other geophysical methods.

5 METHODOLOGY

5.1 Measurement of subsurface conditions by the seismic refraction method requires a seismic energy source, trigger cable, geophones, geophone cable, and a seismograph. The geophones and the seismic source must be placed in firm contact with the soil or rock. The geophones are usually located in a line, sometimes referred to as a geophone spread. The seismic source maybe a sledge hammer, a mechanical device that strikes the ground or some other type of impulse source. Explosives are used for deeper refractors or special conditions that require greater energy. Geophones convert the ground vibrations into an electrical signal. This electrical signal is recorded and processed by the seismograph. The travel time of the seismic wave (from the source to geophone) is determined from the seismic wave form.

5.2 The seismic energy source generates elastic waves which travel through the soil or rock or both. When the seismic wave reaches the interface between two materials of different seismic velocities, the waves are refracted according to Snell's law. When the velocity V_2 is greater than V_1, the ray will bend away from the normal to the interface on refraction, as shown in **Fig. 1A**. In such a case for a particular angle of incidence known as the critical angle i_C, the angle of refraction will be 90 degrees. This gives rise to a critically refracted ray that will then be travelling within the lower medium at the velocity V_2 at grazing incidence along the interface. It should be noted that critical refraction can only occur, where there is an increase in velocity at deeper refracting layer.

5.3 In **Fig. 1B**, the position of a wave front in the lower medium is shown, together with the associated wave front being directed back into the overlying layer. The latter is known as a head wave. The ray paths are also shown. The head wave is attached to the faster traveling wave front in the deeper, higher velocity medium of the refractor. The position of the wave front of the head wave may also be constructed as the envelope of the secondary wavelets, by the application of Huygen's principle. Since the angle of critically refracted ray in the lower medium is 90 degrees for rays, which are either entering or leaving the V_2 refracting layer, the head wave also re-enters the overlying V_1 layer at the critical angle. Since the critically refracted waves are returned to the surface in this manner, they are recorded.

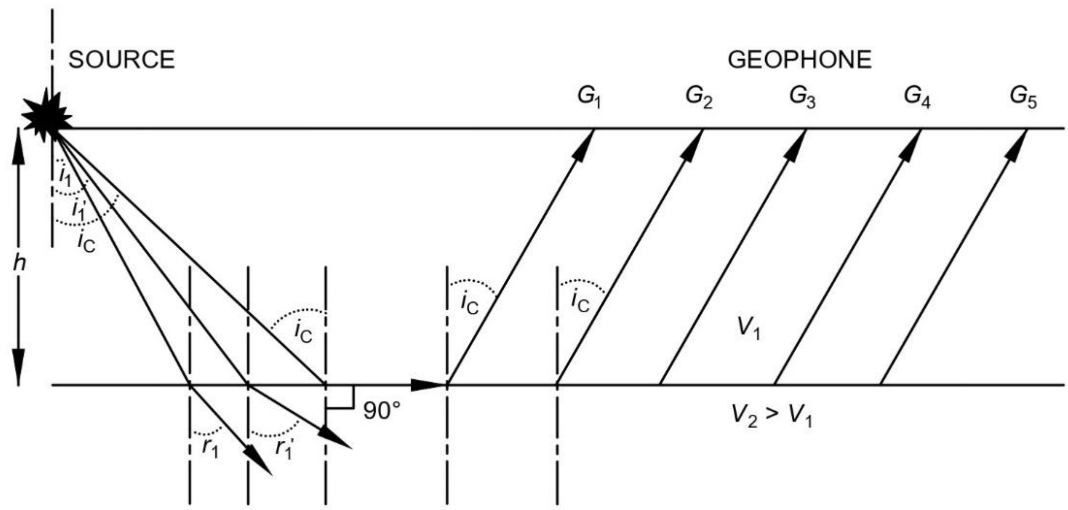

FIG. 1A RAY PATHS FOR A CRITICALLY REFRACTED WAVE

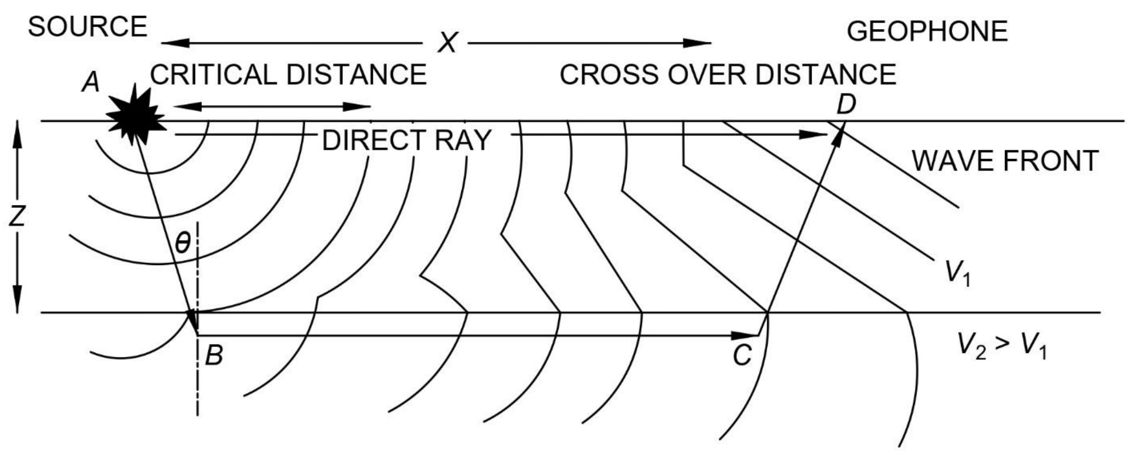

FIG. 1B WAVE PATHS ASSOCIATED WITH CRITICALLY REFRACTED WAVE

FIG. 1 RAY AND WAVE PATHS FOR A CRITICALLY REFRACTED WAVE

5.4 A number of elastic waves are produced by a seismic energy source. As the compressional *(P)* wave has the highest seismic velocity, it is the first wave to arrive at each geophone.

The P-wave velocity V_p *is* dependent upon the bulk modulus and the density and is given by:

$$V_{\mathrm{p}} = \sqrt{\frac{\left(K + \frac{4}{3}\mu\right)}{\rho}} \qquad \text{....(1)}$$

where

V_{p} = compressional wave velocity;
K = bulk modulus;
μ = shear modulus; and
ρ = density.

The energy from the seismic source at each geophone is recorded by the seismograph. From the positions of the pick-up points, the travel times are measured for the first arrivals of seismic waves. The travel times are then plotted at appropriate geophone distances on graph called a travel-time curve, or a time-distance curve, or often abbreviated as $t - x$ curve (*see* **Fig. 2**). Alignments of points on as $t - x$ curve indicates the velocities of seismic waves through different layers and provides the information needed to calculate layer thicknesses.

5.5 Two Layers Analysis

Two layers with plane parallel boundaries are illustrated in **Fig. 2**. The first few arrival times are those of direct arrivals through the first layer and the slope of the time distance curve through those points, $\Delta t/\Delta x$, is simply the reciprocal of the velocity of that layer; that is $1/V_1$. The energy that arrives at the detectors beyond the crossover distance will plot along a line with slope of $1/V_2$,The one through these refracted arrivals will pass through a projection on time axis to intersect it at a time called the intercept time 't_i'.

Thickness of the layer at shotpoint from the intercept time analysis is given by:

$$Z_1 = \frac{t_i V_1 V_2}{2\sqrt{V_2^2 - V_1^2}} \qquad \text{.....(2)}$$

True depth to the second layer is determined simply by adding half the shot to the value of Z_1 computed by equation (2).

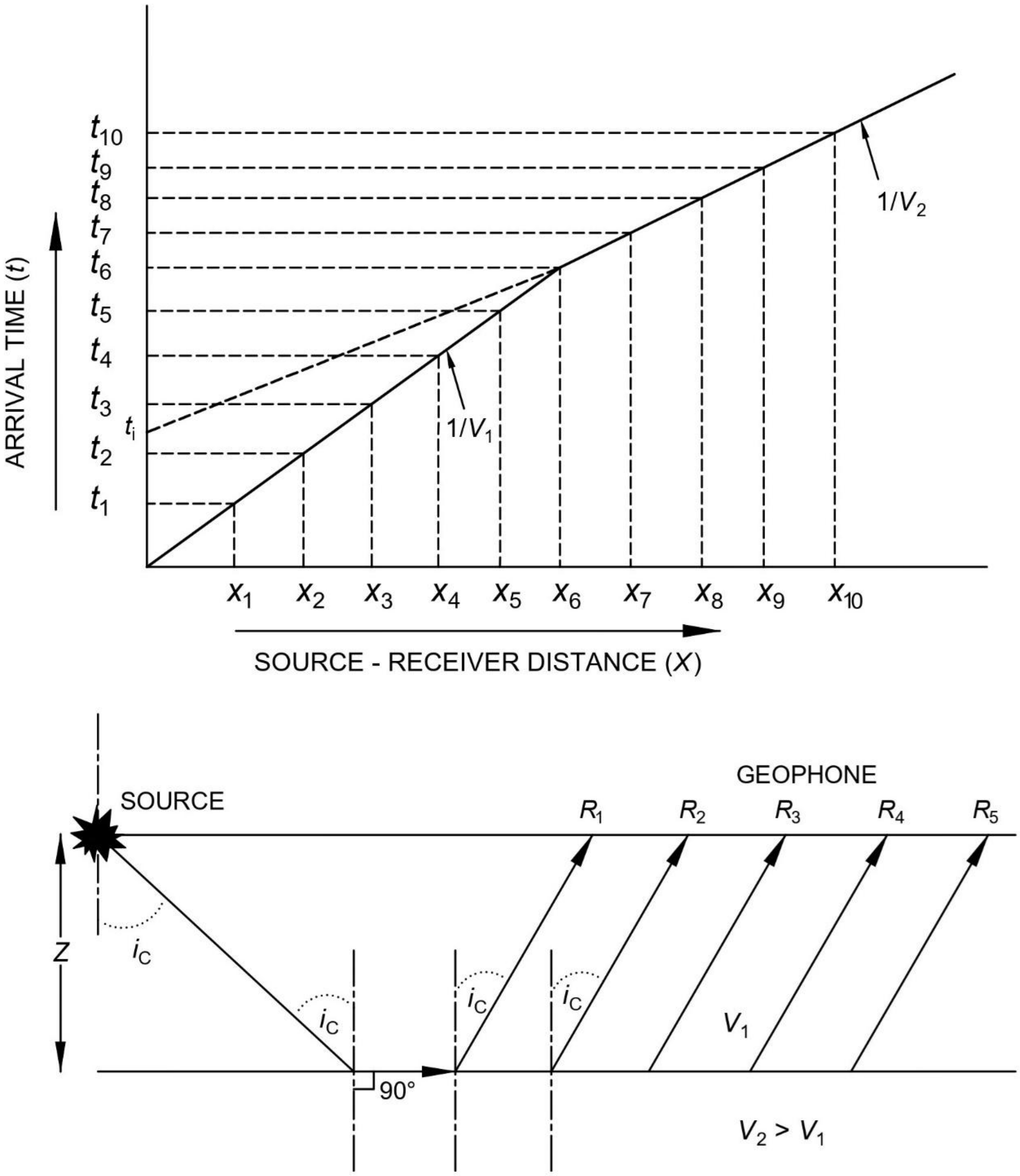

FIG. 2 TIME-DISTANCE CURVE AND RAY PATHS FOR A TWO LAYER CASE

5.6 Three Layers Analysis

The geometry of ray path in the case of critical refraction at the second interface is shown in **Fig. 3**. The seismic velocities of the three layers are $V_3 > V_2 > V_1$. The ray corresponding to the least travel time makes an angle $i_{13} = \sin^{-1}(\frac{V_1}{V_3})$ with the vertical in the uppermost layer and angle $i_{23} = \sin^{-1}(\frac{V_2}{V_3})$ with the vertical in the second layer, i_{23} being the critical angle for the lower interface. The thickness of Z_2 can be computed by:

$$Z_2 = \frac{1}{2}\left(t_{i2} - 2\, Z_1 \frac{\sqrt{V_3{}^2 - V_1{}^2}}{V_3 V_1}\right)\frac{V_3 V_2}{\sqrt{V_3{}^2 - V_2{}^2}} \qquad \ldots(3)$$

The depth to the lower interface is sum of Z_2 and Z_1 where Z_1 is computed by the two-media formula (Equation 2) using the slopes of the first two segments of the time-distance curve and the intercept of the second segment.

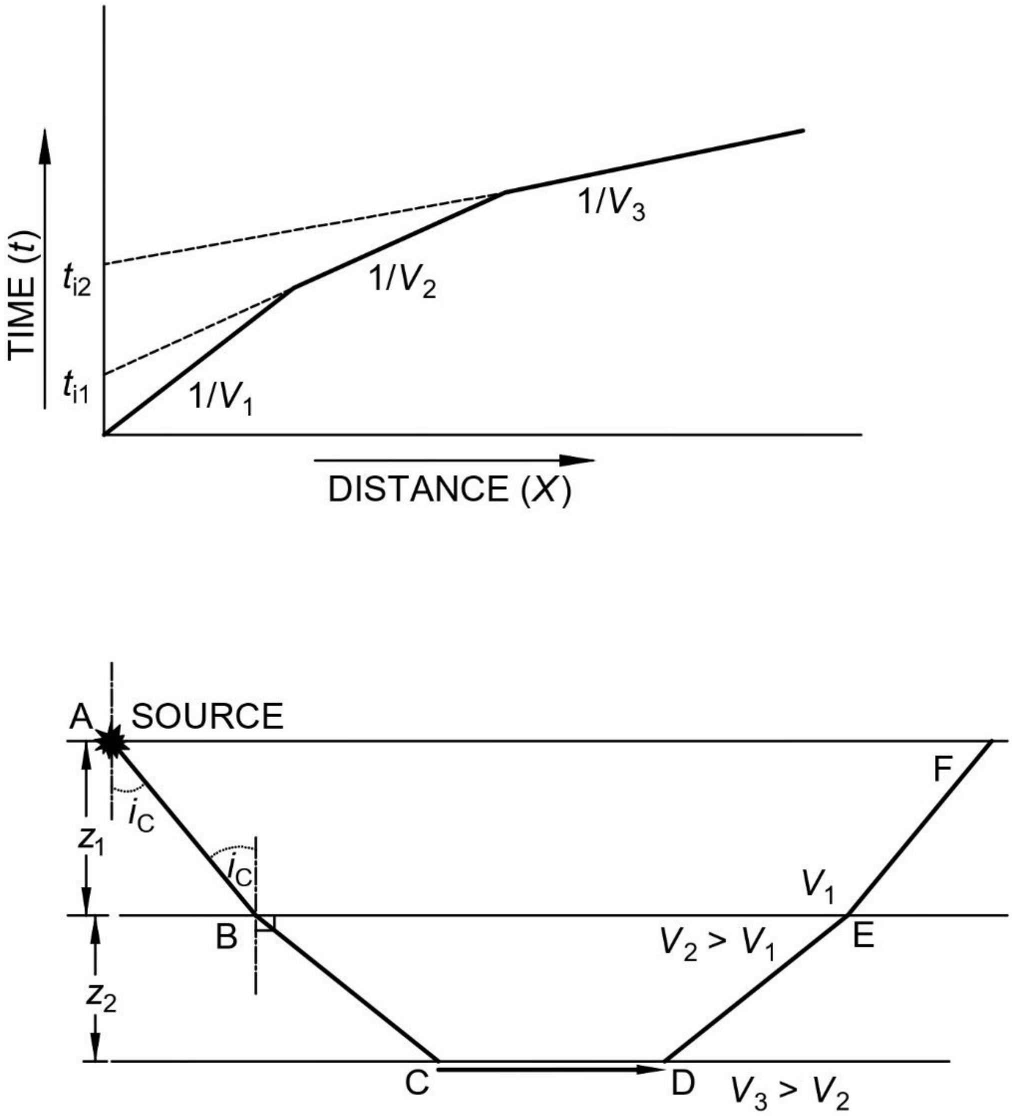

FIG. 3 TIME-DISTANCE CURVE AND GEOMETRY OF RAY PATH FOR CRITICAL REFRACTION FOR THREE LAYER CASE

5.7 Multilayer Analysis

If a structure has n horizontal with the thickness $Z_1, Z_2, Z_{3,} \ldots \ldots Z_n$ and wave velocities $V_1, V_2, V_3, \ldots \ldots V_n$ resting on deeper material in which the wave velocity is V_{n+1} a travel time with $n+1$ straight line segments is expected. The intercept time determined from wave reaching the deepest refractor is given by:

$$T_n = 2 \sum_{k=1}^{n} \frac{Z_k}{V_k} \cos i_{k(n+1)} \quad .....(4)$$

The thickness of the deepest layer is given by:

$$Z_n = \left[\frac{T_n}{2} - \sum_{k=1}^{n-1} (\frac{Z_k}{V_k} \cos i_{k(n+1)})\right] \frac{V_n}{\cos i_{n(n+1)}} \quad .....(5)$$

5.8 Dipping Layers

If the boundaries between interface are not parallel (that is, if they are dipping interfaces), the $t - x$ curve will give only apparent velocities for the refracting layers usage of which can give erroneous depths. Reverse shooting field procedure can provide complete protection against above said errors. Reverse shooting means firing a shot at both ends of the seismic line so that arrival times at each detector are measured from both directions. The case of a dipping boundary and its effect on travel-time plots is as shown in **Fig. 4**.

The condition of reciprocity provides a valuable constraint. The condition of reciprocity states that the total travel time from *A* to *D* must be equal to the total travel-time from *D* to *A*.

The gradients of the travel-time curves of refracted arrivals along the forward and reverse profile lines yield the downdip (V_{2d}) and up-dip (V_{2u}) apparent velocity respectively (*see* **Fig. 4**).

From the forward direction:

$$V_{2d} = \frac{V_1}{\sin(i_{12} + \theta)} \quad ....(6)$$

And, from the reverse direction:

$$V_{2u} = \frac{V_1}{\sin(i_{12} - \theta)} \quad .....(7)$$

Solving for i_{12} and θ :

$$i_{12} = 1/2 \, [(sin^{-1}(V_1/V_{2d}) + (\sin^{-1}(V_1/V_{2u})] \quad ...... (8)$$

$$\theta = 1/2 \, [(sin^{-1}(V_1/V_{2d}) - (\sin^{-1}(V_1/V_{2u})] \quad .... (9)$$

The perpendicular distances Z and Z' to the interface under the two ends of the profile are obtained from the intercept times t_i and $t_i{}'$ travel-time curves obtained in the forward and reverse direction.

$$Z = \frac{V_1 t_i}{2 \cos(i_{12})} \quad .... (10)$$

$$Z' = \frac{V_1 t_i{}'}{2 \cos(i_{12})} \quad .... (11)$$

By using the computed refractor dip θ, the perpendicular depths Z and Z' can be converted into vertical depths h and h' using:

$$h = Z / \cos\theta \quad .... (12)$$

$$h' = Z' / \cos\theta \qquad \text{…….. (13)}$$

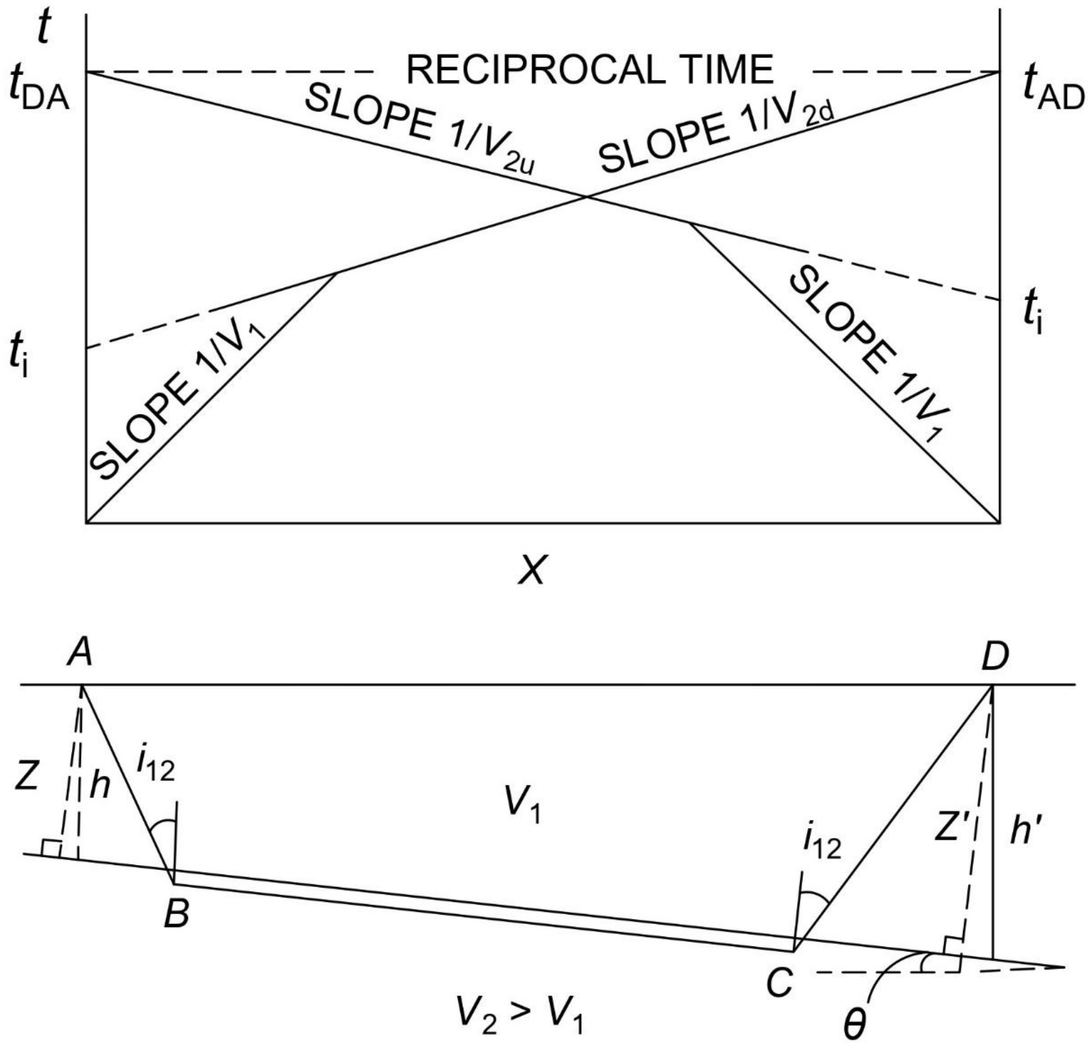

FIG. 4 TIME-DISTANCE CURVE AND GEOMETRY OF RAY PATH FOR CRITICAL REFRACTION FOR TWO LAYER DIPPING CASE

5.9 Seismic Refraction Tomography (SRT)

Seismic tomography allows the reconstruction of an image of the subsurface distribution of seismic wave velocities and its anomalies with high resolving power. The direction of propagation of the waves in depth follows Snell's law and at each interface there are phenomena of refraction, reflection and diffraction. In refraction surveys, as the name implies, only refracted waves will be considered. However, Seismic Refraction Tomography allows to obtain a picture of the velocity distribution in the subsurface highlighting the continuous changes in velocity rather than a layered model.

The data acquired through the conventional seismic refraction method can be processed using the tomographic procedure in order to highlight the local velocity variations in detail. This provides continuous tomograms having better resolution of detailed velocity structure of the subsurface even under areas of high slopes and complex geology. The detailed procedure is given in **Annex A**.

6 EQUIPMENT

Equipment used for surface seismic refraction measurement include a seismograph, geophones, geophone cable, an energy source and a trigger cable or radio link. A wide variety of seismic geophysical equipment is available and the choice of equipment for refraction survey should be made to meet or exceed the objectives of the survey.

6.1 Seismographs

A wide variety of seismographs are available from different manufacturers. They range from relatively simple, single-channel units to very sophisticated multichannel units. Most engineering seismographs sample, record and display the seismic wave digitally.

6.1.1 *Single Channel Seismograph*

A single channel seismograph is the simplest seismic refraction instrument and is used with a single geophone. The geophone is usually placed at a fixed location and the ground is struck with a hammer at increasing distances from the geophone. Seismic wave arrival times are identified on the instrument. For simple geologic conditions and small projects, a single channel unit is satisfactory.

6.1.2 *Multiple Channel Seismograph*

Multichannel seismographs use 6, 12, 24, 48 or more, geophones. With a multichannel seismograph, the seismic wave forms are recorded simultaneously for all geophones for a shot. Most of the modern seismographs are equipped with signal enhancement or energy stacking capabilities that improves the signal to noise ratio. Signal enhancement is accomplished by adding the refracted seismic signals for a number of impacts.

6.2 Geophone and Cable

A geophone transforms the seismic energy into a voltage that can be recorded by the seismograph. For refraction work, the natural frequency of the geophones varies from 4 Hz to 14 Hz and these geophones have a flat frequency response between 4 Hz to 14 Hz. The signals from geophones is brought to the seismograph through geophone cable.

6.3 Hydrophones

Hydrophone is a detector which is sensitive to variations in pressure. The sensing element is usually a piezoelectric ceramic material, such as, barium titanate, lead zirconate, or lead metaniobate. Piezoelectric hydrophones are high-impedance devices and signals from hydrophones, or hydrophone arrays, may be passed through pre-amplifiers or impedance-matching transformers before transmission through the streamer to the recording instruments.

6.4 Energy Sources

The selection of seismic refraction energy sources is dependent upon the depth of investigation and geologic conditions. Four types of energy sources are commonly used in seismic refraction surveys; sledge hammers, mechanical weight drop or impact devices, projectile (gun) sources and explosives.

7 PLANNING THE SURVEY

7.1 Planning and design of a seismic refraction survey should be done with due consideration of the objectives of the survey and the characteristics of the site. These factors determine the survey, design, the equipment to be used, the level of effort, the interpretation method selected, and budget necessary to achieve the desired results. Important considerations include site geology, depth of investigation, topography and access. The presence of noise-generating activities and operational constraints, should also be considered. It is a good practice to obtain as much relevant information (for example, data from any previous seismic refraction work, drilling, geologic and geophysical logs of the study area, topographic maps or aerial photos, or both) about the site, prior to planning a survey and mobilization to the site.

7.2 The first important consideration in planning a field refraction survey is the spacing between the geophones. The spacing will depend on the desired depth and resolution of exploration. Selection of detector spacing is also determined by the required detail of the refractor geometry. This is because the sampling interval of interpretation points on the refractor is approximately equal to the detector spacing on the surface. Thus, the horizontal resolution of the method for subsurface targets is equal to the detector spacing. Once the spacing between geophones is decided, the 'spread' length that is covered by one shot is fixed by the number of channels of the seismic equipment being deployed. Usually, in detailed engineering surveys, a 5m interval between geophones is appropriate. If the profile length required to get the desired subsurface information is more than one 'spread' length, the time-distance information should be collected by overlapping as many spreads as required. In doing so, at least two geophones should be kept overlapping between successive spreads to tie the timings from different shots to make profile continuous. Usually, atleast seven shots are required for each spread.

The depth of penetration varies between 1/5th to 1/4th of profile length approximately. For example, if geophone spacing is 5 m and number of channels are 12, total profile length would be 55 m and depth of penetration may vary between 10 m and 14 m. If geophone interval is 10m and number of channels are 24, total profile length would be 230 m. In this case, the depth of penetration may vary between 50 m and 60m. Seismographs having 48 or more channels can be interconnected for even deeper penetration depth. Investigations depth of up to 100 m can be achieved by using 48 channel Seismograph and geophone spacing of 10 m.

7.3 The advantage of locating the shot points between two geophones is that the reciprocal times between different shot points can be read directly instead of extrapolating beyond the end geophone, which can introduce errors in measurement of reciprocal time, in case of uneven refractor topography. Secondly, it does not disturb the ground under adjacent geophone stations. Any disturbance of the ground caused by placing a shot too close to a geophone station will delay waves arriving at the geophone for all subsequent recording, which will not allow separation of this delay in arrival time from the increase in arrival time coming from deeper layers.

7.4 When explosives are used as sources, charge weights adequate to produce sharp and well defined first arrivals on the seismic records are needed. Charge weight is dependent on:

a) Geology;
b) length of the seismic profile;
c) shot depth; and
d) amount of background noise at the site of work.

For a typical field condition in India, the following charges are found to be sufficient for providing clear first arrivals and are recommended for obtaining good records. Generally, when top layer is not very loose, about 50 gm to 125 gm of explosive for central shot (that is, shot in the middle of the profile) and about 125 gm to 500 gm of explosive end of shots (shots at the end of spreads) is adequate. For 50 m and 100 m offset shots, about 500 gm to 2 kg explosive are enough to produce clear first arrivals. Shot hole depths may vary from 1 m to 3 m depending on the nature of top layer and difficulty of drilling the holes Coupling of explosive energy with the ground should be improved by packing the charge holes and saturating it with water. This will help in transmitting most of the seismic energy into the ground.

7.4.1 Special blasting caps (instantaneous blasting or zero delay type preferably seismic detonators) should be used for seismic survey. The geophones should be held vertically and firmly coupled to the ground, to avoid any delay in the recording of seismic wave arrivals.

7.4.2 It is desirable to maintain a constant shot depth for the survey at a particular site. If it is not feasible to maintain the same depth, a shot depth correction should be added to all arrival times to effectively yield a travel time, which would have been recorded had the shot been at the surface of the ground.

7.5 Seismic cables are manufactured with fixed spacing, that is, the take-out or polarized connector for each detector is molded into the cable and the spacing between these take-outs is fixed. For placing a 10 m array, it is desirable to have cables with spacing of minimum 15 m to accommodate the safe execution of shots between two consecutive geophones. Similarly, for 5 m array, it is desirable to have cables with spacing of minimum 7 m to accommodate the safe execution of shots between two consecutive geophones. The cable should be laid along the ground in a straight line. If the terrain along the seismic line has any relief, ground level survey should be carried out so that the subsurface layer thicknesses can be plotted in true elevation of the site.

7.6 In water, the picking up of the arrivals of compressional waves is done by hydrophones. The hydrophone cable is towed beyond the ship and at some places the cable is tied with the buoy rope so that the cable will float on the water surface. The hydrophone cable is connected to a multichannel seismograph (*see* **Fig. 5**). Shots are fired on the bottom with fixed intervals.

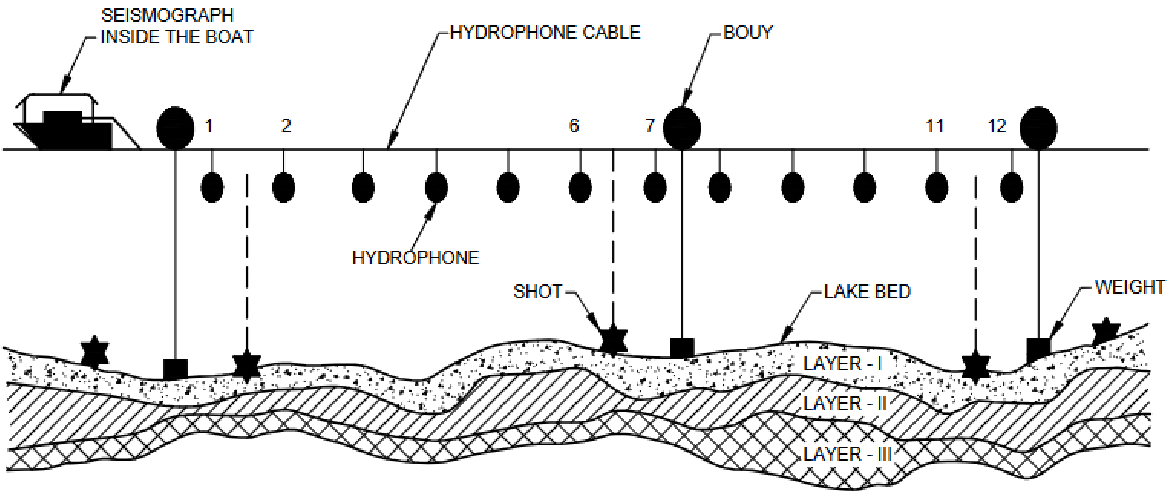

FIG. 5 LAYOUT OF HYDROPHONES FOR UNDERWATER SEISMIC REFRACTION SURVEY

8 LIMITATION OF SEISMIC REFRACTION TECHNIQUE

A hidden layer, or blind layer, is one that is undetectable by refraction surveying. In practice, there are two different types of hidden layer problem.

A layer may simply not give rise to first arrivals, that is, rays traveling to deeper levels may arrive before those critically refracted at the top of the layer in question (*see* **Fig. 6A**). This may result from the thickness of the layer, or from the closeness of its velocity to that of the overlying layer. In such a case, a method of survey involving recognition of only first arrivals will fail to detect the layer. The problem maybe overcome by firing a shot in a deep hole so that arrivals from the intermediate layer are recorded at the surface.

A more insidious type of hidden layer problem is associated with a low velocity layer, as illustrated in **Fig. 6B**. Rays cannot be critically refracted at the top of such a layer and the layer will, therefore, not give rise to head waves. Hence, a low velocity layer cannot be detected by refraction surveying although the top of the low velocity layer gives rise to wide angle reflections that may be detected during a refraction survey.

In the presence of a low velocity layer, the interpretation of travel-time curves leads to an overestimation of the depth to underlying interfaces. Low velocity layers are a hazard in all types of refraction survey. On a small scale, a peat layer in muds and sands above bedrock may escape detection, leading to a false estimation of foundation conditions and rock depths beneath a construction site.

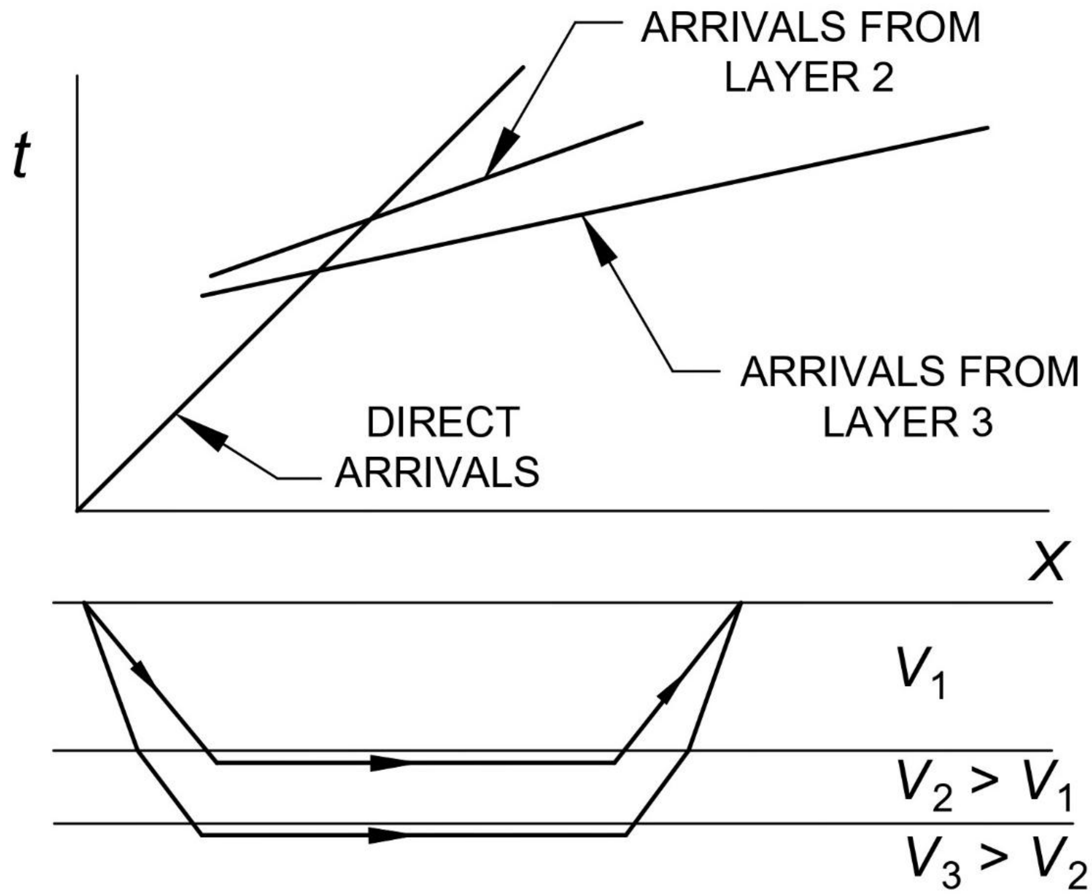

FIG. 6A HIDDEN LAYER PROBLEM IN SEISMIC REFRACTION

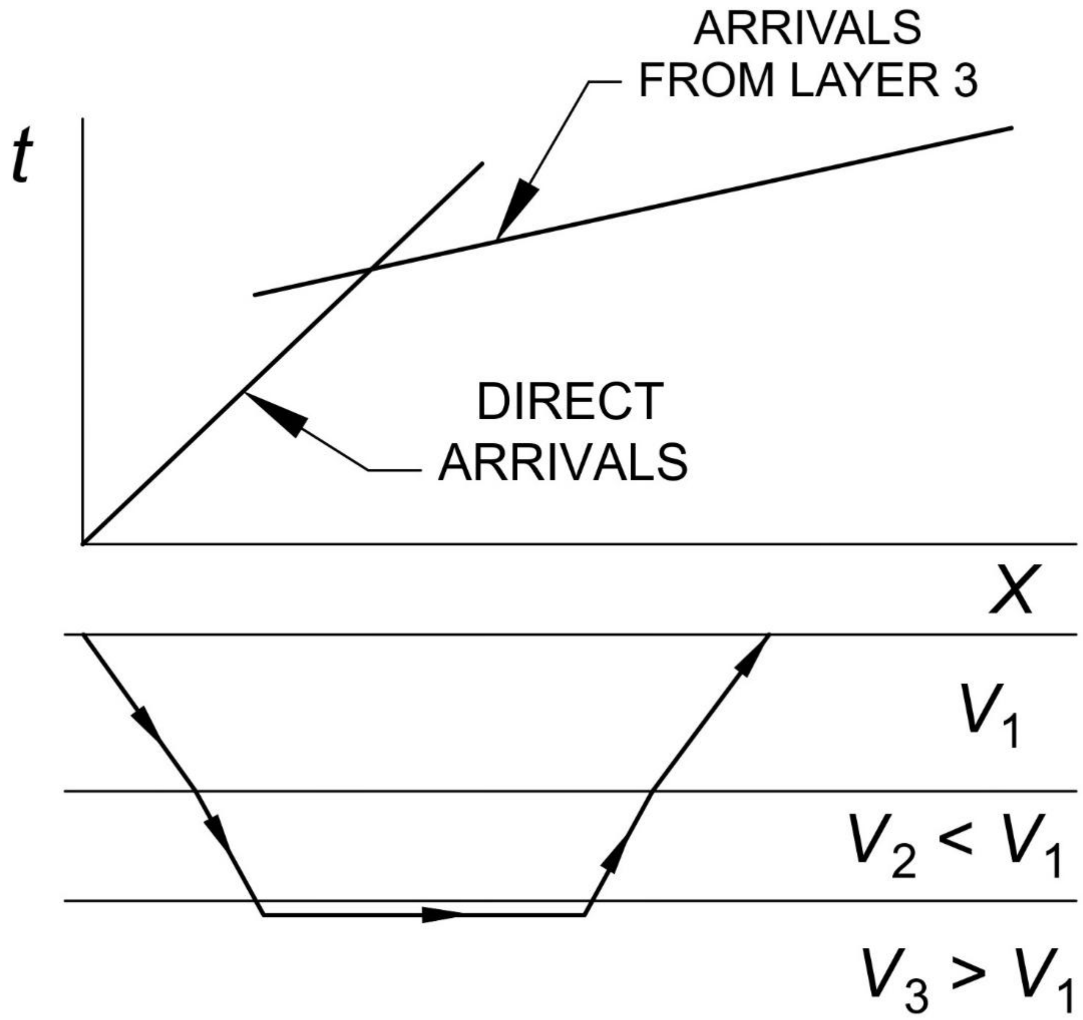

FIG. 6B BLIND ZONE PROBLEM IN SEISMIC REFRACTION

FIG. 6 PROBLEMS IN SEISMIC REFRACTION

9 INTERPRETATION

9.1 In some limited cases, quantitative interpretation of the data may not be required and a simple qualitative interpretation may be sufficient. Examples of qualitative and semi-quantitative interpretation may include the lateral location of a buried channel without a concern for its depth or minimum depth to rock calculations. In most cases, however, a quantitative interpretation will be necessary.

9.2 The level of effort involved in the interpretation will depend upon the objectives of the survey and the detail desired that, in turn, will determine the method of interpretation. A number of manual methods and computer programmed are available for interpretation. While the solution for these methods can be carried out manually, the process can be labour intensive for the more sophisticated methods.

9.3 A problem inherent in all geophysical studies is the non-unique correlation between possible geologic models and a single set of field data. This ambiguity can be resolved only through the use of sufficient geologic data and by an experienced interpreter.

9.4 The first step in the interpretation process is to determine the time interval from the impact of the seismic source to the first arrival of energy at each geophone. When the first arrivals are sharp and there is no ambient noise, this procedure is straight forward. In many cases, noise in the data will make picking the first arrival times difficult. To minimize errors, a consistent approach to the picking of the arrival times should be used. Care should be taken to ensure that each trace is picked at the same point, that is, at the first point of movement or the point of maximum curvature. This procedure will make the interpretation a more uniform process, as the data will be consistent from one trace to the next. In some cases, a first arrival pick from one or more geophones may be uncertain. If this occurs, these picks should be noted. If a computer programme is used to make first arrival picks, these picks should be checked by the individual doing the processing and interpretation.

Corrections to travel-time for elevation or other geometric factors are then made. The two main types of corrections are elevation corrections and weathering corrections. Both are used to adjust field-derived travel times to some selected datum, so that straight-line segments on the time distance plot can be associated with subsurface refractor. These corrections can be applied manually or by computer

With the corrected travel-time data, a time distance plot of arrival times versus shotpoint -to - geophone distance can be constructed. Lines are then fitted to these points to complete a time distance plot. These time distance plots are the foundation of seismic refraction interpretation.

The methods given in **9.4.1** to **9.4.3** are generally used for seismic refraction interpretation.

9.4.1 *Intercept Time Method (ITM)*

The standard ITM is probably the best known of all the methods for the interpretation of seismic refraction data. It can be described as the rigorous application of Snell's law to a subsurface model consisting of homogeneous layers and plane interfaces. These planar interfaces can be either horizontal or dipping. The intercept time method requires that a constant seismic velocity exists in the overburden and in the refractor within a single geophone spread.

The ITM method can be applied where a limited number of refractor depth determinations are required within a single geophone spread; the surface of the refractor can be satisfactorily approximated by a plan (horizontal or dipping); lateral variations in seismic velocity of the subsurface layers can be neglected; and thin intermediate seismic velocity layers and seismic velocity inversions can be neglected. This method is described in **5**.

9.4.2 *Conventional Reciprocal Method (CRM)*

In many ways, the conventional reciprocal method (or Hawkin's method) can be considered to be an improved ITM, whereby the computations are extended from the shotpoints to each geophone location. As with the ITM, the analysis can be separated into the two distinct stages of the determination of refractor velocities, and the computation of a depth related term, similar to half the intercept time, called the time-depth.

A two-layer case is given in **Fig. 7**. The time depth $t_{\mathrm{G}}$the geophone station is obtained by adding together the travel times from both shotpoints to the geophone station, subtracting the shotpoint-to-shotpoint travel-time (the reciprocal time), and halving the result. Thus the time-depth (t_{G}) at the geophone station G is given by:

$$t_{\mathrm{G}} = 1/2(t_{\mathrm{AG}} + t_{\mathrm{BG}} - t_{\mathrm{AB}}) \qquad \text{......... (14)}$$

where t_{AG}, t_{BG} and t_{AB} are the travel times of the critical rays from A to G, B to G, and A to B respectively.

Substituting travel times in terms of their segment travel times as distance times velocity

$$t_{\mathrm{G}} = 1/2\,(GX/V_1 + GY/V_1 - XY/V_2) \quad \text{......... (15)}$$

If the refractor is assumed to be plane between the points X and Y, then from the symmetry,

$$t_{\mathrm{G}} = (GX/V_1 - PX/V_2) \quad \text{........... (16)}$$

which is the expression for the time-depth.

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

$$Z_{\mathrm{G}} = t_{\mathrm{G}}\bar{V}_{\mathrm{G}} \quad \text{........... (17)}$$

where t_{G} is the time-depth to the important refractor and $\bar{V}_{\mathrm{G}}$ is the corresponding composite depth conversion factor.

The composite depth conversion factor is calculated by summing the thicknesses (Z_{a}) upto 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, V, to n$^{\mathrm{th}}$ refractor is

$$\bar{V} = \sum_{a=1}^{n-1} \frac{Z_{\mathrm{a}}}{t_{\mathrm{n}}} \quad \text{.......... (18)}$$

This method can be applied where depths to the refractor are required at each geophone; the surface of the refractor has some relief; lateral variations in seismic velocity of the subsurface layers (over the length of the spread) can be neglected; and thin intermediate seismic velocity layers and seismic velocity inversions can be neglected.

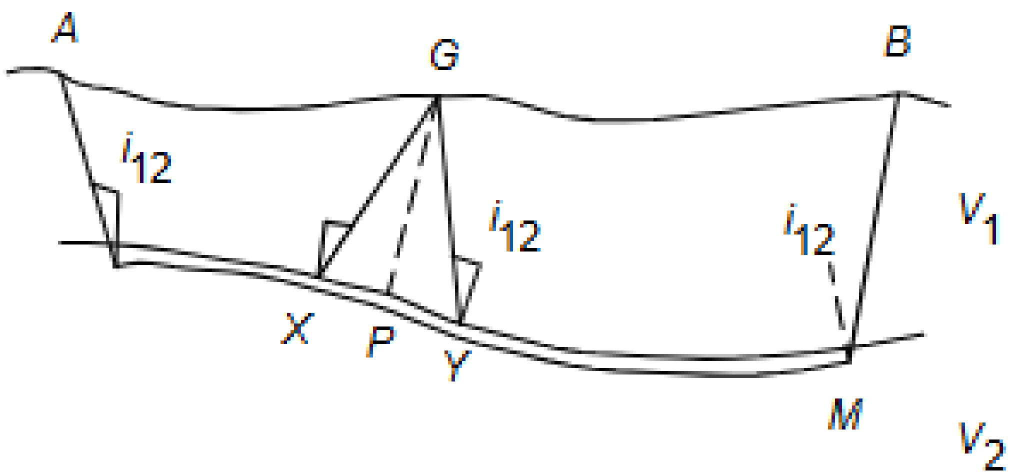

FIG. 7 RAY PATHS CONSIDERED FOR CRMMETHOD OF INTERPRETATION

9.4.3*Generalized Reciprocal Method (GRM)*

The generalized reciprocal method, popularly known as GRM, is the most efficient and accurate interpretation technique for seismic reflection data. The GRM can define layers with varying thicknesses and seismic velocities, unlike the conventional intercept time method.

Like the conventional reciprocal method, the GRM uses both forward and reverse arrival times, and is relatively insensitive to dip angles up to about 20 degrees. As a result, depth calculations to an undulating refractor are particularly convenient, even when the overlying strata have velocity gradients.

The conventional reciprocal method smoothens refractor irregularities because it assumes a plane refractor between the points of emergence of the forward and reverse rays. The GRM employs the principle of migration. Arrival times at two geophones, separated by what is termed the *XY*-distance, are used in refractor velocity analysis and time-depth calculations. A range of *XY* spacing is used, and the optimum value is selected using various tests associated with the method. At the optimum *XY* spacing, the forward and reverse rays emerge from near the same point on the refractor, so the refractor need only be plane over a very small interval.

The two major steps involved in using GRM are as follows:

a) *Velocity analysis function:*

The velocity analysis function, t_{V}, is given by

$$t_{\mathrm{V}} = (t_{\mathrm{AY}} - \mathrm{t_{BX}} + \mathrm{t_{AB}})/2 \qquad \text{...... (19)}$$

The locations of points *A*, *B, X* and *Y* are illustrated in **Fig. 8**. Each t_V value is referenced to the point *G*, which is half-way between the forward direction emerging point *Y* and reverse direction emerging point *X*. The velocity analysis function t_V is dependent on the *XY* distance. Velocity analysis function for different *XY* values is calculated and velocity analysis curves for different *XY* values are plotted. The change of lateral velocity along the refractor can be readily identified from these curves. The velocity analysis function curve which exhibits the least scattering of data points provides the optimum *XY* value and the best fit line to this curve yields the true refractor velocity. This optimum *XY* value is used for subsurface layer depth calculation.

b) *Time-depth function:*

Time time-depth t_{G} is given by

$$t_{\mathrm{G}} = [t_{\mathrm{AY}} + t_{\mathrm{BX}} - (t_{\mathrm{AB}} + \mathrm{XY}/V_{\mathrm{n}})]/2 \qquad \text{..... (20)}$$

Where, V_{n} is the true velocity of the refractor at each geophone position as determined from velocity analysis function.

The time-depth, which is also plotted with respect to *G*, is a measure of the depth to the refractor, expressed in units of time it is related to the thicknesses Z_{jG} of the layers by:

$$t_{\mathrm{G}} = \sum_{j=1}^{n-1} \frac{Z_{JG}\sqrt{(V_{\mathrm{n}}{}^2 - V_{\mathrm{j}}{}^2)}}{\mathrm{V_n V_j}} \qquad \text{....... (21)}$$

A set of curves for various *X*, *Y* values are obtained**.** The curve that yields the maximum detail, that is the refracting horizon in time corresponds to the optimum *XY* value. The optimum *X*, *Y* value obtained from both the velocity analysis and the time depth functions should be the same, which is used for final data interpretation.

The GRM is applied where lateral variations in seismic velocity within a single geophone spread, thin intermediate seismic velocity layers, and seismic velocity inversions cannot be neglected. Geophone spacing for this method is generally smaller to provide sufficient spatial data, The GRM requires the greatest level of field and interpretation effort.

9.5 The choice of interpretation method may vary from site to site and will depend upon the detail required from the seismic refraction survey and the complexity of the geology at the site. The interpretation method will, in turn, determine the approach and level of effort required in the field.

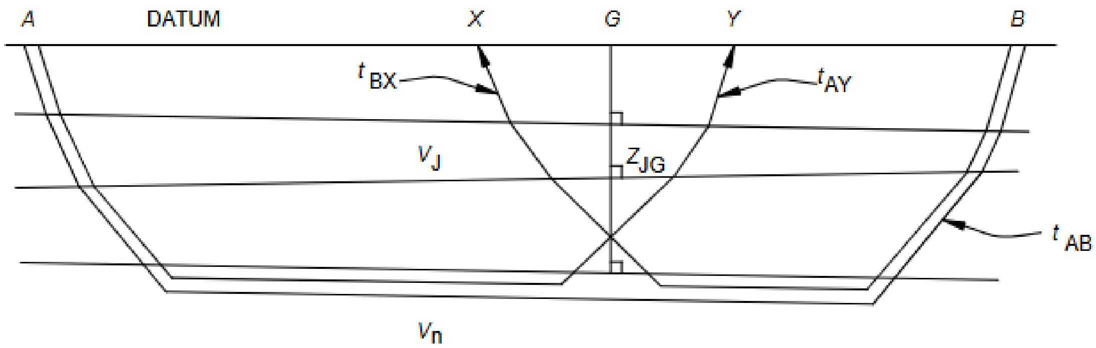

FIG. 8 RAY PATHS CONSIDERED FOR GRM METHOD OF INTERPRETATION

10 PRESENTATION OF DATA

The final seismic refraction interpretation is represented as a depth section, a contour map, or other drawings that illustrate the general geologic and hydrogeological conditions and any anomalous conditions at a site. **Fig. 9** shows the typical travel time curves and corresponding depth section.

The results of seismic refraction tomography are given in terms of Seismic Tomogram. The illustrative tomogram is given in **Annex B** for reference.

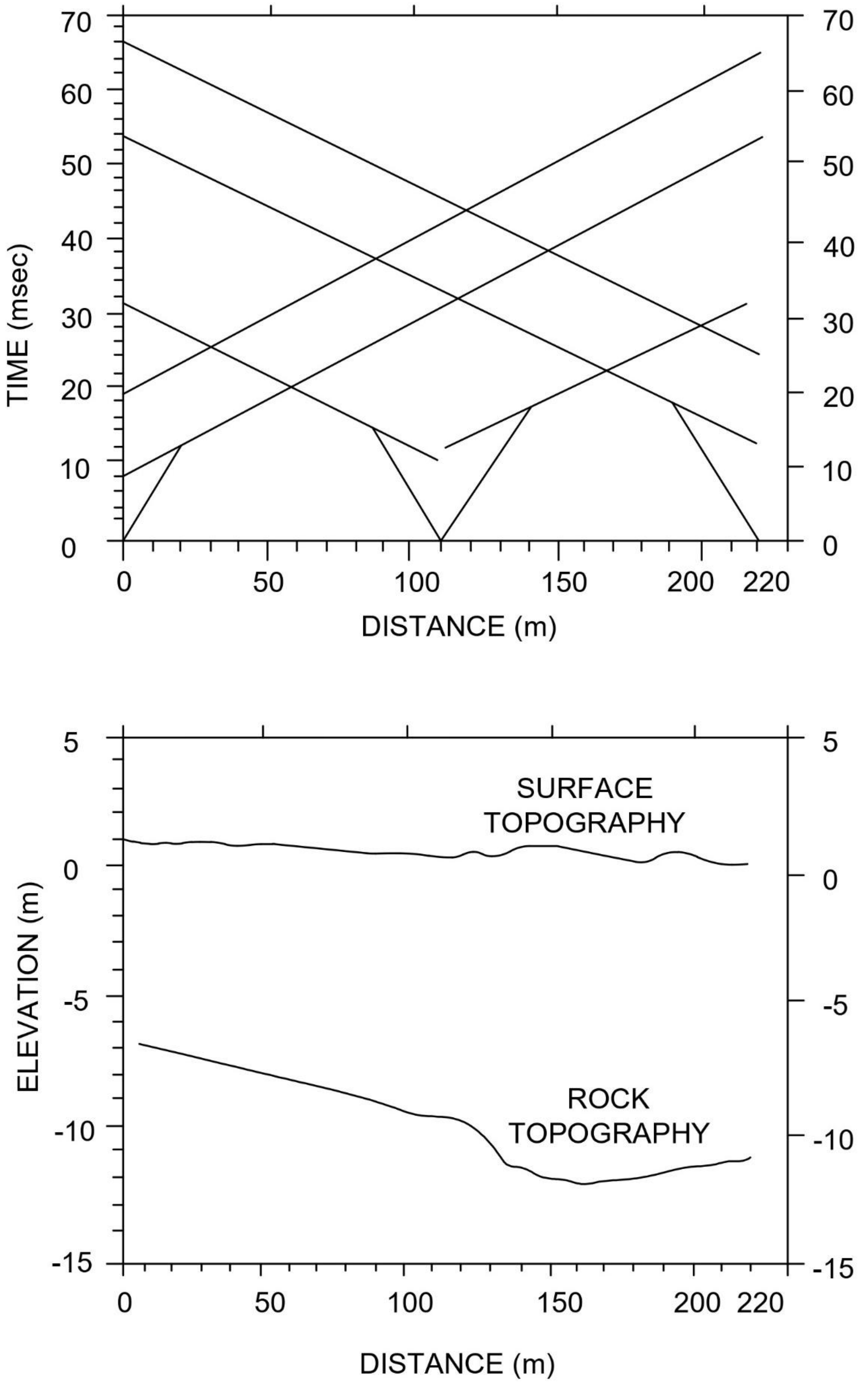

FIG. 9 TYPICAL TRAVEL TIME CURVES AND CORRESPONDING DEPTH SECTION FOR TWO LAYER CASE

ANNEX A

(*Clause* 5.9)

SEISMIC REFRACTION TOMOGRAPHY METHODOLOGY

A-1 Tomographic Technique

It involves the creation of an initial synthetic model of the subsurface and its perturbation in search of the minimum deviation between the measurements made on the ground and the 'virtual' measurements recorded on the synthetic model through an iterative procedure that cycles between the following two phases:

A-1.1 *Forward Phase*

In the 'forward' phase, the arrival times of the seismic pulse are calculated on the synthetic model. The initial velocity model is divided into a grid whose cells have assigned initial velocity values. On the sides of the cell are multiple nodes (the number of which can be selected as per study requirements) that constitute the nodes of the network of hypothetical seismic rays that connect all sources and all receivers that are also themselves nodes. Each node is connected with nodes in neighboring cells. Increasing the number of nodes increases the detail and accuracy in the seismic ray path but also increases the memory usage. The path of the refracted wave corresponds to the path that takes the shortest time to travel between the source and the receiver. The arrangement is depicted in **Fig. 10**.

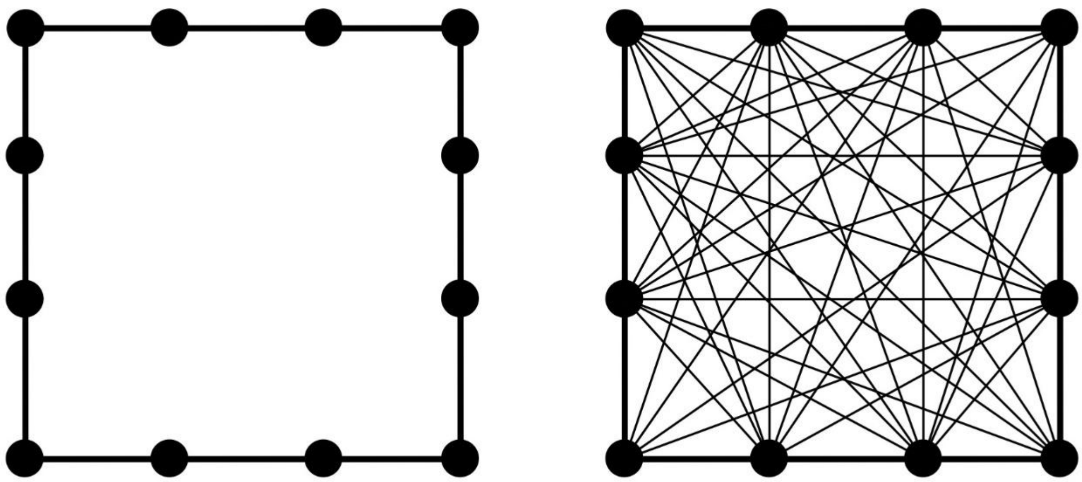

FIG. 10 EXAMPLE OF A CELL WITH 4 NODES ON THE EDGES

The nodes are used to discretize the seismic rays. Cell with all possible ray paths made explicit using four nodes. Increasing the number of nodes improves the approximation of the seismic ray path.

A-1.2 Inverse Phase

In the 'Inverse' phase, the synthetic times calculated in the 'forward' step are compared with the times measured on the seismograms; the differences between the times are used to update the synthetic model. In the implementation of this method the speed is replaced by its inverse, the slowness. For example, considering a generic seismic radius *j* between the source and the receiver the average slowness can be expressed as:

$$S_{ij} = \frac{t_{ij}}{l_{ij}} \qquad .....(22)$$

where, t_{ij} is the measured time between the source (*i*th) and the receiver (*j*th) and l_{ij} is the length of the *j*th seismic ray. Therefore, knowing the measured path times t_m and the calculated path time t_c for the *j*th ray, the residual path time can be calculated:

$$\Delta t_j = t_{mj} - t_{cj} \qquad …(23)$$

The residual of the path times is projected onto each cell *k* on which the slowness correction factor is also calculated as:

$$\Delta S_k = \frac{\sum \Delta t_{jk}}{\sum \Delta l_{jk}} \qquad ….(24)$$

The index i represents each seismic ray incident on the *k*th cell. The slowness correction factor will be used to update the velocity model at the end of each iteration of the resolution cycle. This procedure yields a model, with continuous velocity variations and not necessarily constrained by the presence of strong refractors like the bedrock.

ANNEX B
(*Clause* 10)

ILLUSTRATIVE TOMOGRAM

B-1 The schematic diagram showing the seismic refraction tomography results in terms of ray path and seismic wave velocity tomograms

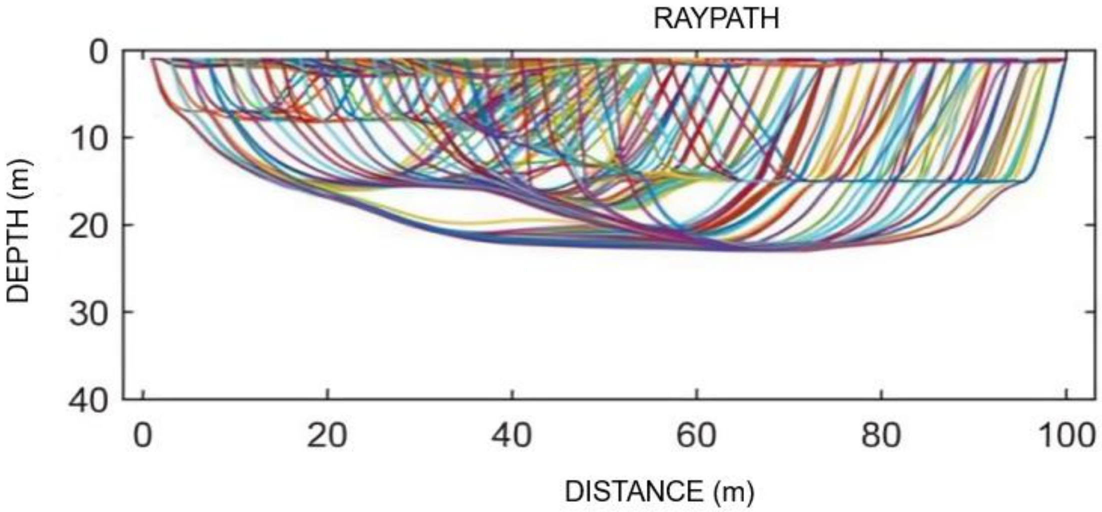

FIG. 11A REFRACTED RAY PATH

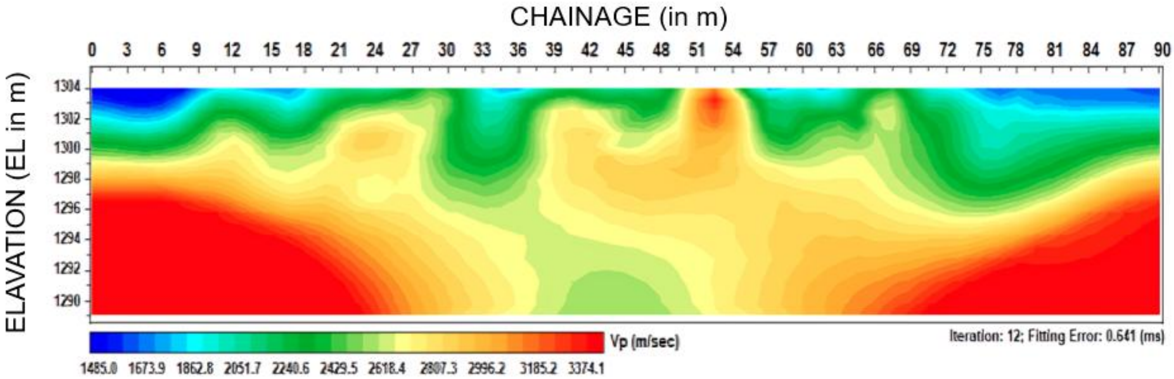

FIG. 11B INVERTED FINAL MODEL

FIG. 11 SEISMIC REFRACTION TOMOGRAPHY RESULTS IN TERMS OF RAY PATH AND SEISMIC WAVE VELOCITY TOMOGRAMS