

Integrated refraction seismics and tomographic study of a gravitational collapse phenomenon

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ABSTRACT The aim of this work is to create and test an automatic procedure to define an accurate subsurface velocity model by using the first arrivals in the case of seismic acquisition of a large quantity of data. We developed an integrated procedure involving conventional refraction analysis and joint tomography of the direct (diving waves) and refracted arrivals (head waves). We can thus obtain 3D velocity models which yield detailed images of subsoil structure, and allow to define reliable geological-geophysical models of use to mitigate landslide phenomena. We tested the procedure in an area affected by gravitational collapse located in north-eastern Italy, in the Dolomites near the city of Belluno; the application of the proposed method allowed the definition of the depth and shape of the bedrock horizon.

Key words: velocity model, tomography, refraction analysis.

1. Introduction

This paper describes the theoretical and operational methods of geophysical surveys carried out under the convention between the Department of Soil Defense of the Veneto Region and the National Institute of Oceanography and Experimental Geophysics in Trieste (OGS).

The method proposed in this work combines refraction tomography with classical refraction analysis by using the first arrivals picked on seismic data. Standard refraction processing uses different methods to estimate 2-D subsurface velocity model such as the Plus-Minus method (Hagedoorn, 1959) or the generalized reciprocal method [GRM: Palmer (1986)]. These methods, which need a specific designed survey (reciprocal arrivals), provide a rough estimate of the subsurface velocity and structure, and in general they suffer the presence of strong lateral velocity variations. On the other hand, refraction tomography (both from diving and head waves) may give more detailed depth models even in presence of complex velocity structures, but its dependency on the initial model can decrease in some cases the reliability of the inversion. In this respect, we can use the model obtained from classical refraction analysis as initial model for tomography of the refracted arrivals in order to avoid this possible drawback.

Mari and Mendes (2010) designed a similar procedure to investigate the subsurface structures. They applied Plus-Minus method to create a preliminary velocity model then used as initial guess for the refraction tomography based on diving ray-paths.

Unlike general use in refraction processing, in this work we applied the time intercept method, because it gives more flexibility in acquisition planning; in fact, it does not need reciprocal times, which, in this case, cannot be extracted in all the acquired lines of the survey, due to irregular

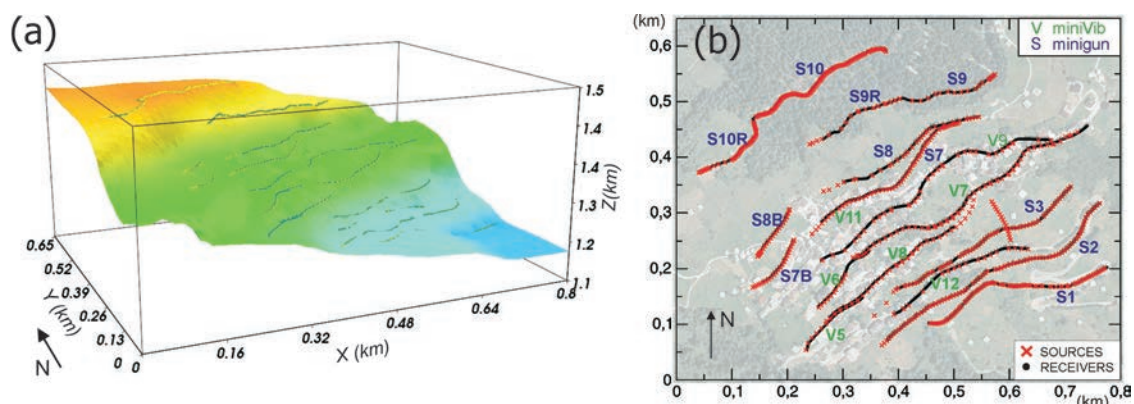


Fig. 1 - Location of the seismic lines acquired in the investigated area: a) 3D view of the topographic surface; b) a plane view of the acquisition.

positions of the receivers. In the tomography step, we inverted both diving and refracted from head wave arrivals by using an automatic procedure to identify and separate the different kind of picked data. Furthermore, all these travel times are jointly inverted in order to increase the reliability of the results obtaining a more accurate final velocity model (Böhm *et al.*, 2006).

After a geologic characterization of the studied area and the description of the seismic survey, we describe the proposed method in details and show the results of its application in the real test site.

2. Geology of the test area

The area of investigation, located near the village of Costalta (Belluno, northern Italy), is affected by phenomena of gravitational collapse that caused damage on several buildings and infrastructures in this area. From a geological point of view the substrate is composed almost exclusively of lithotypes of the phyllitic complex of the crystalline basement that rests over the Quaternary cover. The basement is fractured and altered and in some areas it crops out (as along the north-eastern border of the village). The available information shows that the top of the substrate is placed at a maximum depth of 25-30 m below the topographic surface, even if the stratigraphic information indicates the presence of unconsolidated levels at greater depth. Such levels could be caused by fractures and alteration of the substrate composition. The Quaternary cover has different origins with a prevalence of materials derived from colluviums and slope debris, or materials resulting from grinding and transformation of the phyllitic complex in a fine-grained matrix. There are also glacial deposits in various guises, ascribable to the lateral moraines of the Piave glacier that repeatedly occupied the valley during advances and retreats of the glacier front.

3. Data acquisition

The seismic data used for this analysis are part of a seismic survey acquired in the area of Costalta, comprising 14 2D lines, sub-parallel to each other in the SW-NE direction, within a rectangular area of 800x600 m (Fig. 1) including the entire village of Costalta and the surrounding area. A test phase

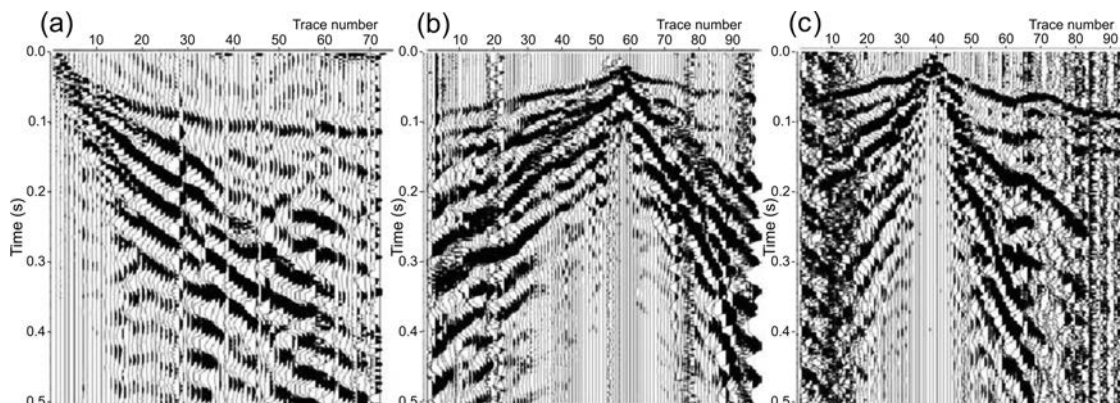


Fig. 2- Examples of seismic records: a) vibratory source, Line V6; b) impulsive source, Line S8, with bullet in the soil; c) impulsive source, Line S10, with bullet on plate.

preceded data acquisition to select the optimum geometric and recording parameters.

The seismic data were acquired with two different systems: lines on paved roads (lines V5 to V9, V11 and V12 in Fig.1), with a 72-channel Land Streamer and a vibratory source IVI miniVib; lines on soft soil or dirt roads with nail geophones (24 to 96 channels) and an impulsive source (mini-gun) (lines S1 to S3 and S7 to S10 in Fig.1).

Fig. 2 shows some examples of records obtained from different sources.

The seismic acquisition was rather complex due to logistical difficulties caused by strong topographic gradients and very difficult access.

The in-line spacing of receiver stations was 2.0 m for all lines, while the sources were spaced from 12.0 m to 3.0 m apart, depending on logistic conditions and desired coverage. Almost 65,000 first breaks, picked from more than 700 shots distributed on 12 lines, were used for the travel time tomography.

4. The method

Tomographic analysis of large number of seismic records (over 10,000) faces a crucial problem of data management, in particular in the interpretative part and in the picking of the travel times to be inverted. Many automatic tools for first break picking are presently available in software packages, which can reduce processing times but cannot distinguish different arrivals.

We developed an integrated procedure involving conventional refraction analysis and joint tomography of direct arrivals (diving waves) and refracted arrivals (head waves), which also include automatic tools to recognize the travel times associated with these different arrivals. It can be summarized in the following steps:

1. analysis of the apparent velocity graph, of all the picked data, and removal of the records affected by velocity errors greater than a threshold (Fig. 3);
2. automatic identification of the cross-over distance for each shot gather, defined as the separation point between direct arrivals (diving waves) and refracted arrivals (head waves) (Fig. 4);

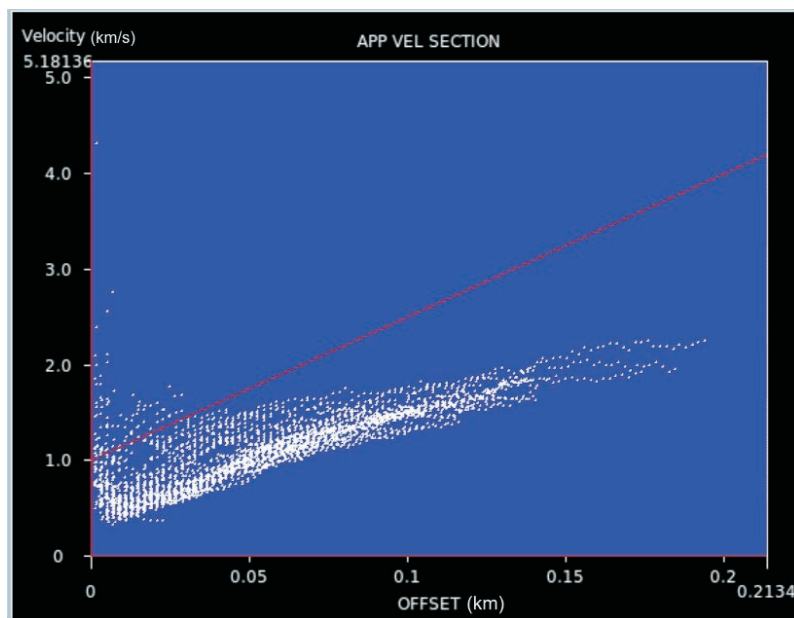


Fig. 3 - Velocity vs. offset computed from the picked travel times ($\text{velocity} = \text{offset} / \text{time}$). The points above the red line are eliminated from the data.

3. tomographic inversion of direct arrivals only;
4. definition of the surface from which the head waves are generated, by using the slope and intercept times of dromochrones and by applying the classical formulae of refraction analysis. The velocity of the layer above the refraction surface was obtained from inversion of direct arrivals computed in the previous step;
5. eventual static corrections of refracted arrivals by using the velocities obtained in the previous steps;
6. tomography of the refracted events (head waves), by using as initial model the surface and the velocity field defined in the previous step;
7. joint inversion of direct and refracted arrivals;
8. null space map and travel time residual analysis.

The first step concerns the test on data quality executed through the computation of apparent velocity, obtained by the ratio of distance (offset) over arrival time (Fig. 3). From the corresponding plot (velocity vs. offset), we identify and remove data which have unrealistic velocities (too high) or records associated with very short offsets, which are more sensitive to small time errors in the picking steps.

The identification of the cross-over distance is computed for all the shot gathers by applying an automatic procedure. From a geometrical point of view it represents the first significant bending point (knee point) of the offset-time curve (dromochrone). The definition of this point is done by seeking the first minimum of the second derivative of the curve obtained by using sliding windows, with different samples, along the offset of the curve and approximated by a polynomial fit (Fig. 4).

The travel times selected before the cross-over point are inverted as direct arrivals by using the diving ray paths. This leads to a detailed reconstruction of the P-wave velocity distribution in the

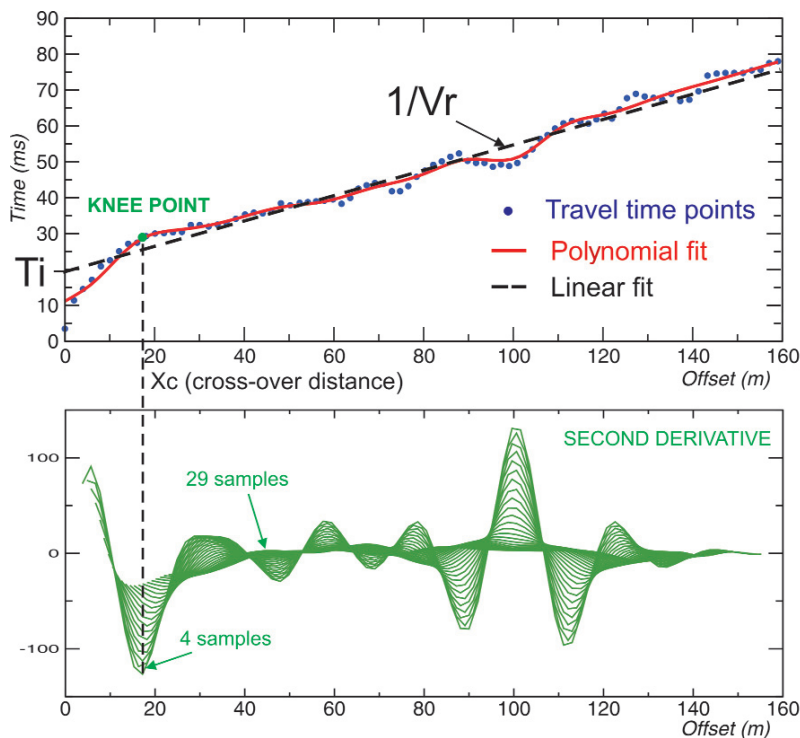


Fig. 4 - Example of knee point definition on the offset-time curve in a common shot gather (above). The second derivative (below) is computed with different sample windows, from 4 to 29 samples.

shallower part of the model, which will be used in the following steps as velocity of the unconsolidated layer.

The estimation of the depth of the refractor is made using the classical refraction formula:

$$Z = T_{int} \frac{V_R V_0}{\sqrt{(V_R^2 - V_0^2)}} \tag{1}$$

where V_R was obtained from the slope of the straight line that fits the time-offset dromochrone (ang. coeff. = $1 / V_R$), T_{int} is the time intercept associated with the same line, and V_0 is the velocity of the upper layer obtained from the inversion of direct arrivals.

In areas of complex topography, it is necessary to apply a static correction to first arrivals in order to define more accurately the slope of the offset-time curve on refracted arrivals. In this case in fact, as shown in Fig. 5, the velocity of the refractor, obtained from the linear fit of the black dromochrone, could be wrong. The correction is computed by defining a horizontal plane (datum) between the free surface and the refractor. The depth of this horizon is estimated by using the same formulae described above applied to the travel times without static corrections. Each static is computed on the segment of the ray that comes out from the datum to the receiver (blue arrow) rather than on the vertical path (red arrow) that would lead to an inaccurate correction. The output angle is estimated by applying Snell's law and by using the velocity field obtained from the inversion of direct arrivals and the velocity obtained from the slope of the refractor

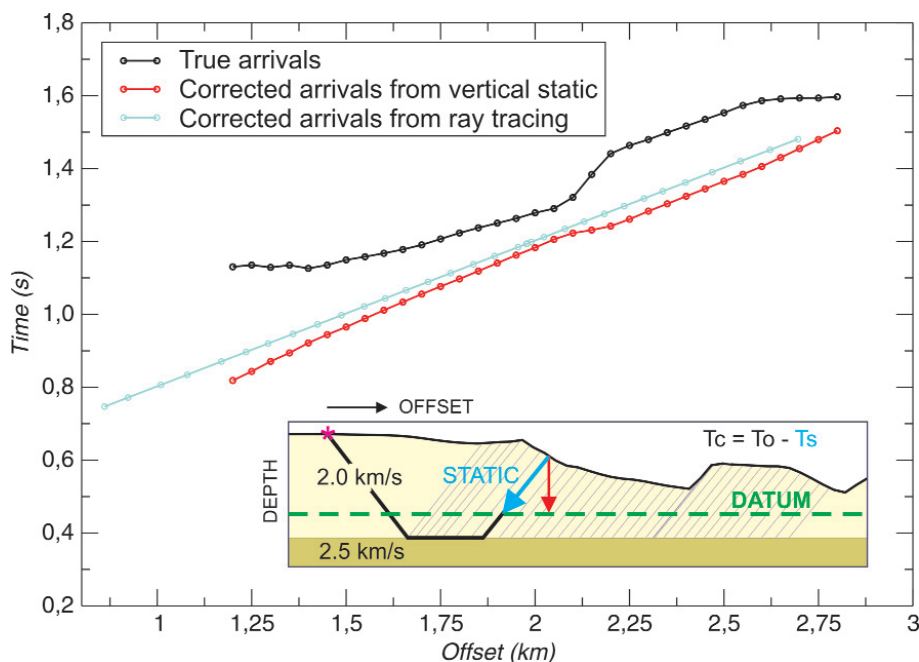


Fig. 5 - Static correction applied in a common shot gather to detect the correct slope (inverse of velocity) of the dromochrones associated with refracted arrivals.

dromochrone. The leftward shift of the corrected points is due to the fact that offsets are associated with the points of the ray leaving the datum and not with the corresponding receiver.

Regarding tomographic inversion (steps 3, 6 and 7), we used the software *Cat3D*, based on the SIRT method [Simultaneous Iterative Reconstruction Technique: Gilbert (1972)] and minimum-time ray tracing (Böhm *et al.*, 1999). It estimates the velocity field and the position of the refractor horizons. It uses an iterative procedure starting from an initial model that can be defined as a constant velocity field and horizontal flat interfaces. In each iteration, firstly it inverts the picked travel times (refracted events) and updates the velocity model, then it estimates the new interface by following the principle of minimum dispersion of refracted points; the travel time residual associated with each refracted event is converted into depth by using the velocity field updated in the first step of any iteration. The new interface is defined by interpolating all the new estimated refraction points (Vesnaver *et al.*, 1999).

In the velocity estimation, we applied the staggered grid method (Vesnaver and Böhm, 2000), which is a procedure to optimize the grid used in the inversion. It averages the velocity values obtained from different inversions of a regular coarse grid slightly shifted in space. Staggered grids can reduce the ambiguities and instabilities of the tomographic imaging; the method combines the advantages of low-resolution grids (the inversion of which is fast and stable) with the desired high resolution of seismic data processing.

To conclude the procedure, a joint inversion of the direct and refracted arrivals is performed (Fig. 6). All picked data are inverted together by using, as initial guess, the model obtained from the inversion of the refracted arrivals and adding some additional horizons in the layer above the

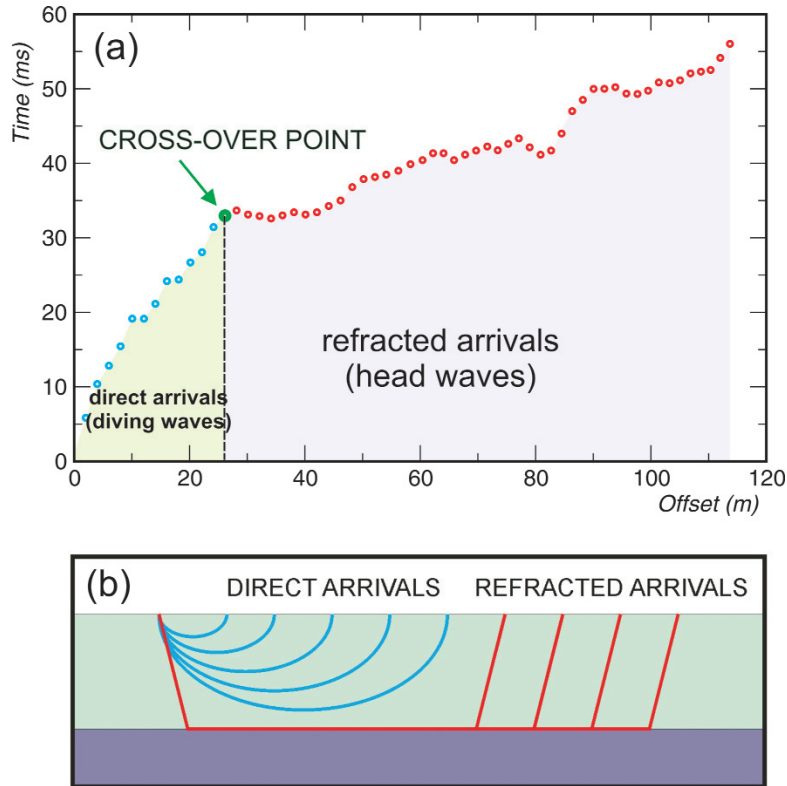


Fig. 6 - Joint inversion of direct and refracted arrivals: a) the different arrivals from the first breaks picked on a single shot; b) the corresponding ray paths.

refractor horizon, in order to detect the presence of a possible vertical gradient of velocity above the refractor. Furthermore, the joint inversion allows us to define more precisely the whole model involved in the inversion, because of the tomographic matrix which contains the information of both (refracted and direct) ray paths (Böhm *et al.*, 2006).

As a measure of the reliability of the tomographic results, a null space map and a time residual analysis are computed. The distribution of the null space on the discretized area represents the best measure of the reliability of tomographic system (Vesnaver, 1994), which relates the ray paths' distribution with the grid chosen to discretize the investigated area; it is obtained from the singular values decomposition of the tomographic matrix but it could be very expensive in terms of computation time. Time residual, which is the difference between observed data (picking) and the travel times obtained from the final model, is the best estimate of the goodness of the tomographic velocity field, and it is considered as the cheaper way to test the reliability of inversion. The time differences were reported as a percentage on the observed data, from which we computed the rms (root mean square) value for each inversion.

5. Data inversion

After evaluating the quality of picked data by the velocity vs. offset plot (Fig. 3), we defined the knee points (cross-over distances) on the dromochrones for each shot gather of each single

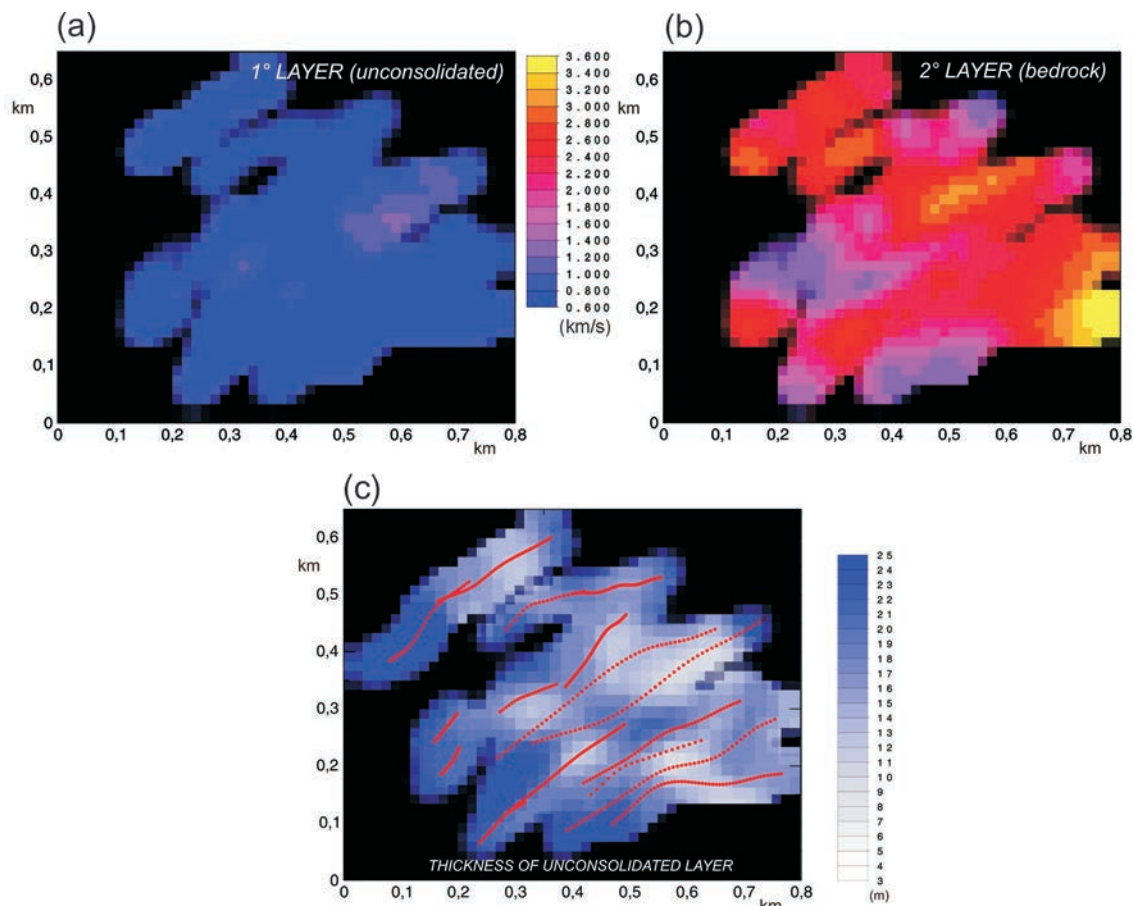


Fig. 7 - Diving wave tomography + refraction interpretation technique: a) plan view of velocity field beneath the topographic surface (unconsolidated layer) obtained by the inversion of direct arrivals; b) velocity of the bedrock obtained from the standard refraction technique; c) depth of the bedrock with respect of the topographic surface, obtained by the application of the classical refraction Eq. (1). The black zones are the parts not affected by the inversion (not crossed by rays); the red dots are the samples used to compute the depth of bedrock.

line in order to extract the direct and the refracted arrivals, as described in step 2 of the procedure.

The first part of the picked times, from 0 offset to the knee point, was used for the inversion of direct arrivals (Fig. 7a). For this purpose, we defined some thin layers, each 10 m thick, below the topographic surface; we used diving ray paths (defined by an arc with a slight upward concavity), assuming the presence of a vertical velocity gradient below the surface of the real model, without which they cannot exist. At the first inversion step we started with a constant velocity model and we used straight ray-paths for the diving arrivals (the arcs were defined by a constant offset/depth ratio). The resulting model, obtained from this first inversion, was used as new initial model for the next inversion steps, applying the bent ray-paths. The inversions stopped when the new model differed from the old one by a chosen threshold. In order to enhance the tomographic model, during this procedure we eliminated those records that had time residuals higher than $\pm 10\%$ threshold (see also Böhm *et al.*, 2006).

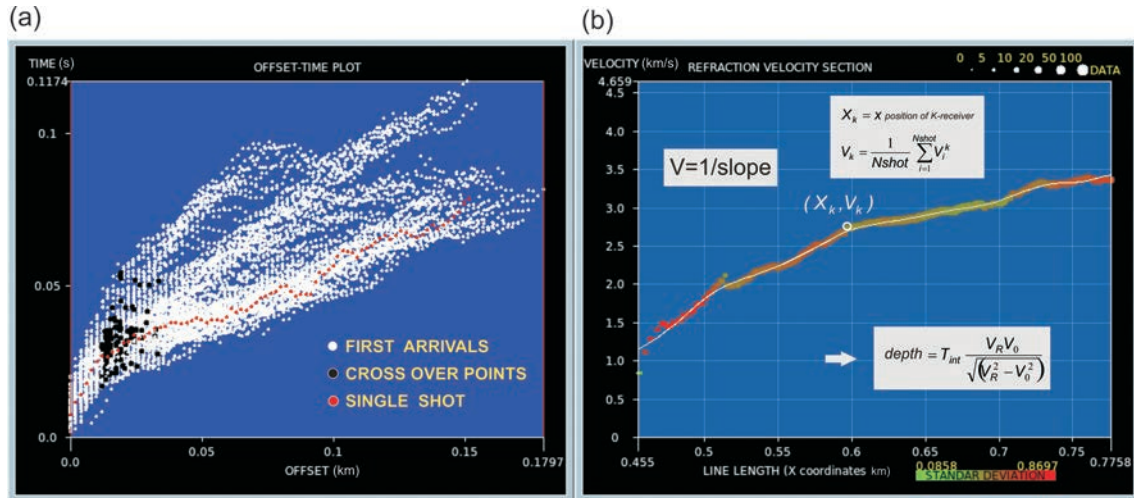


Fig. 8 - Definition of velocity and depth of the refractor by applying the classical formulas of refraction analysis along the receivers: a) plot (offset vs. time) of the picked points referred to the first arrivals of a single line on which the cross over points are computed for each shot (black dots); b) plot of the velocity obtained from the slope of the refracted arrivals of each shot; the points (X_k, Y_k) are defined by the average of the slopes of the dromochrones for each receiver k . T_{int} is the time intercept associated with the straight line that fits the time-offset dromochrone related to the refracted arrivals. Upward velocities (V_0) are defined from the inversion of direct arrivals (step 3); refractor velocities (V_R) are defined from the polynomial fit (white line) of all the considered points.

Based on these results, we created a 2-layer model by using the following components: a first layer based on the velocity field resulting from the inversion of direct arrivals and obtained by computing a vertical mean of the velocities of the three shallow layers; a second layer based on the velocity field computed from the slope of dromochrones; the interface between the two layers, corresponding to the bedrock, obtained from the refraction Eq. (1) (Fig. 8).

This model, which defined the shallower velocity layers, was used as initial model for the travel time tomography of the refracted events associated with head waves, by which we obtained an estimate of the refractor velocity and depth (Figs. 7b and 7c). As the final step, we jointly inverted the direct and refracted arrivals, obtaining a more reliable velocity field above and below the top of bedrock (Fig. 9).

To validate this final result, we computed the time residuals and the null space energy on the final model. The null space map confirmed the validity of the chosen model grid with respect of the acquisition scheme. The rms value in percentage of the time residuals, referred to the final step, was 8.42 (see the residual distribution in Fig. 10).

6. The final model

The final model, obtained by applying the complete procedure, consists of two layers separated by a surface that defines the top of bedrock present in the considered area (Fig. 9). The first layer represents the unconsolidated part of the soil; the second layer, instead, identifies the bedrock structure with P-wave velocity values from 2.0 km/s to 3.5 km/s. Both layers show an

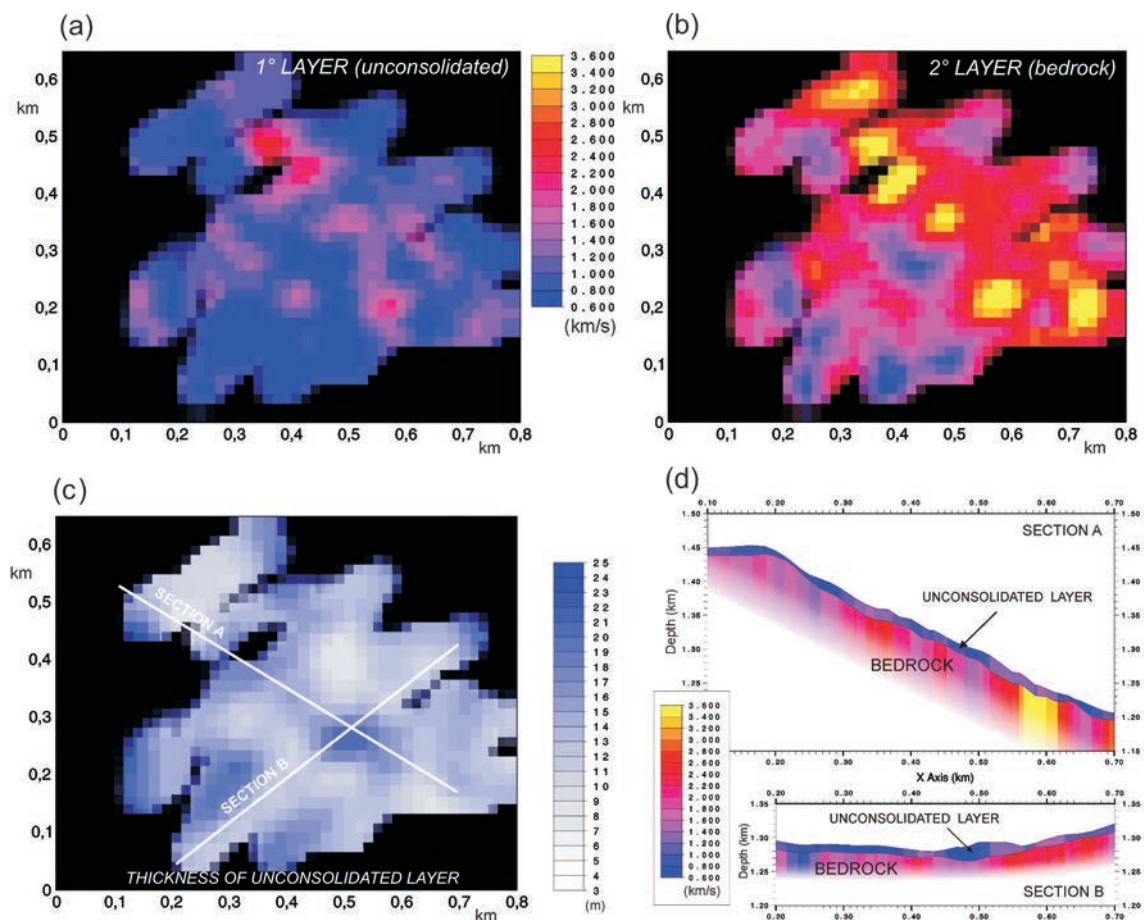


Fig. 9 - Joint inversion of direct and refracted arrivals. Plane view of the final velocity fields obtained by the joint inversion of direct and refracted (head waves) arrivals: a) the layer below the topographic surface (unconsolidated layer) and b) the velocity of the bedrock; c) the depth of the bedrock with two vertical sections (white lines). In black are the areas not affected by the inversion (not crossed by rays); d) two vertical sections (A and B) display the velocity of unconsolidated and bedrock.

increase of velocity to the NE of the investigated area; in particular the unconsolidated layer exceeds the value of 2 km/s. This probably is a consequence of the averaged velocities obtained by the inversion of the two layers due to the fact that in this zone the limit between the bedrock and the unconsolidated layer turns out to be not well defined with respect to the SE part. Moreover, the higher-velocity bedrock present in the NE part of the model could indicate a different lithologic unit with respect of the other zones of the area.

The average thickness of the first layer, which represents the depth of the bedrock, ranges from 10 to 15 m over the entire area, unlike the central part of the model that presents an increase in thickness to form a small basin (displayed in Fig. 9d, section B at distance X=0.5). This anomaly could be associated with an ancient landslide; the local morphological aspect (a hill above) and the presence of some landslide deposits around this zone seem to validate this hypothesis.

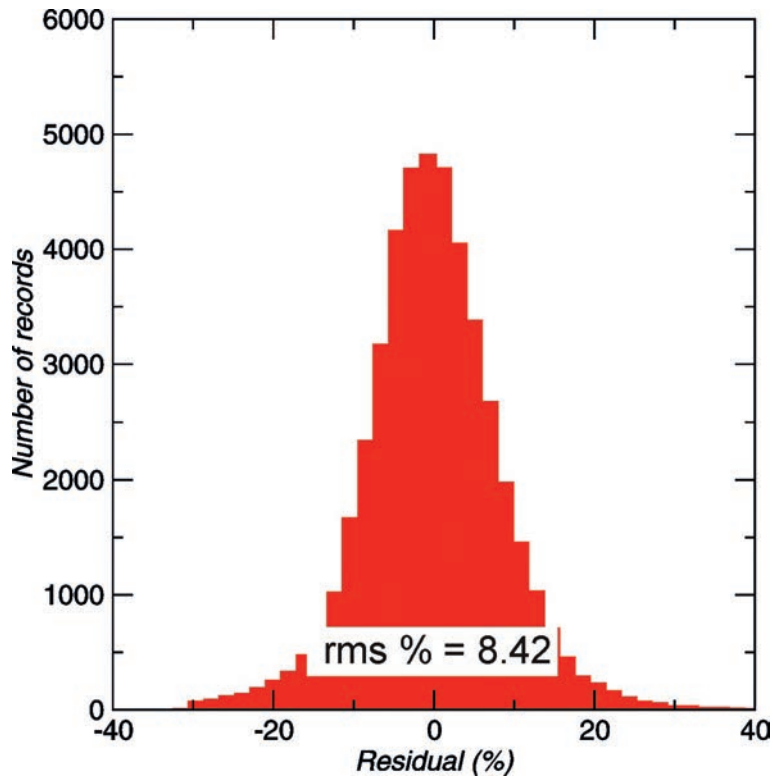


Fig. 10 - Distribution of time residuals obtained from the final model of Fig. 9.

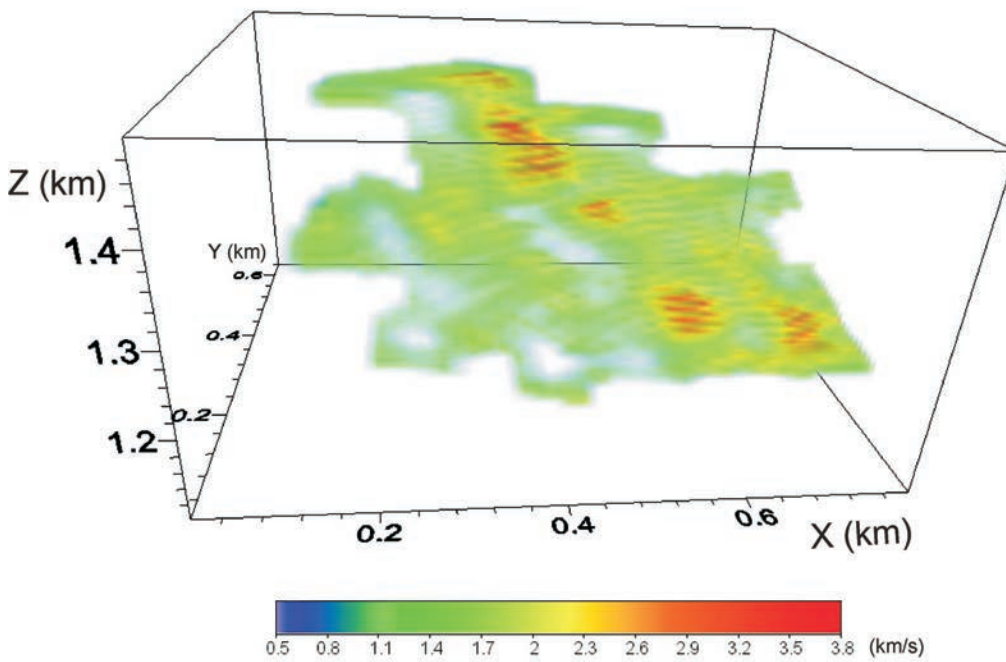


Fig. 11 - 3D image of the final velocity model.

7. Conclusions

The procedure used in this work was able to reconstruct correctly the shape and depth of the shallower structures present in the investigated area.

The main advantage of the proposed method is that it integrates the classical refraction analysis with the travel time tomography by using the joint inversion of direct and refracted arrivals. It is especially useful for processing large amount of data without sacrificing the quality of results because it uses an automatic procedure to separate direct from refracted arrivals in the first break picked data.

This approach, applied in an area affected by gravitational collapse, produced a 3D velocity model of shallower structures (Figs. 9 and 11), which shows the following main aspects:

- the presence of higher velocity structures in the NE part of the model indicates a different property of bedrock with respect to the SW part;
- the higher velocity of the unconsolidated part can be justified by the not clearly defined limit with the bedrock, which causes average values from sub soil and bedrock velocities obtained by the inversion;
- the presence of a small basin in the central part of the model, slightly elongated in a NW-SE direction, is probably due to a local old debris landslide.

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