Chapter II: Geophysical prospecting methods

Choice of methods.

The choice of a geophysical method depends on the objective sought (very deep, deep, shallow). There are no absolute rules when it comes to choosing which methods to adopt, as the problems that arise in nature are never simple and never sufficiently well-defined. The complex geological structures we seek to detect and define always deviate from the simplified types (direct and inverse problems in geophysics), because the physical constants of the rocks in the subsoil vary according to the terrain traversed. Since geophysical measurements are carried out on the surface, the depth of investigation and the penetration depth of the physical fields applied determine the choice of geophysical method to be used.

Objectives

The primary objective of a geophysical prospecting campaign is to better map the geometry and structure of the subsurface by collecting and processing acquisition data in order to identify geological targets.

II.1 Seismic methods (seismic refraction and seismic reflection)

It is a geophysical method, and its theory is based on knowledge of elasticity, geometrical optics, vibratory physics, signal processing and geology. To understand the geological make-up of a region, geophysicists take various surface measurements. In particular, to determine the contour lines of geological layers, they use seismic prospecting methods: an explosion is triggered in the vicinity of the surface layers of the terrain under study. The artificially generated shock wave propagates underground. Since geological layers differ in density and nature, when the wavefront crosses the boundary separating two layers, part of the energy transported is reflected and refracted towards the surface, due to the discontinuity in the elastic constants of the layers. On the surface, seismographs record the arrival of the energy released by the explosion during the 4 or 5 seconds following it. By plotting these arrivals on seismograms (time section) and cross-referencing their indications with those provided by other measurements, the geophysicist draws up isochrone maps that translate the position of the various structures in terms of depth. Knowledge of a velocity law enables these isochron maps to be converted into isobath maps (equal depth). There are two main methods of seismic prospecting: seismic reflection and seismic refraction. Both are designed to determine the depth and shape of the geological discontinuities that make up the subsoil.

Seismic, whose principle is to differentiate between formations on the basis of the propagation velocity of the waves passing through them, is a relatively costly and slow method, but the results are often excellent. This method is frequently applied to alluvial sites, to determine the thickness of loose

rock on the bedrock (sand velocity: 600 m/s, limestone velocity: 5000 m/s). In hydrogeology, seismic refraction is mainly used. However, recent advances in computer technology now make it possible to use seismic reflection even at shallow depths.

II.1.1 Seismic refraction

In the case of a medium composed of two terrains, seismic waves refract on the surface of the second medium, characterized by a higher elastic wave propagation speed. A seismic refraction survey involves inducing a surface vibration and recording the arrival time of the refracted waves. By processing the dromochrony of the refracted wave recorded from geophones, we can determine the propagation speed of the refracted wave in the second medium, as well as its depth.

II.1.1.1 Behavior of an acoustic wave:

When the surface is shaken, the waves travel at speed V, forming a half-sphere with center E, and at point S only one wave train is recorded (direct wave).

In stratified media, a refracted wave is added on the 2nd diopter (the separating surface of 2 media p and p+1, with respective velocities Vp and Vp+1).

According to Huygens' principle, each point I of the refracted wave will give rise to waves of radius I1S1, I2S2, I3S3, I4S4, I5S5, in effect each point behaving like a new light or sound source. Any particle that enters into oscillation transmits its motion to the surrounding particles. Rays parallel to the rays reflected at point I are refracted rays. Only one ray at point I is confused with the reflected ray.
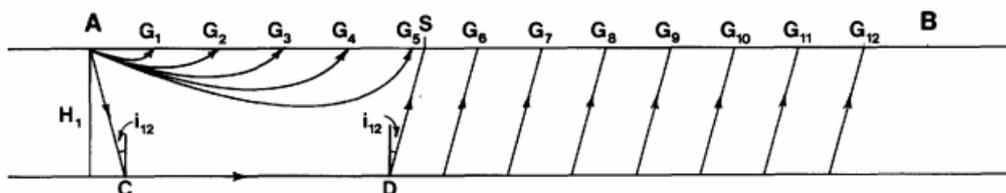
II.1.1.2 Principle of seismic refraction: (Case of a single refracting plane parallel to the surface):

Seismic refraction uses the first arrivals, i.e. the wave trains coming from an explosion point E and arriving first at the geophones. Let's consider the following stratification:

$$T_1 = \frac{\overline{AS}}{V_1} = Tc_1 = \frac{\overline{AC}}{V_1} + \frac{\overline{CD}}{V_2} + \frac{\overline{DS}}{V_1}$$

ou

$$\frac{\overline{AS}}{V_1} = \frac{\overline{CD}}{V_2} + \frac{2\overline{AC}}{V_1} \tag{3}$$

avec

$$\overline{AC} = H_1 / \cos i_{12}$$

et

$$\overline{CD} = \overline{AS} - 2H_1 \, tg \, i_{12} \text{ (relation trigonométrique).}$$

En remplaçant $\overline{AS}$ par Xc_1 dans l'équation (3), nous retrouvons que:

$$\frac{Xc_1}{V_1} = \frac{2H_1}{\cos i_{12} \, V_1} + \frac{Xc_1}{V_2} - \frac{2H_1 \, tg \, i_{12}}{V_2} \tag{4}$$

ou

$$\frac{Xc_1}{V_1} = \frac{Xc_1}{V_2} + \frac{2H_1}{\cos i_{12}} \left(\frac{1}{V_1} - \frac{\sin i_{12}}{V_2} \right) \tag{5}$$

En isolant Xc_1 et en remplaçant $\sin i_{12}$ par V_1/V_2 et $\cos i_{12}$ par $\dfrac{\sqrt{V_2^2 - V_1^2}}{V_2}$ (car $\sin^2 i + \cos^2 i = 1$) dans (5), nous retrouvons que:

$$Xc_1 \left(\frac{1}{V_1} - \frac{1}{V_2} \right) = \frac{2H_1 \, V_2}{\sqrt{V_2^2 - V_1^2}} \left(\frac{1}{V_1} - \frac{V_1}{V_2^2} \right)$$

ou

$$Xc_1 \left(\frac{V_2 - V_1}{V_1 \, V_2} \right) = \frac{2H_1}{\sqrt{V_2^2 - V_1^2}} \left(\frac{V_2}{V_1} - \frac{V_1}{V_2} \right)$$

Par simplification, nous aurons donc:

$$\frac{Xc_1 \, (V_2 - V_1)}{2 \, (V_1 \, V_2)} = \frac{H_1 \sqrt{V_2^2 - V_1^2}}{V_1 \, V_2}$$

et en isolant H_1, nous trouvons:

$$H_1 = \frac{Xc_1 \, (V_2 - V_1)}{2 \, (V_1 \, V_2)} \frac{V_1 \, V_2}{\sqrt{V_2^2 - V_1^2}}$$

ou encore:

$$H_1 = \frac{Xc_1}{2} \sqrt{\frac{V_2 - V_1}{V_2 + V_1}} \tag{6}$$

ou encore, exprimé différemment:

$$H_1 = \frac{T_1}{2} \frac{V_1 \, V_2}{\sqrt{V_2^2 - V_1^2}} \tag{9}$$

Le temps T_1 nous est donné, en prolongeant la droite de pente $1/V_2$ sur l'ordonnée à l'origine, les vitesses V_1 et V_2 par les dromochroniques.

● **Dromochronic:**

The curve of the function $T = f(x)$ is called dromochronic; it gives us information on the number of terrains, the slopes of these lines give us the velocities V1, V2 as well as their thickness h of the two terrains.

$$T_1 = \frac{x}{V_1} \text{ Onde directe, } \quad T_2 = \frac{x}{V_2} + \frac{2h_1 \cos\alpha}{V_1} \text{ onde réfractée.}$$

1.2.1 / Cas de 3 terrain horizontaux :

$$T_3 = 2T_{EC} + 2T_{CD} + T_{DE} \text{ -}$$

$$T_3 = 2\frac{EC}{V_1} + 2\frac{CD}{V_2} + T_{DE}$$

$$T_{DE} = T_X - T(2C_1D + 2C_1E')$$

$$T_{DE} = \frac{x}{V_3} - (2\frac{C_1D}{V_3} + 2\frac{C_1E'}{V_3})$$

$$T_3 = \frac{x}{V_3} + 2(\frac{EC}{V_1} - \frac{C_1E'}{V_3}) + 2(\frac{CD}{V_2} - \frac{C_1D}{V_3})$$

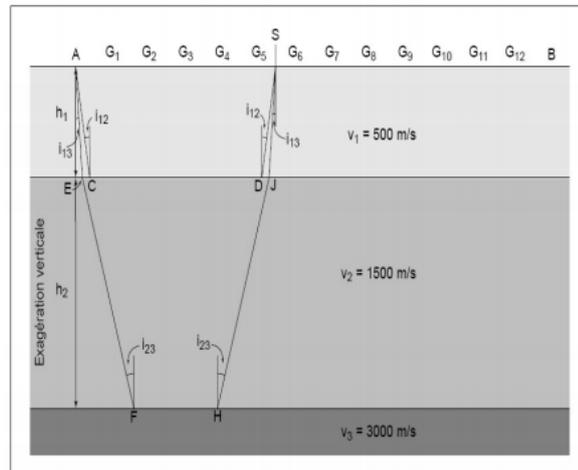$$T_3 = \frac{x}{V_3} + \frac{2h_1 \cos\beta_1}{V_1} + \frac{2h_2 \cos\beta_2}{V_2}$$

Figure 7.11 – Représentation schématique des rais sismiques, pour un cas trois terrains horizontaux.

1.2.2 / Cas de n terrain :

$$T_n = \frac{x}{V_n} + \frac{2h_1 \cos\gamma_1}{V_1} + \dots\dots + \frac{2h_{n-1} \cos\gamma_{n-1}}{V_{(n-1)}}$$

Applications:

-Locate fault or shear zones;

-Determine the thickness of different layers underlain by harder ground.

-Measure the depth of the water table;

-Identify sub-vertical geological contacts.

II.1.2 Seismic reflection

Seismic reflection is a geophysical prospecting method in which a source emits elastic waves which penetrate the ground, propagate and reflect at the interfaces between media with different wave velocities (the reflected signals are collected to establish the wave velocity in these media and the geometry of the media traversed). This geophysical prospecting technique represents the area where investments in prospecting (mainly oil) are the highest.

The ability of seismic waves to penetrate to depth depends on the length of the emitted signal: the longer the wavelength, the greater the penetration.

II.1.2.1 Case of a horizontal reflector

Let's take the very simple case of a horizontal reflector at depth h, under a homogeneous medium where the wave velocity p is V. A source in E emits waves which are recorded by a sensor located in S at distance x from E.
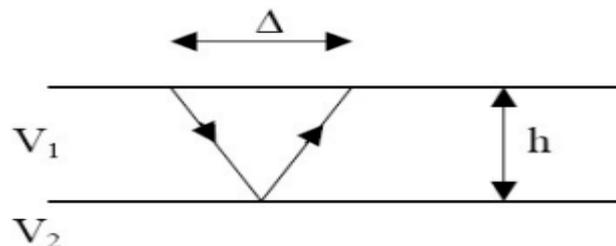
The propagation time of the reflected wave

$$t = \frac{2}{V}[h^2 + (\frac{x}{2})^2]^{1/2} .$$

We can also express the thickness h of the medium, if we give V and measure t

$$h = \frac{1}{2}[(Vt)^2 - x^2]^{1/2}$$

The relationship between travel time and source-receiver distance is known as the hodochrone, in the form of a hyperbola. Note that only the first term depends on the distance x. The second term depends only on the layer parameters, so our hodochrone becomes :

$$t^2 = (\frac{x}{V_1})^2 + t_0^2$$

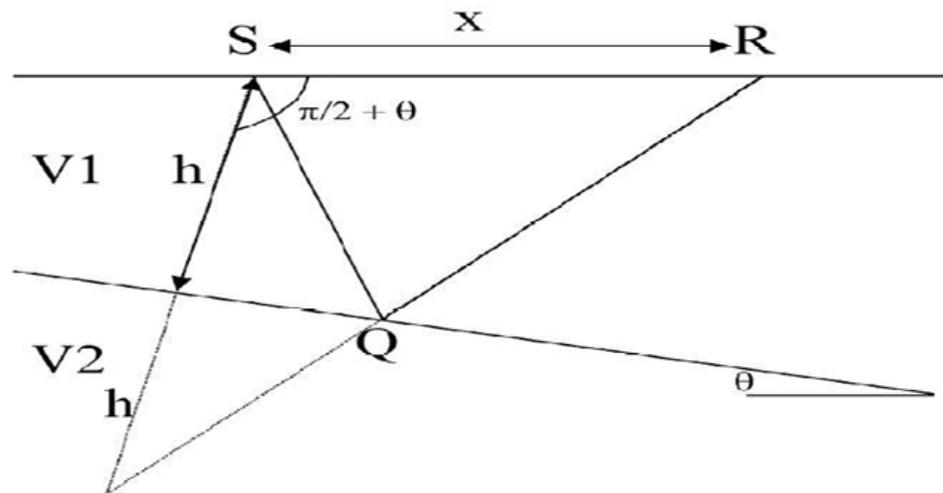**II.1.2.2 Case of a sloped interface:**

FIG : Sismique réflexion pour une couche pentée d'un angle θ

Note that in this case, the reflection point (Q) is not exactly halfway between source and receiver. To solve this problem, we proceed as in the previous case, i.e. we determine the distance travelled and divide it by the speed of the medium. To make things easier, we turn the path SQ in relation to the reflector plane: the total path is then from the intersection of the two dotted lines (P) to point R. We find this distance PR by applying the Law of Cosines, as the triangle SPR does not contain a right angle.

$$(PR)^2 = d^2 = x^2 + (2h)^2 - 4hx\cos(\pi/2 + \theta)$$
$$d^2 = x^2 + 4h^2 + 4hx \sin \theta$$
$$d^2 = x^2 + 4hx\sin\theta + 4h^2 x\sin^2 \theta + 4h^2 \cos^2 \theta$$
$$d^2 = (x + 2h\sin\theta)^2 + (2h\cos\theta)^2$$

D'où on tire le temps de parcours :

$$t^2 = (\frac{x + 2h\sin\theta}{V_1})^2 + (\frac{2h\cos\theta}{V_1})^2$$

We can see that the hodochrone still describes a hyperbole. Let's look at the second term:

As in the previous case, it does not depend on x. We can see that in fact this term is nothing other than the t0 of the previous case divided by cos θ; in other words, it's the t_0 for a Propagation velocity $V_v = V_1/ \cos \theta$. V_v is the apparent vertical velocity greater than V_1. The analysis of a hodochrone therefore gives us information on the velocity of the layer and its thickness.

The amplitude of a reflected wave depends essentially on the impedance contrast between the two media.

Impedance is defined as the product of velocity and density

$Z = \frac{1}{2}V$. The reflection coefficient R, for a wave incident normally on an interface, is given by:

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} = \frac{\rho_2 V_2 - \rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1}$$

So the greater the difference between two media, the greater R will be. Note also that R is positive from a slow medium to a fast medium and vice-versa.

Applications:

-Oil and gas exploration;

-Geological mapping;

-Mineral exploration;

-Civil engineering site surveys
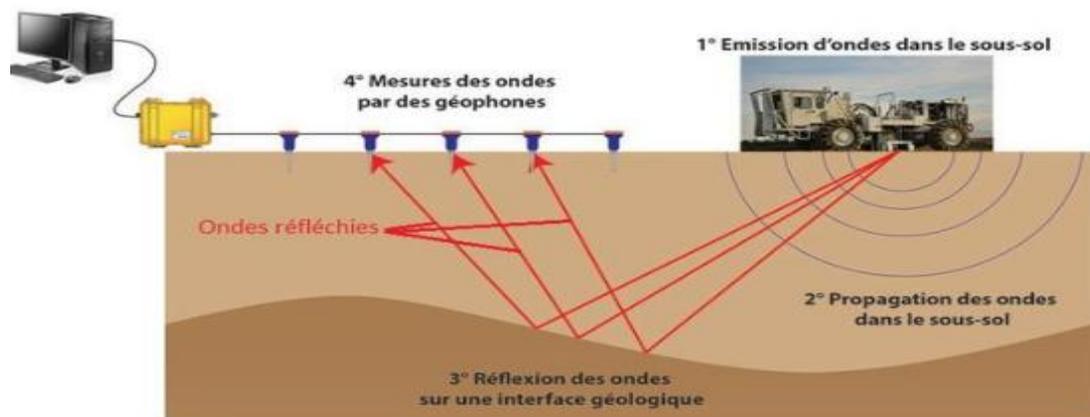
LE PRINCIPE DE LA SISMIQUE REFLEXION

Differences between the two methods:

Critère	Sismique de Réfraction	Sismique de Réflexion
Principe	Réfraction des ondes à l'interface de couches	Réflexion des ondes à l'interface de couches
Profondeur d'étude	Principalement utilisée pour les couches peu profondes	Permet d'étudier des structures géologiques profondes
Applications typiques	Géotechnique, cartographie des couches superficielles	Exploration pétrolière, gaz, et cartographie des structures géologiques profondes
Simplicité des interprétations	Relativement simple (l'onde suit une trajectoire prédéterminée)	Plus complexe, nécessite des traitements de données pour reconstruire les structures géologiques