Theoretical basis

1.1 Preface

The aim of the geophisical survey based on the seismic cone technique consists in the directly evaluation of the propagation velocities inside the subsoil of both compression (P) and shear (S) waves and in the indirectly assessment, by the means of the velocity values obtained, of the mechanical properties of the investigated lithologies. Through a sampling step usually set to 1 m, subsoil stratigraphy is determined.

The seismic cone technique involves placing a vibration source on the ground surface and the measurement of the waves by the seismic cone. The probe contains one 3- components geophones or accelerometers (1 vertical and 2 horizontal, orthogonal disposed)to discriminate between P and S waves. The vibration source is composed by beating hammer, which in the same time works as a starter, being linked by the means of a trigger to the seismograph. Execution involves a vertical blow, to generate P waves, and two horizontal blows, with pulse direction inverted, to produce S waves.

1.2 Interpretation

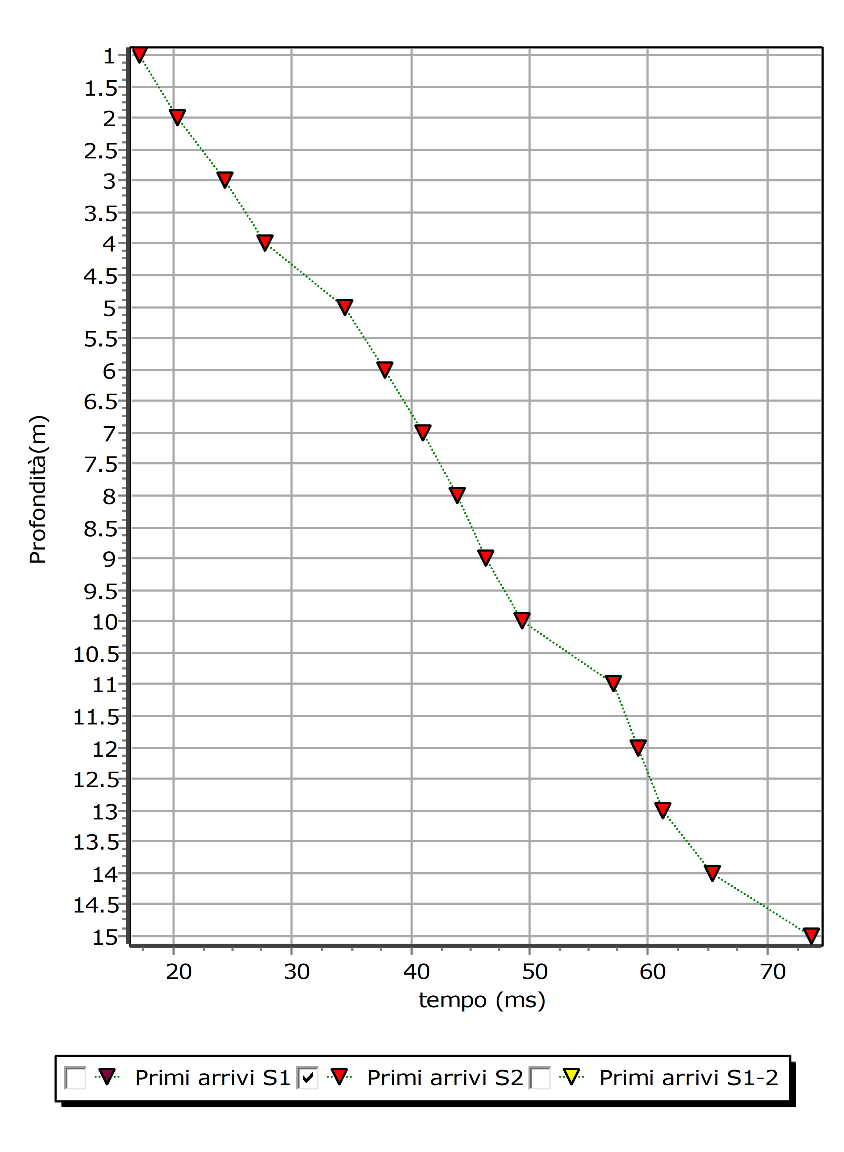
Analysis may be executed both in time and frequency domains.

In the time domain one has to proceed by picking the first arrivals both in the P wave and S wave traces. First arrivals have to be initially corrected as a function of surface source position. In case of homogeneous soil, correction assumes the following form:

$$t^* = \frac{z}{\sqrt{z^2 + x^2}} t$$

where z is the receiver depth, x is the horizontal distance between borehole and source and t the recorded arrival time.

Conversion from first arrivals to wave velocity (Vp and Vs) is performed, assessing the slope of the straight segment that joins the contiguous points, in the time-depth chart.



Time-depth chart

In alternativa si può procedere stimando la differenza dei tempi di arrivo in due posizioni successive del cono sismico. Siano t1 e t2 i tempi di arrivo misurati, eseguita la correzione in funzione della posizione delle sorgenti in superficie, la velocità di propagazione nell'intervallo Δs, con Δs = passo di campionamento, è data da:

$$V = \Delta s / (t2^* - t1^*) = \Delta s / \Delta t^*$$

La velocità V ricavata viene detta 'velocità di pseudo-intervallo'.

As an alternative one can proceed assessing the difference between the first arrivals in two contiguos positions of the probe. Being t1 and t2 the measured first arrivals, after executed the time corrections as a function of the source position, propagation velocities in the Δs interval, with Δs = sampling step, is given by:

$$V = \Delta s / (t2^* - t1^*) = \Delta s / \Delta t^*$$

The calculated velocity V is named 'pseudo-interval velocity'.
Still operating in time domain, dt variable may be obtained in a direct way, without executing the signal picking, by the Cross Correlation method. Cross correlation function is calculated summing the product of the signal amplitudes recorded by the two receivers, x(t) and y(t), progressively shifting one of them of a time interval τ, increasing it up to a maximum value equal to the total recording duration:

$$CC_{xy}(\tau) = \int_{-\infty}^{+\infty} x(t) \cdot y(t+\tau)\, dt$$

where time τ, in which the function reaches its maximum value, represents the time shifting undergone by the signal moving from the depth h to the depth h+Δs . Consequently velocity is given by:

$$V = \Delta s / \tau$$

As an alternative one may execute the interpretation in frequency domain too. By the means of the direct Fourier transform (FT), from the two recorded signals the corresponding Fourier spectra can be obtained, both the amplitude and phase ones. The the Cross Power Spectrum (CPS), defined as the product of the Fourier spectrum of the y(t) signal and the conjugate complex of the Fourier spectrum of the x(t) signal:

$$CPS_{yx}(f) = Y(f) \cdot X^{*}(f)$$

CPS vector is characterized by an amplitude A_{cps} and a phase ϕ_{cps}, respectively given by the product of the amplitudes e by the difference of the phases of the correspondent Fourier spectra of the signals x(t) and y(t).
Phase velocity V(f), as a function of frequency, is given by the following relationship::

$$V(f) = 360° \cdot \frac{\delta_{12}}{\phi_{CPS}(f)} \cdot f$$

where δ_{12} is the receiver spacing. The inverse Fourier transform of the CPS vector gives, in a more directly and efficient way, time τ, that is the time shifting undergone by the signal moving from depth h to depth h+Δs. In this case too, velocity is given by:

$$V = \Delta s / \tau$$

1.3 Geotechnical parameters

- LOW STRAIN PARAMETERS.

SHEAR MODULUS.

$$G(kPa) = \rho V_s^2$$

where:
ρ (kNs^2/m^4) = mass density = unit weight / g (9.81 m/s^2);
V_s (m/s) = S wave velocity.

BULK MODULUS.

$$M(kPa) = \rho\left(V_p^2 - \frac{4}{3}V_s^2\right)$$

where:
V_p (m/s) = P wave velocity.

OEDOMETRIC MODULUS.

$$E_{ed}(kPa) = \rho V_p^2$$

YOUNG MODULUS

$$E(kPa) = 2\rho V^s{}_2(1+\nu)$$

where:
ν = Poisson's ratio, given by:

$$\nu = \frac{\left[0.5\left(\frac{V_p}{V_s}\right)^2 - 1\right]}{\left(\frac{V_p}{V_s}\right)^2 - 1}$$

- HIGH STRAIN PARAMETERS

YOUNG MODULUS

E = 0.1877 Ey (Fahey & Carter, 1993):

where:

Ey(MPa) = low strain modulus.

PEAK ANGLE OF INTERNAL FRICTION

$$\varphi(°) = 3.9 V_{s1}^{0.44}$$ (Uzielli et al., 2013)

where: $V_{s1} = \frac{V_s}{\left(\frac{\sigma_v'}{\sigma_{atm}}\right)}$, and σ_v'= vertical effective lithostatic pressure σ_{atm} = atmospheric pressure = 9.81 kPa

UNDRAINED COHESION

$$c_u(kPa) = \left(\frac{V_s}{7.93}\right)^{1.59}$$ (Levesques et al., 2007),

R.Q.D.

$$RQD\% \approx 100\left(\frac{Vs}{Vs_{lab}}\right)^2$$

where:

Vs_{sito} = S wave velocity misured in the site;
Vs_{lab} = S wave velocity of the intact rock.