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 Second edition

Geological Exploration by Geophysical Method (Seismic Refraction) - Code of Practice

0. Foreword

This Tanzania standard describes the best way of conducting Geological Exploration by Geophysical Method. The standard recommends the best practice that may be adopted by professionals during Geological Exploration by Geophysical Method specifically in Seismic Refraction method.

In preparation of this Tanzania standard main assistance was drawn from IS 15681:2006 Geological Exploration by Geophysical Method (Seismic Refraction) — Code of Practice

1. Scope

This standard deals with seismic refraction method including the equipment, field procedures, and interpretation of data for assessment of subsurface materials. Seismic refraction measurements, as described in this standard, are applicable in mapping subsurface conditions for various uses including geological, geotechnical, hydrological, environmental, mineral and archaeological investigations. 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.

Interpretation of the data collected during the seismic refraction survey is referred to in this standard only in a general way. For full details of the theory, field procedure, or interpretation of the data, reference should be made to specialized texts.

2. Terms and definitions

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. Bulk Modulus

A measure of how incompressible/resistant to compressibility that substance is. It is defined as the ratio of the infinitesimal

2.3. Buoy

Anchored float serving as a navigation mark, to show reefs or other hazards, or for mooring.

2.4. 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.

2.5. 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 P-wave and longitudinal wave.

2.6. Critical distance

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

2.7. 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.

2.8. Elastic wave

Waves of energy caused by the sudden breaking of rock within the earth or an explosion which travel through the earth and recorded on seismographs.

2.9. Geophone interval

The distance between adjacent geophones within a group.

2.10. Head wave

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

2.11. Huygen's Principle

The concept that every point on an advancing wavefront can be regarded as the source of a secondary wave and that a later wavefront is the envelope tangent to all secondary waves.

2.12. Intercept time

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

2.13. Overburden

The section above a refractor or a reflector.

2.14. Reciprocal time

The common travel time on reversed refraction profiles. Surface to surface time from a shotpoint at A to a geophone at B must equal that from a shotpoint at B to a geophone at A.

2.15. 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.

2.16. Refraction wave

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.

2.17. 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.

2.18. 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.

2.19. 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 wavefront 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-and S-waves.

2.23. Surface wave

Energy which travels along or near the surface.

2.24. Time-Distance curve

A plot of the arrival time against the shotpoint-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. Wave front

Surface connecting all points of equal travel time from the source

3. Measured parameter and representative values

The seismic refraction method gives the velocity of compressional (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, 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.

Table 1. Range of velocities for compressional waves in soil and rock

Medium type (Soil/rock)	Velocity (m/s)
Weathered surface material	240 - 610
Gravel or dry sand	460 - 915
Sand(saturated)	1220 -1830
Clay (saturated)	915 -2750
Water	1430 - 1665
Sea water	1460 - 1525
Sandstone	1830 - 3960
Shale	2750 - 4270
Chalk	1830 - 3960
Limestone	2135 - 6100
Granite	4575 - 5800
Basalt	6000 - 6400
Quartizite/phyllitic quartzite	4000 - 6000
Quartizite phyllitic/phyllite	2500 - 3500
Gneiss	4000 - 6000

4. Methodology

4.1 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 may be 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.

4.2 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 $\mathbf{V_2}$ is greater than $\mathbf{V_1}$ 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 $\mathbf{i_C}$ the angle of refraction will be 90°. This gives rise to a critically refracted ray that will then be traveling 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.

4.3 In Fig. 1B, the position of a wavefront in the lower medium is shown, together with the associated wavefront 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 wavefront in the deeper, higher velocity medium of the refractor. The position of the wavefront 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° 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.

4.4 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 is dependent upon the bulk modulus and the density and is given by

$$\mathbf{Vp} = \sqrt{(\mathbf{K} + \left(\tfrac{4}{3}\right)\boldsymbol{\mu})/\boldsymbol{\rho}} \qquad \text{………………….. (1)}$$

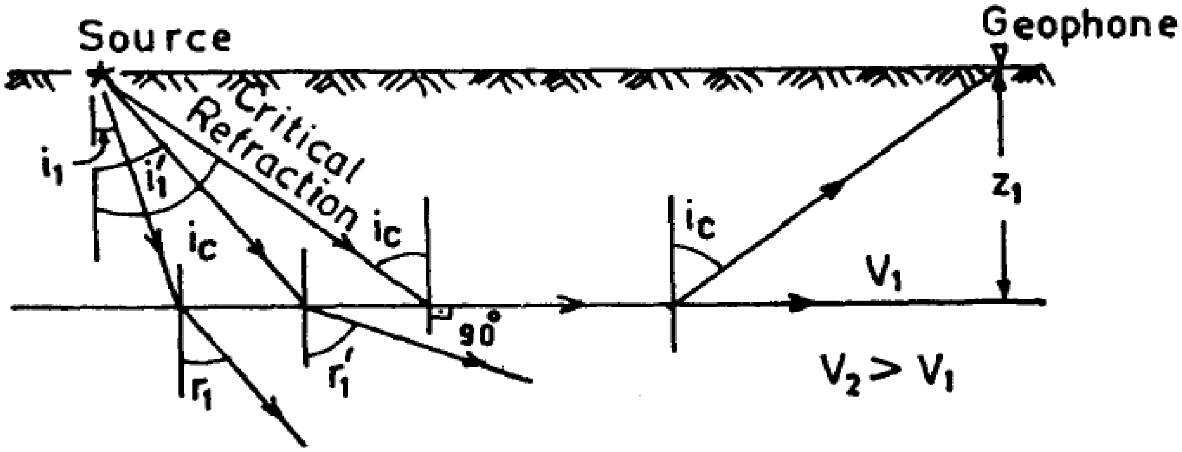
where,

$\mathbf{Vp}$ = compressional wave velocity,

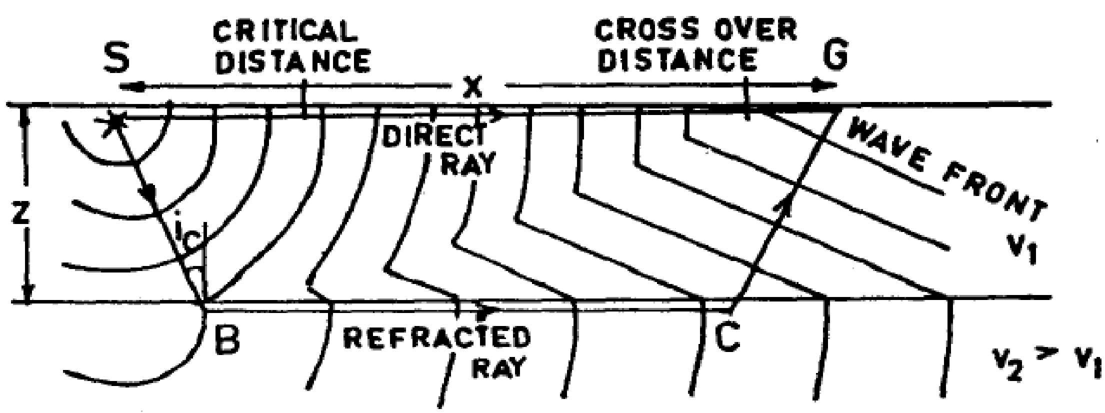
$\mathbf{K}$ = bulk modulus,

$\boldsymbol{\mu}$ = shear modulus,

$\boldsymbol{\rho}$ = density.



1A Ray Paths for a Critically Refracted Wave



1B Wave Paths Associated with Critically Refracted Wave

Figure. 1 Ray and wave paths for a critically refracted wave

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 a t-x curve indicates the velocities of seismic waves through different layers and provides the information needed to calculate layer thicknesses.

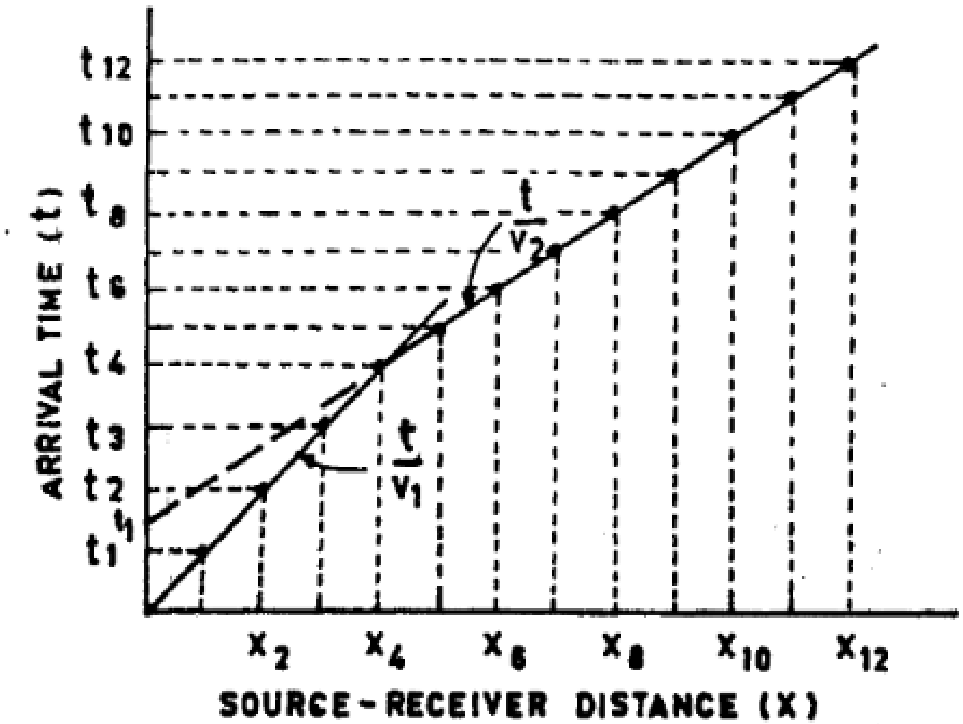


Figure. 2 Time-Distance curve

4.5 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 $\frac{\Delta t}{\Delta x}$**,** 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:

$$\mathbf{Z1} = \frac{\mathbf{t1V1V2}}{2\sqrt{((\mathbf{V2})^2 - (\mathbf{V1})^2)}} \qquad \dots\dots\dots\dots\dots\dots\dots\dots (\mathbf{2})$$

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

4.6 Multilayer Analysis

If a structure has **n** horizontal layers with the thickness Z_1**, Z_2, Z_3, ……, Z_n** and wave velocities **V_1, V_2, V_3, ….., 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:

$$\mathbf{Tn} = \sum_{k=1}^{n} \frac{\mathbf{Zk}}{\mathbf{Vk}} \cos \mathbf{ik}(\mathbf{n}+\mathbf{1}) \qquad \dots\dots\dots\dots\dots\dots\dots\dots\dots\ (\mathbf{3})$$

and the thickness of the deepest layer by

$$\mathbf{Zn} = \left(\frac{\mathbf{Tn}}{\mathbf{2}} - \sum_{k=1}^{n-1} \frac{\mathbf{Zk}}{\mathbf{Vk}} \cos \mathbf{ik}(\mathbf{n}+\mathbf{1})\right) \frac{\mathbf{Vn}}{\cos \mathbf{in}(\mathbf{n}+\mathbf{1})} \qquad \dots\dots\dots\dots\dots\dots\dots\dots.\ (\mathbf{4})$$

4.7 Underwater seismic refraction survey

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. 3). Shots are fired on the bottom with fixed intervals.

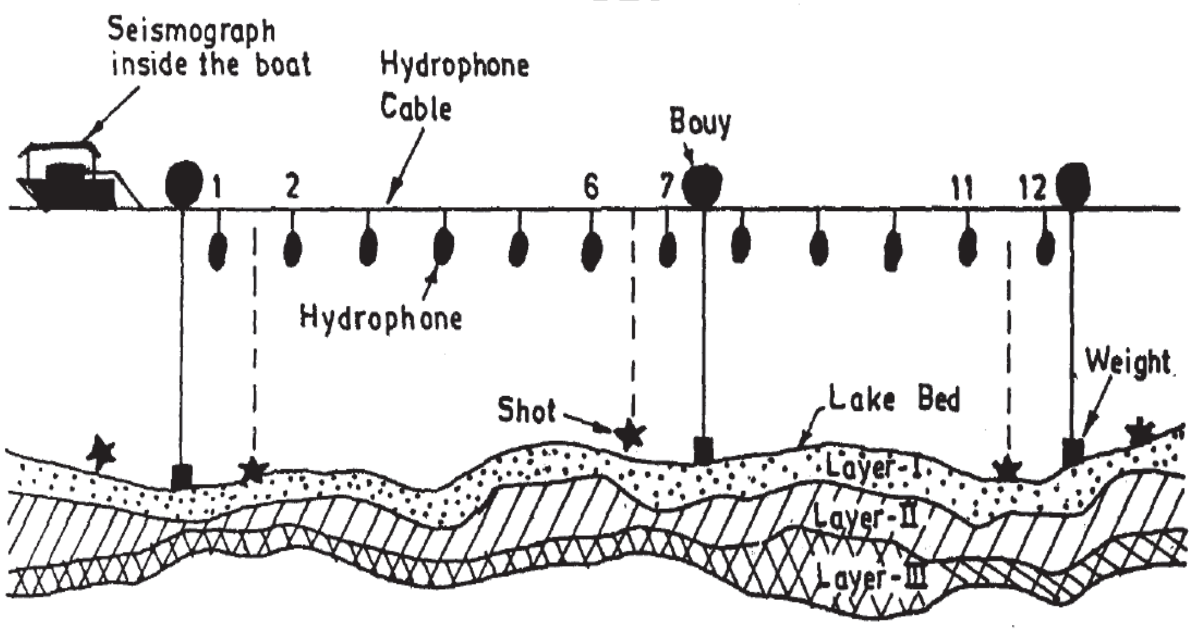


Figure. 3 Underwater seismic refraction surveys

5. 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.

5.1. Seismographs

Seismograph is a recording system for seismic waves. 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.

5.2. Geophone and Cable

A geophone transforms the P-wave 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.

5.3. 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.

5.4. 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.

6. Planning the survey

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. Interpretation

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 programs are available for interpretation. 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.

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 straightforward. 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.

8. 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 hydrogeologic conditions and any anomalous conditions at a site. Figure 4 shows the typical travel time curves and corresponding depth section.

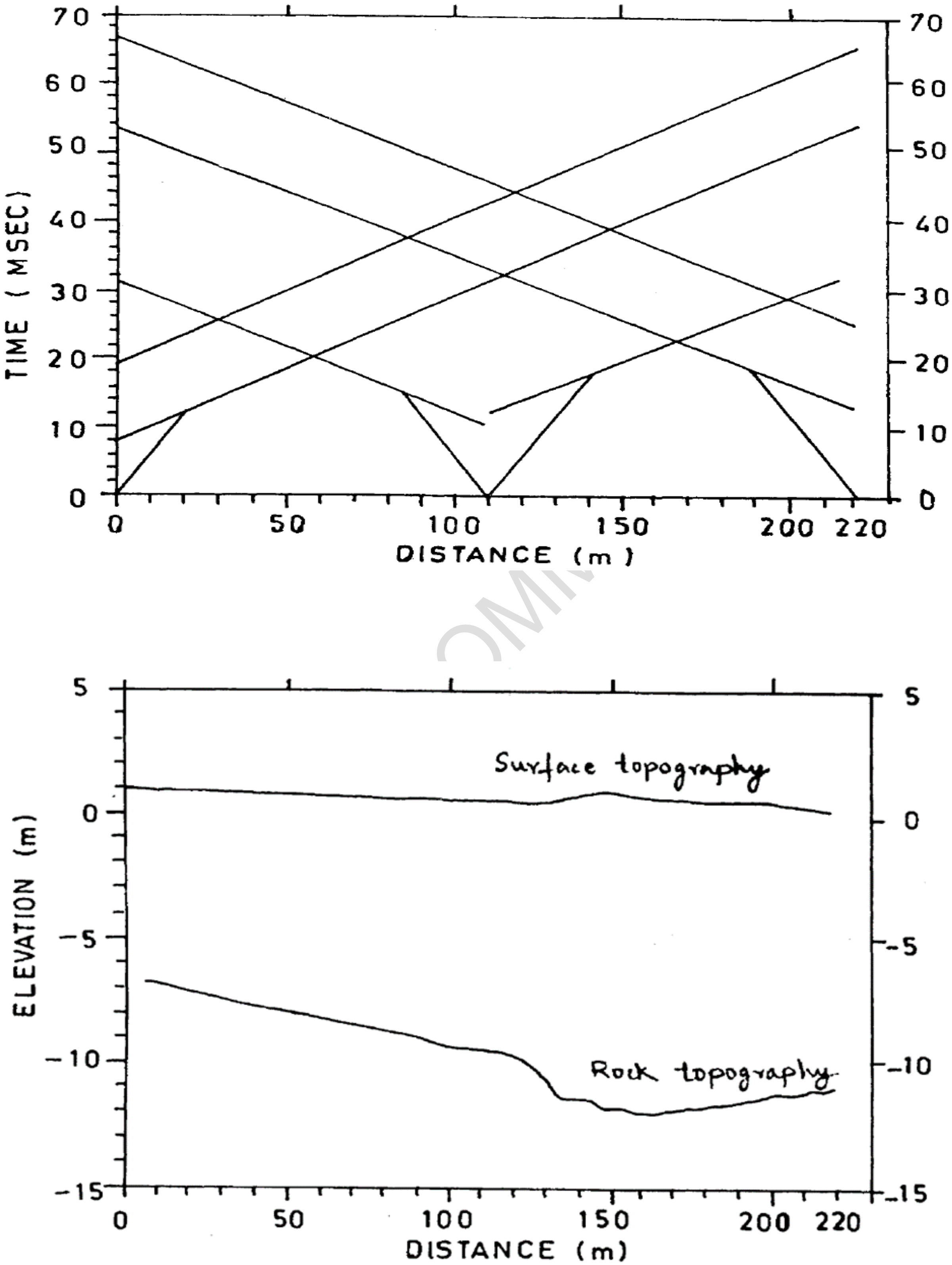


Figure. 4 typical travel-time curves and corresponding depth section