



OPERATIVE GUIDE REFRACTION SEISMIC

Refraction seismic procedure

- **Generals**

Refraction seismic is a widespread methodology that allows reconstruction of seismic velocities and subsoil geometries. For this reason it is widely used for geotechnical surveys (Signanini & Torrese, 2004), seismic micro-zonation (Rainone *et alii*, 2007), water research, environmental studies and static correction of reflection seismic surveys.

Regulations and reference specifications

ASTM D 5777 - 95 - Standard Guide for Using the Seismic Refraction Method for Subsurface Investigation

In refraction seismic prospection, different speed of longitudinal waves is exploited (**P waves** or "compression and expansion waves"), or transversal (**SH waves** or "shear waves"), to determine thickness and geometry of different seismic layers into the ground.

Superficial prospections of refraction seismic have no environmental impact (except when using explosive as energizing system), are less expensive and can cover wide areas.

Survey finds its best application field with depth of exploration of 40-50 meters and when results to obtained are of good quality and precision.

Recording is done through an array of geophones placed at regular intervals along investigation profile.

Spacing between geophones and their number depends from detail and target (required depth of investigation). P waves arrival time measure to each geophone allows to reconstruct trend and depth of refractors horizons present into the soil, and, in case of measurement of also secondary or shear waves (S), allows to compute elastic-dynamics characteristics of investigated soils and rocky mass.

Prospection consists of generating a seismic compression or shear wave into the soil through a determined energy source and then measure time taken to travel from energizing point to receivers (*geophones*) following rules of optical refraction (*Snell Rule*), that is thwarting on separation surface between two overlapping layers of increasing density (elastic module).

Necessary instrument consists of a series of receivers (geophones) placed at definite

spacing along an array (seismic base) and a seismograph which records starting instant of elastic perturbation and first arrival times of waves for each geophone. Therefore, observing first arrivals on points placed at different distances from energizing source, it is possible to build a time-distance curve (*dromochrone*) representing variation of minimum path according to time. Through analytics methods it is possible to get speed of longitudinal elastic waves (V_p) or transversal waves (V_s) of crossed means and their thickness.

LIMITS OF THE METHODOLOGY:

- a level can be underlined only if its longitudinal waves transmission speed will be higher than that of above levels (effect of speed inversion);
- a limited thickness level compared to geophone spacing and its depth can be not relevant;
- an intermediate speed level between an overlying layer of less speed and another below of higher speed can be not relevant because covered by "arrivals" of below layer (effect of hidden layer and "black area");
- when increasing spacing between geophones, also investigation depth increases, but obviously precision in determining depth of passage limits between all different levels can decrease. In presence of a series of levels with speeds (increasing) slightly different one another, intermediate speed horizons with power at 1/3 of used spacing can be ignored. Limit between two horizons can pass "through" 1/3 not highlighted;
- similarly, gradual speed increasing with depth generate dromochrones which allow more than one interpretation. Possible error can be reduced if calibration surveys are available and "searching for" layers seismic basis dromochrones with speeds as much as possible similar to that obtained with calibration.

INSTRUMENT FOR REFRACTION SEISMIC

A6000S, Sysmatrack, X610S

- **Recording modality**

More in detail, to perform test it is necessary to have at least the following equipment:

- seismograph with at least 24 channels, with possibility of seismic pulses stack, analogical and digital filters which can be configured (active filters such as high pass, band pass and



band reject), signal vertical gain (in amplitude) and sensitivity between 6 and 92 decibel, digital data registration for following elaborations with output format at 16 bit minimum;

- 24 receivers (12 receivers) :
 - for P waves, vertical geophones with proper frequency within 8 and 40 Hz;
 - for S waves, horizontal geophones with proper frequency within 8- 14 Hz;
- energization system proper to length of the array to perform; it can be made of:
 - instrumented hammer let fall powerfully on a metallic plate placed on the ground;
 - seismic cannon;
 - oleo-pneumatical and/or gravimeters oleo-pneumatic energizers and/or pulled or transported gravimeters;
 - explosive charges.

Choice of the type of energization depends on investigation site features and on the analysis of cost/benefits; more stronger it is, the more benefits will be in terms of signal/noise ratio and signal quality.

It is necessary that system allows to determine irrefutably first arrivals after few stacks (maximum 5) on all receivers on the array.

- STARTER for acquisition: trigger is made of an electric circuit closed through a starter geophone in the instant when energizing system (guns, mallet, hammer...) hits hammering base so starting recording.

Refraction seismic array must be preceded by evaluation of the target to reach, according to which best geometric configuration with proper length and number of shots are chosen. Generally for each array maximum depth of seismic prospection depends on seismic velocities of each layer and the length of seismic shots.

Indicatively spacing between geophones can vary within 1/4 and 1/5 of target depth and at least 3 energizations are necessary (direct, central and inverse).

Distance between shot point and geophones substantially regulates investigation depth. The bigger this length is, the deeper the investigation will be. Of course if distance is increased too much, input energy (source) must be stronger.

After a preventive visit onsite to check eventual logistic problems for placing of geophones,

shot points and instrument necessary for the analysis, it is possible to prepare array.

Particular care must be paid to geophones placing (geophonic coupling) and shot points.

Number of shots for each seismic line can be a minimum of 3 (direct, inverse and central hammering) up to a maximum of 9, according to accuracy with which user wants to reconstruct final section, investigated materials and array cable length.

External shots usually are done at a distance from the first geophone equal at least to spacing between each geophone; to check reciprocity between direct and inverse shots, it is possible to consider two more external shots at longer distance, for example 3-4 times receivers offset.

Generally speaking, for arrays shorter than 100 mt, also 5-7 shot points can give good results.

When recording P waves, if on natural soil, place hammering plate in the most adherent to soil and horizontal position possible; in presence of cement, use of a rubber towel it is recommended to reduce high frequencies and register a more clear signal.

For long arrays, if industrial or explosive gun is used, charge is exploded at the bottom of a pre-hole properly made in depth according to target of investigation (usually depth of 0.5-1 mt is enough).

For SH waves generation a wooden or polyethylene parallelepiped is normally used, with a shape that can be hit on both sides with an heavy mass; main axis of source system must be placed orthogonally to array direction.

It is important that parallelepiped is graved by an additional static load especially when it is hit, so that wave train generated is dissolved as less as possible. A good pairing is obtained on soils with fine grain size; in case of coarse soils of rough surfaces, it is recommended to include a layer of fine soil such as sand.

For the correct determination of shear waves, when there are no specific sensors, it is necessary to perform also combined recording (reversed of 180° on horizontal plain compared to array direction); in this way it will be possible to correctly determine shear wave arrival (where there will be phase inversion) on seismograph.

Once connected geophones to cables, and cables to instrument, parameters can be set and recording phase can start.

INSTRUMENT FOR REFRACTION SEISMIC : A6000S, Sysmatrack, X610-

Parameters to set are mainly referred to recording length and sampling interval, and can be set through configuration screen.

In that screen it is possible:

- to set number of channels (geophones) and then save. This number refers to consecutive channels from the first and it does not depend on the selection operated into geophones visualization section. Select which channel to visualize on the display (by thickening each box, corresponding channel is visualized).
- to set number of samples to record. It is possible to select number of pages taking into account that each page is made of 512 points (a point represents a sample).
- to select sampling frequency, that is the number of times that signal coming from geophones is sampled in a second. Given that number of samples that can be recorded is settable, but constant, it is possible to select between higher temporal resolution in signal reading (high frequency) and a longer acquisition period (lower frequency).

It is recommended to use 8 pages to record single files of refraction seismic.

- set trigger sensitivity, that is threshold value after which acquisition starts. Moving cursor in different positions, it is possible to read below corresponding value of threshold expressed in mV. The lower this value is, the more sensitive to trigger signal the instrument will be. A sensitivity of 208 mV can be relevant.
- Pre-trigger: usually can be deactivated or at least set at 5-10 ms.

- **Sampling frequency:** at least 7500 samples per second
- **Pages number:** 8 (4096 samples)
- **Trigger sensitivity:** 208 mV
- **Pre-trigger:** deactivated or 5-10 ms
- **Gain:** increasing from closest to furthest geophone to shot point

In Gain screen it is possible to create groups of geophone in order to change amplification simultaneously and with the same value for each geophone belonging to groups.

Moreover it is possible to set amplification for each single channel with no concern for belonging group. CONFIGURATION button allows to go back to previous menu.

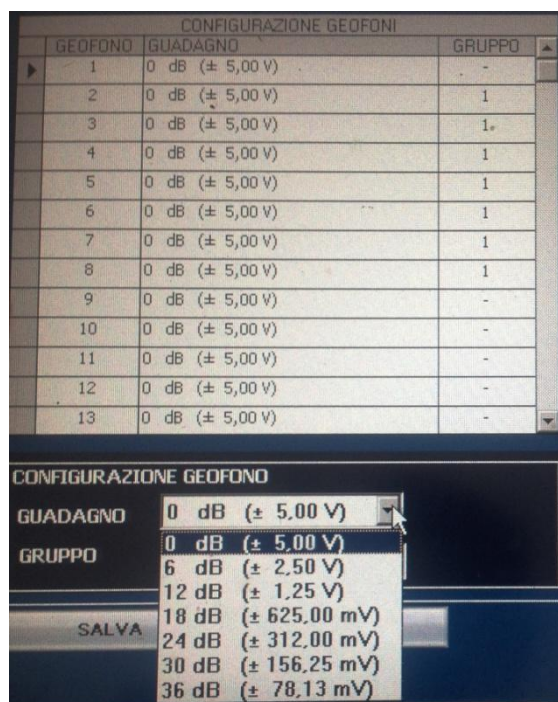
It is possible to set up to 9 different groups labeled with progressive number. Association of a particular geophone to a group can be done by simply selecting channel in left table and,

from menu named GROUP, select belonging group. Once concluded that operation, on the right side of the screen, a summarizing table for existing groups is visualized.

At this point it is possible to give amplification value to the whole group or the single geophone with following steps:

- Select channel in right table or the group in left table
- Select amplification from below drop down menu.

Last operation prevails on previous therefore if gain of a particular channel belonging to a group is modified, just select it and give required amplification.



Usually for not very long arrays, with direct shot acquisition it is recommended a configuration with increasing groups as in picture.

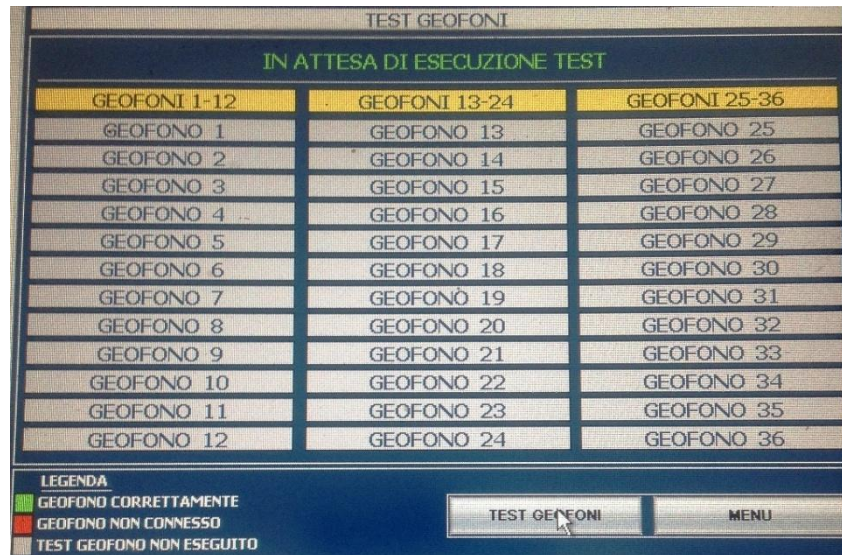
CONFIGURAZIONE GRUPPI			
	GRUPPO	GUADAGNO	GEOFONI
	1	0 dB (± 5,00 V)	2,3,4,5,6,7,8,1
	2	6 dB (± 2,50 V)	9,10,11,12,15,1
	3	12 dB (± 1,25 V)	17,18,19,20,21,

Once connected arrays to geophones, before starting measurement it is recommended to do a preventive checking on connections.

This operation is automatically performed by instrument by simply accessing GEOPHONES TEST menu.

Once concluded the test, working geophones are colored in green while not working in

red. It is recommended to solve any eventual malfunctions by checking connection and its functionality.



In this menu it is possible to analyze background noise detected from geophones when energization is not present. In the screen that will be visualized, all channels selected in configuration menu are present. Consecutive acquisitions will be performed without waiting for trigger signal and so visualization won't be fluid due to waiting for acquisition memory filling.

It is possible to perform a measurement by clicking on ACQUISITION button or go back to main menu with STOP button.

By clicking ACQUISITION button in main menu, instrument waits for trigger signal. Once detected it, after few seconds, a screen showing captured signals will appear.

SH waves recordings will be performed with cross-over method through polarity inversion tool offered by instrument, that is doing difference among same number of hammerings on right and left with polarity: in this way, first arrival instant of SH waves is underlined while any eventual P spurious waves are deleted.

Further to seismic survey, a topographical measure shall be performed with determination of plain-height of geophones, referring to notable points or known cartographical elements for investigated area; it can be enough to express it in relative coordinates.

Modern methods of seismic data elaboration, such as the Generalized Reciprocal Method

(GRM: Palmer - 1980), Delay time and Intercepts Times Method, allow to reconstruct buried morphology of more overlapped refractors, variously “rough” and with variable speeds along the profile, even in presence of surface morphologies which are not plain: good precision, especially if there are calibration surveys, allows to turn seismic prospection from simple qualitative evaluation into valid quantitative support to geognostic survey.

Recorded files can be processed also through subsoil modeling on anisotropic base, that is tomographic technique which will provide an elaboration with inversion iterative methodologies such as R.T.C. (Ray Tracing Curvi-linear) and tomographic reconstruction algorithms (algorithms ART - Algebraic Reconstruction Technique, SIRT - Simultaneous Iterative Reconstruction Technique or ILST - Iterative Least Square Technique).

Seismic tomography limits problems caused by layers of speed inversion (ghost layer) or reduced thickness and improves results that can be obtained by traditional methodology, increasing effectiveness in reconstructing subsoil; it is useful in complex situations such as geometry of landslides and detection of buried structures.

From executive point of view, test is performed similarly to traditional test but to ensure better coverage, more energizations internal to array must be considered.

Generally speaking, inversion process consists in generating an initial simplified model and then model waves arrival times are computed and compared to recorded measurements. Model is updated according to errors and test is repeated iteratively until reliable threshold is obtained.

Operations on field are described below.

Lay metric rib for the required length and fix geophones at established spacing; they must be well-fixed into the ground so that signal/noise ratio is improved.

If both P and SH waves must be recorded, it is recommended to fix both geophones for example on right and left of metric rib.

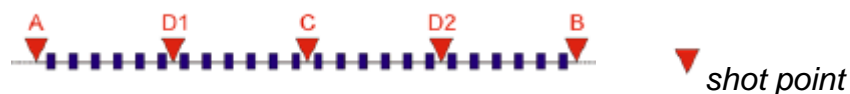
Once placed geophones, they must be connected to cables respecting plugs dimensions which give polarity (big with big and small with small). Metallic connections must not touch the ground or other surfaces especially if wet.

Each cable has 12 takeouts. Seismic cable connector must easily reach seismograph to which it will be connected.

Regarding instrument position, it must be central between 1-12 and 13-24 cables as shown in picture.

It is recommended to prepare shot points before starting acquisition especially for internal shots and for generation of SH waves.

A widely used configuration for not very long arrays requires 5 shot points, 2 external and 3 internal. By using this configuration, it is recommended to place intermediate shots (D1 and D2 in picture) between the 6° and the 7° receiver and between 18° and 19°. Middle shots (C) will be done between 12° and 13° geophone, while direct (A) and inverse (B) at beginning and end of the line.



Once connected receivers and cables to instrument, bring starter geophone (*trigger*) where shot shall be done and connect starter to extension cable which will be connected to the instrument. Finally place *trigger* at about 5-10 cm from energization point.

When dealing with paved ground, asphalt, cement or when it is difficult to fix geophones, aluminum tripods will be used, in order to ensure good sensitivity to receivers.



Once completed line mounting, it is possible to access seismograph and patiently wait automatic starting phase of acquisition *software*; it is recommended to advise second staff person to prepare for shot.

Once set instrument as indicated in previous paragraph and performed geophones test, acquisition operations can start.

At the end of each shot, a .seg2 file will be saved, so once finished survey there will be 5 files for P waves and 5 for SH waves.

Survey starts with direct shot (A) and signal restitution on seismograph is observed, so as to acknowledge possible precautions in following operations and to improve recorded track.

If first arrival signal is clear on farthest receiver (24°) it is possible to record other shots.

In case a better definition of first arrival phase is required, as described previously, it is possible to increase gain; usually it is increased in a progressive way towards farthest geophones.

In case there are problems of signal saturation, especially on channels close to the source, gain can be reduced. In fast soils, even selecting 0db reliable traces are obtained.

In any case, if signal coming from a single energization results “weak” and/or of difficult interpretation, it is possible to proceed to an iteration with another shot and adding new energy to all channels. If it is required to sum up on traces a further shot, it is possible to do another iteration until a signal with clear first arrival is obtained.

Once user is sure to have recorded a good seismic trace for the considered *shot*, file can be saved and it is possible to move to D1 intermediate point.

Reconnect trigger and proceed to energization.

Take into account recommendations listed above before saving file.

Move to shot points C, D2 and B and record related field traces.

Seismic refraction line in P waves is now ready to be processed.

Similarly to P waves acquisition phase, also SH waves acquisition is performed.

Configuration parameters can remain the same although it is recommended to increase time of acquisition setting an higher number of pages (ex n°10).

In some *shots* which are considered significant, especially where there are disturbed traces and first arrival is not clear, it is possible to operate through polarity inversion by energizing SH source with direct (S+) and inverse (S-) polarization on parallelepiped

sides, in order to better evaluate shear wave first arrival deleting any eventual influence from faster longitudinal waves arrival; these can be more or less evident according to SH source efficiency.

To save file with polarity inversion, in iteration process difference option on considered channels must be executed.

Please remember that during acquisition phase of SH waves, a good soil-parallelepiped pairing is important.

- **Elaboration**

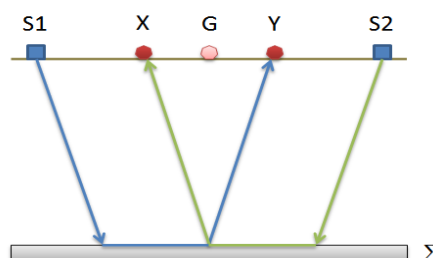
Interpretation of detected signals and later estimation of resulting seismic section mainly consist of:

- First phase of individuation of first arrival through seismographs observation and picking operation with proper analysis and signal filterings;
- Second phase represented by dromochrones reconstruction and related interpretation to reconstruct subsoil model (Delay-time, GRM, intercept time).

Once saved different files in .Sg2 format, each one for a shot point, it is possible to analyse them by importing into dedicated *software PSLab* where they will be properly elaborated and interpreted.

PsLab software uses Generalized Reciprocal Method discussed by Palmer in 1980.

The method is based on the research of virtual spacing between geophones XY so that seismic rays starting from energization points symmetric to the array, arrive to the geophone placed in X position and that one placed in Y position, coming from the same point of refractor.



First operative step is building a diagram time-distance by individuation of seismic waves

first arrivals into resulting seismograms. To determine optimal XY distance is necessary to consider more shot points at extremes and in the middle of the array. It allows to better individuate times related to the same refractor which are useful to characterize dromochrones, important for the interpretation.

From dromochrones reconstruction it is possible to determine, through some equations, speed function and through time-depth function it is possible to find refractor depth expressed in time units. Finally, through a relation it is possible to determine thickness of the refractor in order to reconstruct a seismic-stratigraphical section.

One of the main advantages of G.R.M. elaboration method is that depth conversion factor is relatively insensitive to inclinations up to about 20°.

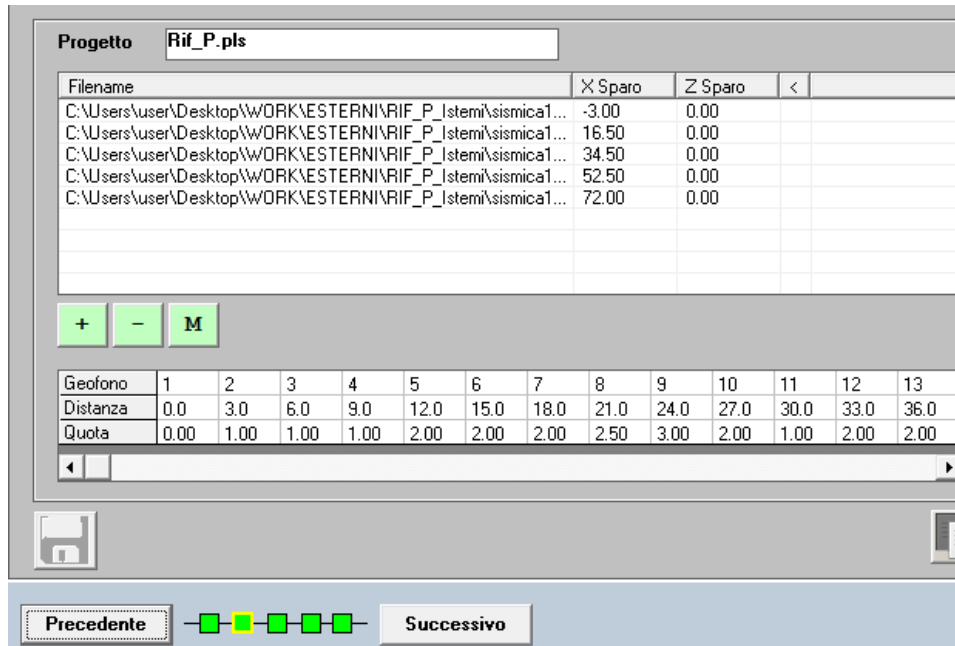
When starting program and selected surface analysis, work project is created with **.pls** extension which can be saved in a particular path.

Through five main steps user will be guided into elaboration procedure which, starting from field data, allows to get final seismic section and a detailed report, complete with graphics and tables.

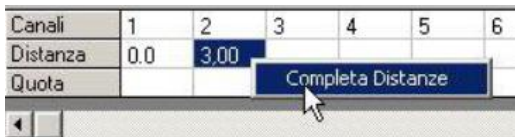


Field files must be uploaded by clicking on adding button (+).When importing file of specific shot, user must specify distance and altitude in order to set exact geometry of the array.

In picture there is an example in which seismic survey was performed with 5 shots and an offset of 3 mt.



Once concluded process of inserting files .Seg2, it is necessary to save project and move to following step, where it will be possible to visualize all different recorded traces and perform first arrival picking.



To enter geophones distance, just enter in geophone 2 its distance from geophone 1 and then click mouse right button and select Complete Distances.

On the screen "First arrival research" inserted .Seg2 files will be listed followed by a circle colored in red if that file has no picking, or colored in green if picking was concluded.

Intermediate *shots* will be divided into two screens of separate seismographs in order to allow a better comparison with all shots on the left (SX) and on the right (DX) of shot point.

Clicking on file SEG2 name, screen with all seismograms will be opened.

FIRST ARRIVALS RESEARCH

RICERCA PRIMI ARRIVI		
N.	File	
1	sismica1_0.sg2	●
2	sismica1_20.sg2 [SX]	●
3	sismica1_20.sg2 [DX]	●
4	sismica1_40.sg2 [SX]	●
5	sismica1_40.sg2 [DX]	●
6	sismica1_60.sg2 [SX]	●
7	sismica1_60.sg2 [DX]	●
8	sismica1_80.sg2	●

Once opened recorded traces screen, it is possible to start first arrivals individuation; to facilitate operation some tools can be used, such as offset removal, equalize or underline required phase (positive, negative, none) and zoom each single channel to make wave more clear and to better select picking.

Zoom tool on each single channel is activated by placing cursor on seismogram to analyse, clicking right button of the mouse and selecting ACTIVATE ZOOM. To go back to total visualization, select DEACTIVATE ZOOM.



Picking is simply performed by placing cursor on the point considered first arrival of seismic pulse on the considered channel and doing double click with mouse to which a red line is assigned. Line will indicate first arrival time.

After picking on all uploaded files .Seg2, it is possible to check first arrivals in summary table:

FIRST ARRIVALS TABLE

TABELLA PRIMI ARRIVI							
	-3.00	16.50	34.50	52.50	72.00		
0.0 mt.	13.33	22.00	45.20	59.47	40.53		
3.0 mt.	18.67	18.80	41.20	58.40	39.20		
6.0 mt.	22.67	14.80	38.40	55.73	38.13		
9.0 mt.	26.67	8.00	34.00	53.60	36.93		
12.0 mt.	36.00	7.20	28.40	51.47	36.00		
15.0 mt.	39.33	2.80	26.00	48.80	35.47		
18.0 mt.	46.67	3.33	20.00	47.20	34.00		
21.0 mt.	53.33	8.53	13.60	44.80	32.40		
24.0 mt.	58.00	11.47	11.20	42.40	31.07		
27.0 mt.	61.33	13.73	7.60	39.47	30.40		
30.0 mt.	62.67	16.80	4.80	36.53	28.93		
33.0 mt.	64.67	20.00	1.20	31.47	27.33		
36.0 mt.	68.67	23.47	1.60	28.80	26.00		
39.0 mt.	70.00	26.13	6.93	25.60	24.93		
42.0 mt.	71.33	28.67	10.80	19.73	23.07		

In horizontal heading, distances of shot points are detailed while in vertical one geophones distance is detailed. Therefore each column identifies an acquisition and each line a geophone.

Times detailed in table can be manually changed by entering Edit mode (yellow cell). It is recommended to always save changings after acting on picking or times in manual mode.

Final phase of data processing consists in define Dromochrones and so calculate resulting G.R.M. section.

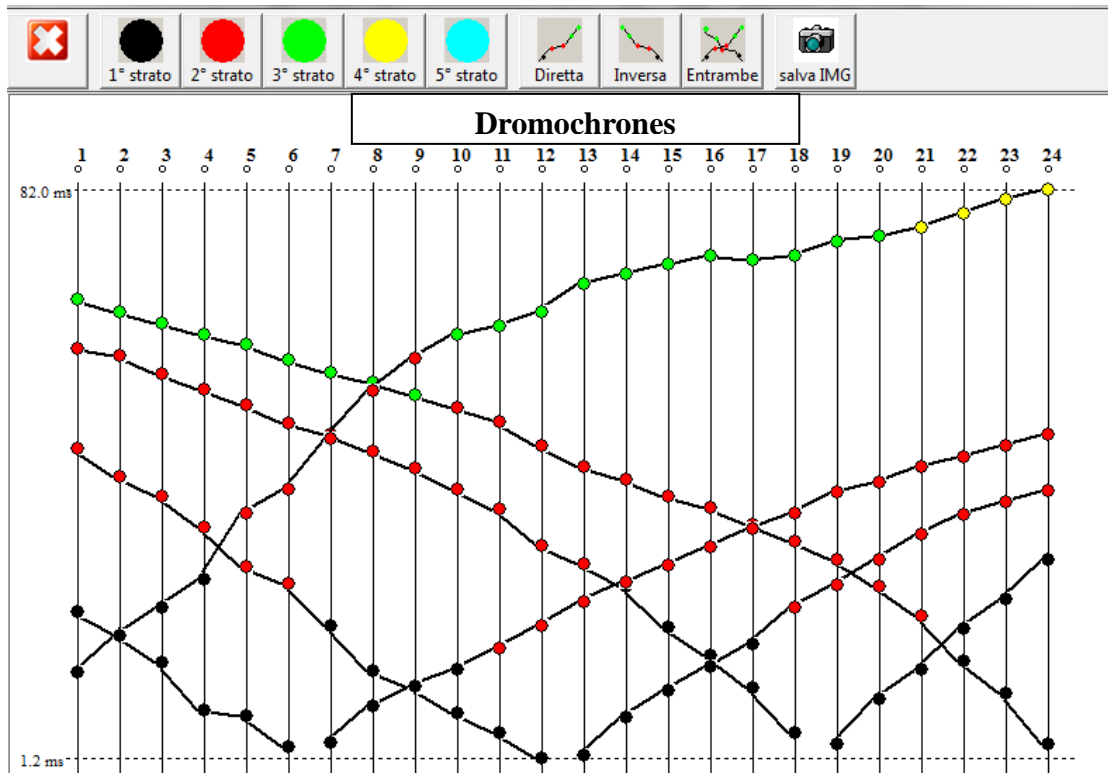
User must estimate analysed subsoil layers; it is recommended to get some stratigraphic information along section that will be reproduced in order to improve uncertainty caused by the sole seismic survey and sole first arrival times.

A quick comparison on recorded data reliability can be done among times related to different shots, especially direct and inverse, and related "knee" points that can be visualized in Dromochrones.

Slope changings of time-distance curves (dromochrones) called "knees" represent a different time response of seismic signal to each single receiver and so they indicate a

possible changing of investigated material, in other words a different seismic layer.

Knowledge of subsoil and depth of lito-stratigraphical contacts along array will help user to select and assign single layers and main refractors that will generate final refraction seismic section.



Balls different colors which identify each receiver for each shot point, correspond to different layers assigned; they are assigned by selecting from top bar required layer and placing cursor on corresponding point in dromochrone graphic.

Elaboration with PsLab software ends by clicking on button G.R.M. computing, through which resulting seismic section is visualized and seismic layers depth together with seismic velocities are shown.

