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Application of inverse ray-tracing seismic modelling techniques in the Ikaria airport site

V. K. Karastathis[1], J. F. Louis[2], M. Arvanitis[2] and P. Karmis[3]

[1] National Observatory of Athens, Institute of Geodynamics, P.O. Box. 20048, 118 10 Athens, Greece
[2] University of Athens, Panepistimioupolis, 157 84 Athens, Greece
[3] Institute of Geology and Mineral Exploration, Mesogeion 70, 115 27 Athens, Greece

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Abstract : *The implementation of the seismic refraction method in the Ikaria Island Airport site, Greece, in 1995, was a characteristic case of detection degraded areas by geophysical prospecting, in a zone where the Airport's runway had been planned for expansion. The degradation was mainly presumed by the low values of the measured seismic wave velocity and the estimated dynamic modulus of elasticity. The processing of the data had been based on ray-tracing inverse modelling techniques. The geophysical survey had assisted to the proper design of the runway expansion.*

Six years later, we reprocessed the data with modern inverse modelling techniques in order to assess the validity of the older refraction modelling results and to make a general assessment about the degree that the new techniques could additionally assist the quantification of the dynamic properties of the rocks in engineering applications.

Key Words: *Ray-tracing, Inverse Modelling, Seismic Refraction, Geotechnical Applications.*

INTRODUCTION

In the last fifteen years, many automatic seismic inverse modelling algorithms have been developed providing a fast and valid tool for seismic refraction processing and wide-angle reflection data (Spence *et al*., 1985; Huang, Spencer and Green, 1986, White, 1989; Lutter *et al*., 1990; Podvin and Lecomte, 1991; Zelt and Smith, 1992; McCaughey and Singh, 1977; Zhang, *et al*., 1998). Many of these algorithms have been extensively used after 1995 in deep structure surveys. In the last few years, the applications of these algorithms were also expanded to the geotechnical and archaeological surveys (Lanz *et al.,* 1998; Karastathis *et al*. 2001). The prior works of Scott, Tibbets, and Burdick (1972); Scott (1973, 1977) and Haeni *et al*. (1987) can be considered as a precursor of today's ray-tracing refraction inversion algorithms. These algorithms have been widely used till the early 90s in mining, engineering and hydrological applications (Haeni, 1986). After 1995, in most of the applications, these algorithms have been replaced by modern ones as ZS92 (Zelt and Smith, 1992).

The main advantage of the modelling techniques in comparison with the respective classical reciprocal algorithms (i.e. Hagedoorn's, 1959; Palmer, 1980) was that they could handle more complex earth models than the later, which were taking into account considerations of simple structured earth i.e. continuity of the earth layers.

The introduction of the inversion procedure in the modelling overcomes the serious problem of the long processing time (especially in cases with large datasets) and also provides the quantification of the validity of a resulted model. However, the native problem of non-uniqueness remained unsolved, and in many cases, additional information is usually needed.

In 1995, we conducted a seismic refraction survey in the Airport area of Ikaria Island, Greece. The aims of this survey were to describe the structure of the subsurface layers and to make an initial assessment of the dynamic properties of the subsurface where the Airport's runway had been planed to be expanded on. This four hectares area was on top of an embankment, at the 24 m elevation level, where the airport has been founded (Fig. 1). The seismic refraction investigations were conducted in combination with geoelectrical and time domain electromagnetic surveys. The aim of non-seismic techniques was to detect the sea intrusion in the studied area. Since the results of the whole project have been published in a geotechnical issue (Karmis, *et al*., 1997), in the present paper we focused only to present how the modern seismic ray-tracing modelling techniques can alter or assist the interpretation of the results acquired by the prior forms of inverse modelling. The matter is not only to show the abilities of the modern software but also to give an answer on how crucial and necessary would be a possible reprocessing of an old refraction dataset with modern modelling techniques.

FIG. 1. The runway of the Ikaria airport is oriented NNE-SSW and terminated on an embankment area near the coast. At this area the runway was planned to be extended. (photo: Air Traffic Safety Electronic Engineers Association of Hellenic Civil Aviation Authority: http://www.hcaa-eleng.gr/ikaria.htm)

GEOLOGICAL SETTING

The bedrock that underlies the embankment is a metamorphosed unit constituted by phyllite and schist, with a succession of intercalated carbonate layers. Highly fractured carbonate layers are observed on the outcrops. The surface sediments consist of sand and pebble conglomerate. The embankment material is made of scree and boulders.

DATA ACQUISITION AND PROCESSING

A number of P-wave seismic refraction profiles were conducted in the investigated area. Additional P-wave refraction survey was carried out to estimate the Poisson ratio of the bedrock in an adjacent area where the bedrock outcropped. Some shorter S-wave refraction profiles were also conducted in order to contribute to the assessment of the dynamic properties of the layers.

The locations of the P-wave refraction profiles IKRP1, IKRP2, IKRP3 and IKRP4 are shown in Figure 2. The dataset IKRP1 was acquired with the use of 48 geophones and spacing interval of 4 m. A 24 geophone layout was used in all the other lines. The receiver interval was 4 m for IKRP2 and IKRP3 and 2 m for IKRP4. The lengths of the IKRP1, IKRP2, IKRP3 and IKRP4 were 188, 92, 92 and 46 m respectively. Dynamite was used as seismic source for the data acquisition and the resonant frequency of geophones was 10 Hz. The data recording unit was an ABEM Terraloc instrument.

The first processing of the data (Karmis *et al*., 1997) was done by the use of the inversion ray-tracing modelling algorithm SIPT1 of Haeni *et al*. (1987), based on the previous work of Scott, Tibbets and Burdick (1972) and Scott (1973, 1977). The program could handle models with steeply dipping layers and abrupt changes in velocity. Its ability for data processing was limited to 48 traces per shot and seven shots per spread. The algorithm could support models only with five or less layers. The inputs required by the program are the first arrival times, the assignment of arrivals to the corresponding refractors as well as the positions (elevation and location) of the sources and receivers. By the use of a delay-time method the program performs a first approximation of the

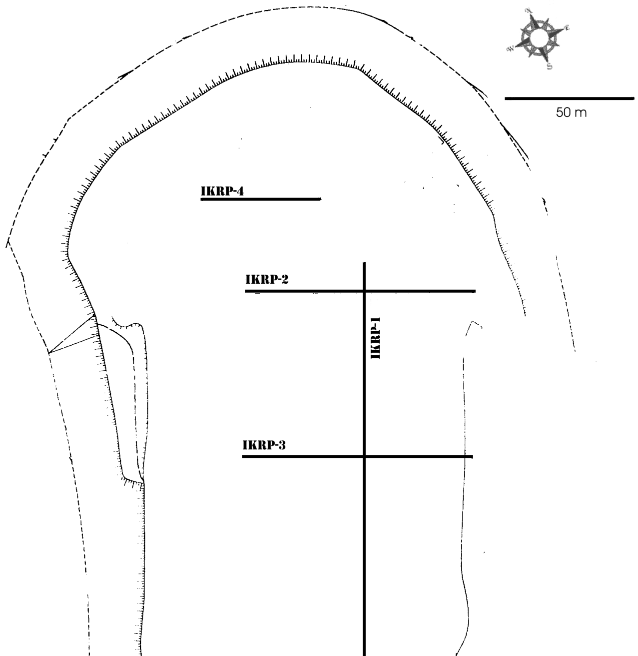

FIG. 2. Sketch map of the P-wave refraction profiles.

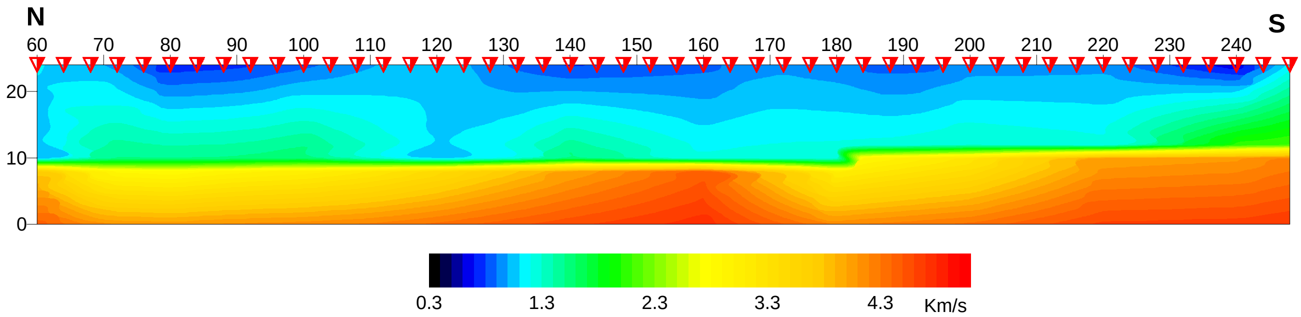

FIG. 3. Velocity structure of the refraction profile IKRP1. Triangles denote geophone positions.

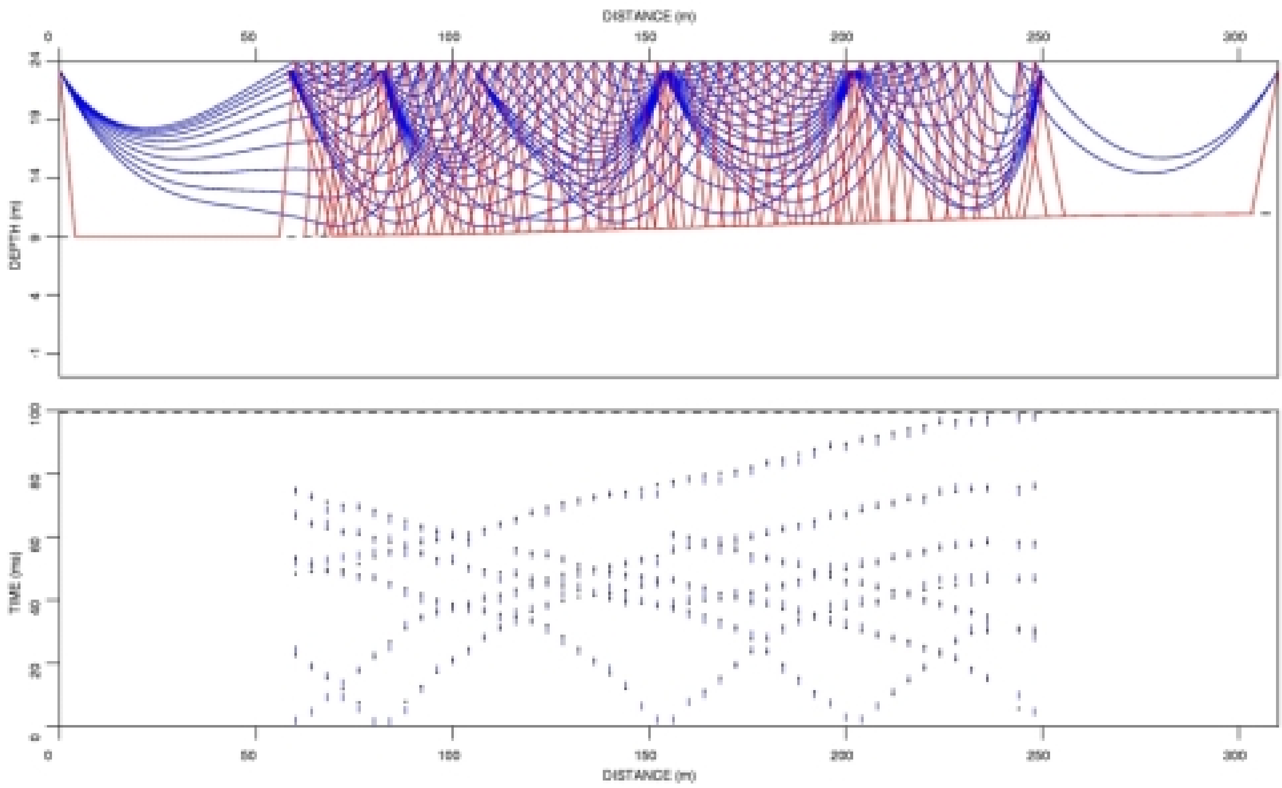

FIG. 4. Top: The first arrival ray-paths through a two-layer model of IKRP1. Bottom: Comparison of observed (bars represent ±1.2 ms uncertainty) and predicted travel times shown by dots. Overall RMS misfit was 1.18 ms for 288 arrivals.

layered model. This initial model is improved by the implementation of an automatic inversion procedure based on a ray-tracing technique. In particular, a set of travel times are calculated by the program, and compared with the observed data and if the misfit is not within a user-specified limit, the refractor interface is adjusted in a such way to improve the model travel times fitting. The procedure is iterative and is continued until the limit was reached. The resulted model is finally smoothed.

The program Rayinvr (Zelt and Smith, 1992; Zelt and Forsyth, 1994) was implemented for the reprocessing of the data. This is a ray-tracing algorithm accompanied with a least-square inversion routine that uses any type of seismic wave arrivals and provides a simultaneous determination of the 2-D velocity and interface structure. It uses a layered model consisted of trapezoids cells. The user defines the number and the shape of the trapezoid cells and also sets the velocity values on their corners. This definition is done by setting up the respective "boundary" and "velocity nodes". The velocity values within the trapezoids come from a linear interpolation between the four defined corner velocities. The algorithm not only improves the time required for data processing in comparison to the forward modelling but also estimates model parameter resolution, uncertainty and non-uniqueness. The Rayinvr has been mostly used in crustal studies such as those reported by Zelt and Ellis (1989); O'Leary, *et al*. (1995); Zelt and White (1995); Clowes, *et al*.,(1995); and Sato and Kennett (2000). The data processing was done on a Sun Ultra 10 workstation.

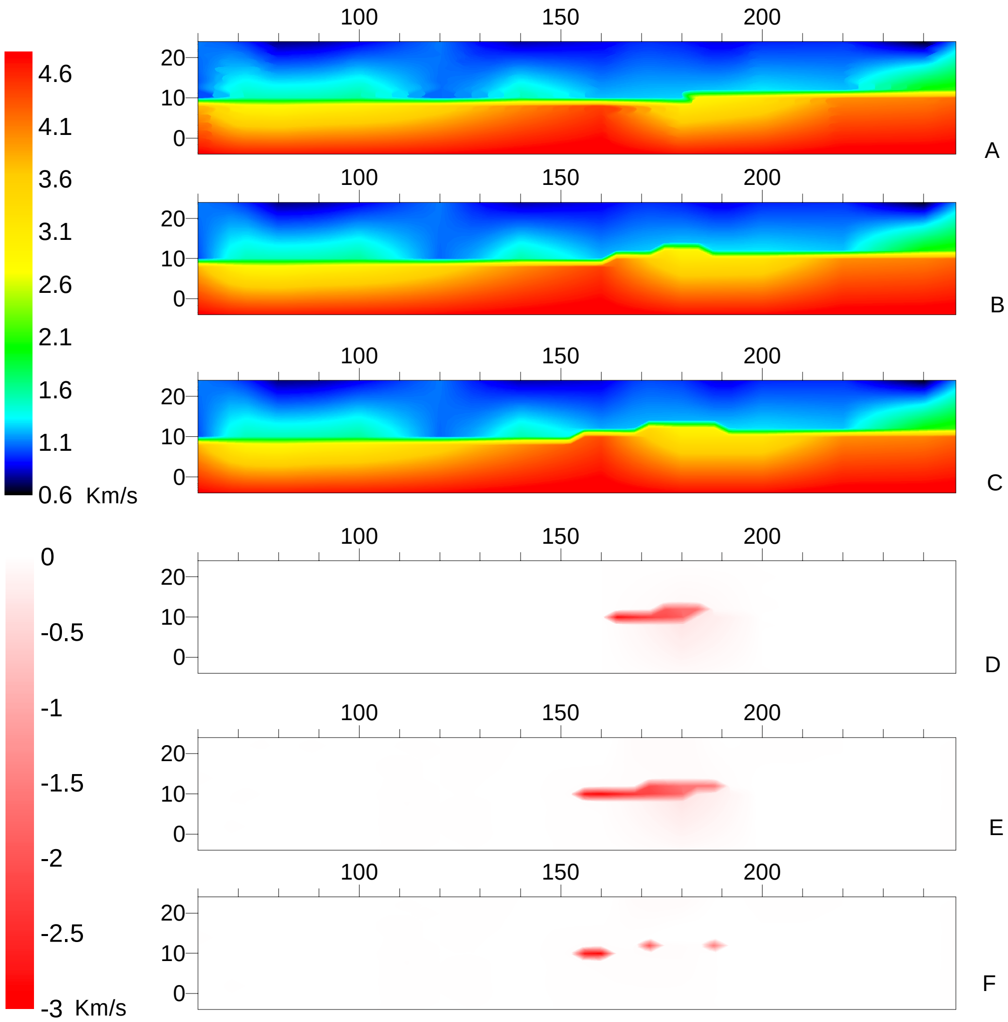

FIG. 5. A single parameter resolution test. The final model (A) was perturbed by raising the 180 m node by 3 m. The resulting model (B) was used to produce a new arrival time dataset. The inversion of the final model (A) with the perturbed time dataset resulted to a new model (C). The next model (D) presents the initial perturbation which created the perturbed time dataset. Model (E) shows the resulted perturbation on the final model crated by inverting the perturbed time dataset. The models (D) and (E) are little different. The difference is shown in model (F).

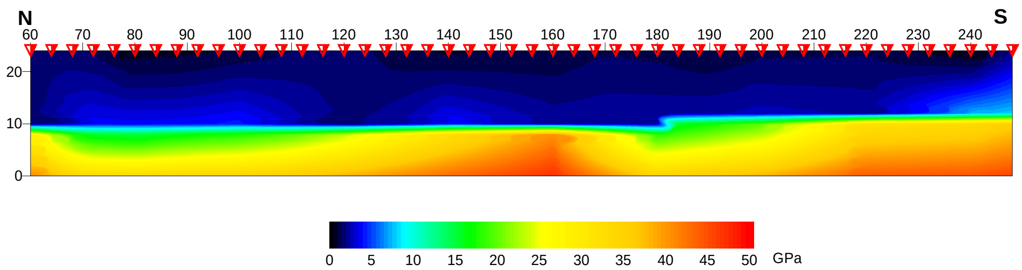

FIG. 6. Section representing the estimated elasticity modulus of the line IKRP1.

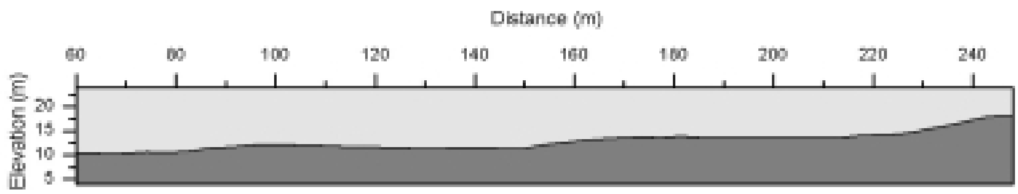

FIG. 7. The refraction seismic section after processing with the SIPT1 algorithm.

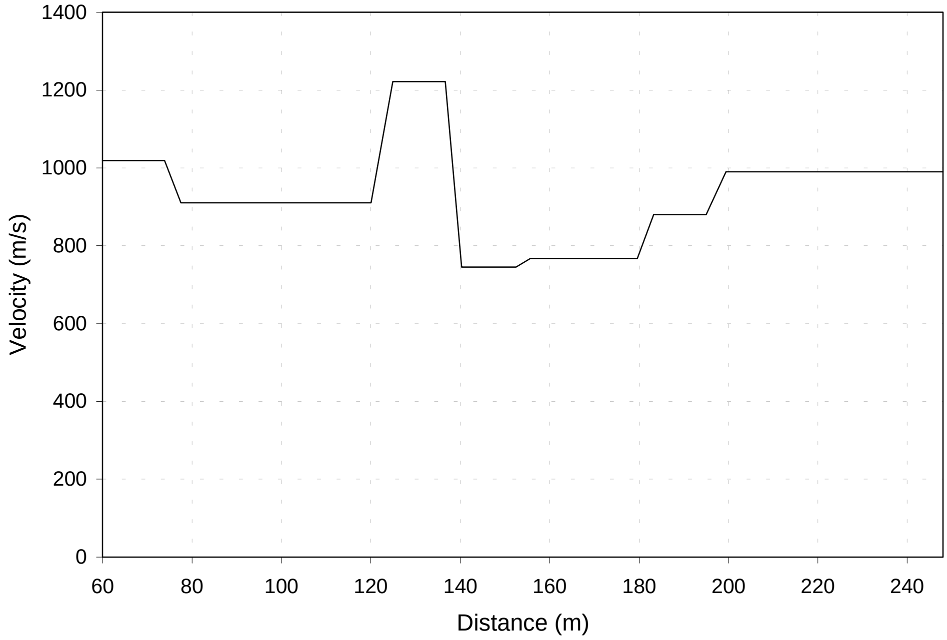

FIG. 8. The horizontal variation of the overburden layer velocity as calculated by the algorithm SIPT1 on the IKRP1 data.

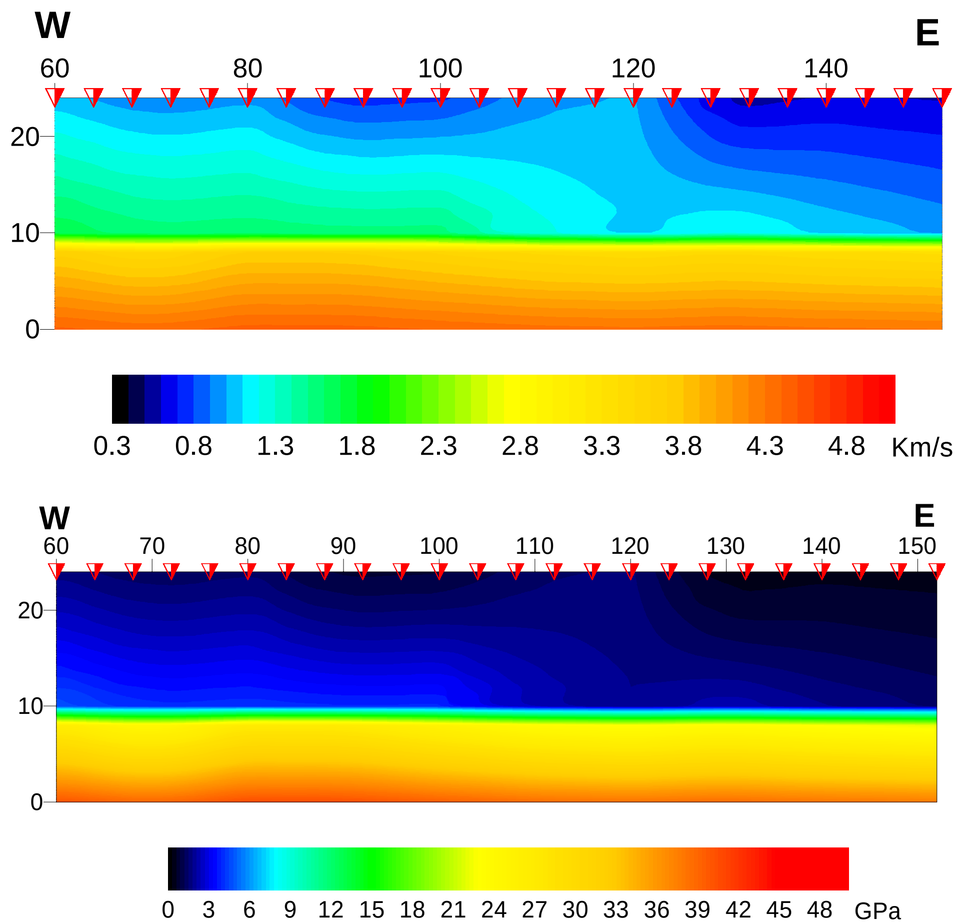

FIG. 9. The velocity model (top) and the respective presentation of the estimated elasticity modulus (bottom) of the seismic line IKRP2.

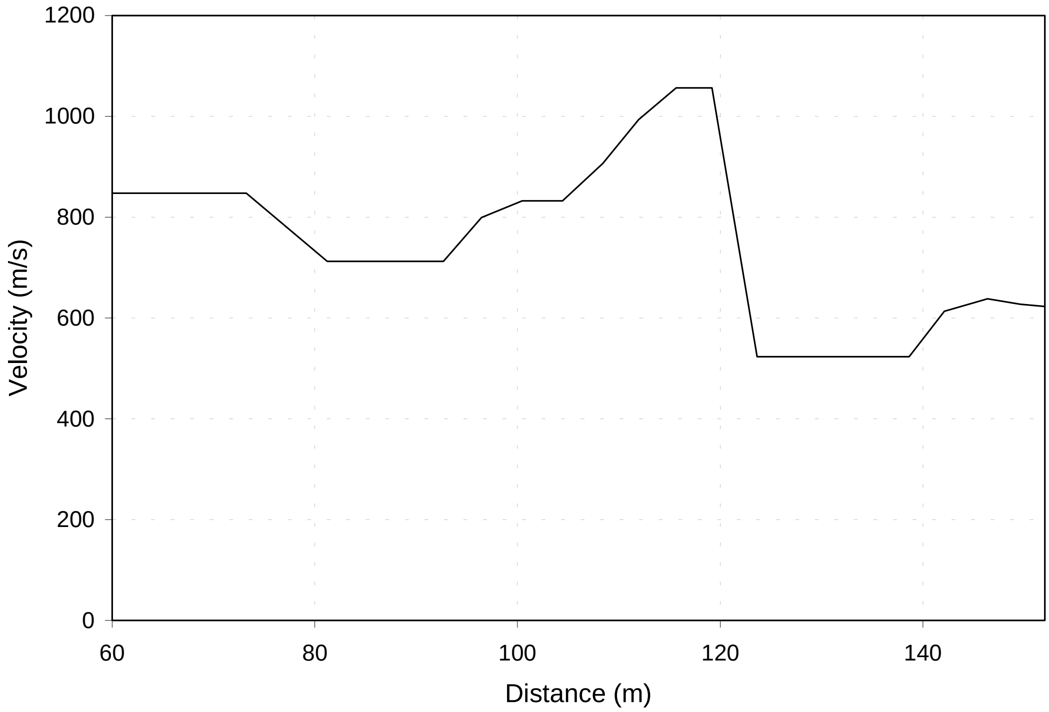

FIG. 10. The horizontal variation of the velocity of the overburden in IKRP2 line, as calculated by the algorithm SIPT1.

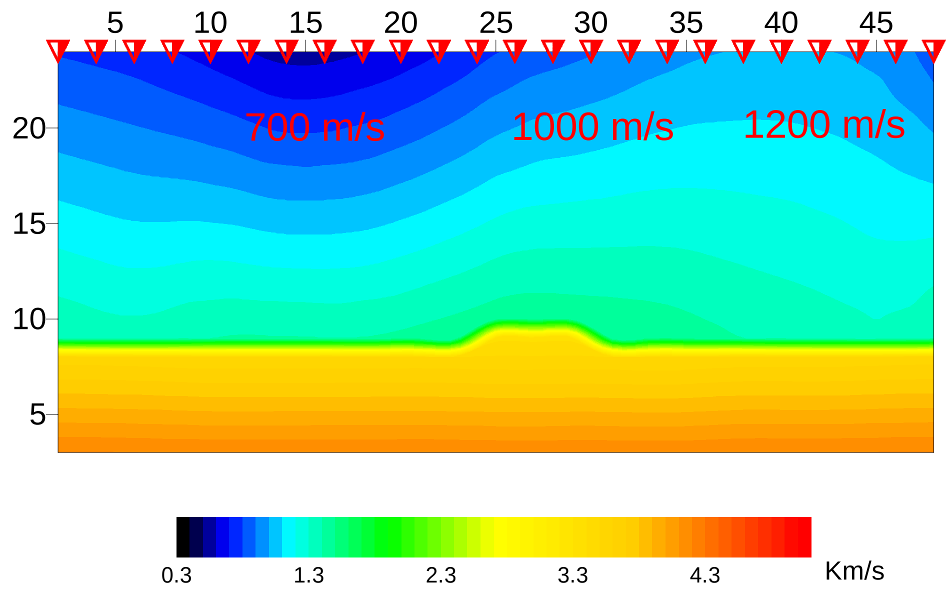

FIG. 11. The velocity structure of the refraction profile IKRP4 as resulted from the processing with the Rayinvr algorithm. The numbers inside indicate the velocity values as calculated by SIPT1.

RESULTS

The results of the seismic and geoelectical surveys in 1995 (Louis and Karastathis, 1996; Karmis *et al.*, 1997), described a deteriorated zone at the eastern side of the investigated area. Although seismic refraction survey succeeded to detect this deterioration, questions remained outstanding about the precision and the completeness of the results. The comparison of the previous results derived by the SIPT1 algorithm with the new ones acquired by one of the most popular and modern inversion modelling algorithms, the Rayinvr, provided us with useful answers to all these questions.

The line IKRP1 could be considered as the backbone line of the seismic survey. The model resulted after processing with Rayinvr is presented in Figure 3. The structure is simple without any abrupt anomaly in the depth of the bedrock interface or in the P-wave velocity values. The lowest values of the P-wave velocity of the first layer (800 – 900 m/s) around 80-100 m and 130-160 m are concentrated in very shallow depths and could not lead to any concern about the compactness of this layer. These low values can be attributed to a natural deterioration of the superficial materials.

The ray-coverage of IKRP1 was dense enough to describe the P-wave velocity of the first layer and the upper part of the bedrock (See Figure 4 – upper panel). This was succeeded by utilizing 48 geophones and 7 shots which are the maximum limits of the processing capabilities of the SIPT algorithm. The fitting between calculated and observed times was very good (Figure 4 – lower panel) since the RMS error was not higher than 1.2 ms.

We also tested the stability of the final model (Fig. 5a) by perturbing it at one point (180 m). Actually, we moved the boundary node of this point upwards for 2 m. The velocity model then was modified (Fig. 5b). A new data set was created by forward modelling. This data was inverted by using the final model as a starting model. The inversion produces a new model (Fig. 5c). The purpose was to check if the final model was sensitive to small perturbations. We found out that the model was stable, since the smearing around the anomaly was very small. The resulted model after the inversion of the perturbed data is shown in Figure 5c. Figure 5d shows the initial perturbation of the model (difference between 5a and 5b), the Figure 5e shows the resulted anomaly (difference between 5a and 5c) and the Figure 5f shows the difference between the two anomalies (5d and 5e). We can notice that the difference is very small and we can conclude that the inversion is stable.

We also estimated the elastic modulus of the materials in the IKRP1 section. The resulted section is shown in Figure 6.

The comparison of the new results with the previous ones showed a very good agreement in the depth estimation of the bedrock. Figure 7 shows the refraction profile as resulted from the SIPT1 processing. The velocity distribution of the first layer is presented in Figure 8. The estimated velocity values by SIPT1 (see Fig. 8) agreed well with the values of the first six meters material in the Rayinvr model. This was expected since the major part of the first layer rays came through these first meters. If Karmis *et al*., (1997) had not conducted supplementary geophysical methods such as geoelectrical profiling or electromagnetic soundings, they could not be able to evaluate the quality of the interpretation for the layers deeper than 5-6 m. The modern modelling technique able to handle models with linear velocity increase allowed estimating velocity at those depths.

The deteriorated area at the eastern part of the investigated area was detected by both the IKRP2 and IKRP3 lines. We present P-wave velocity and elasticity modulus sections obtained from the modelling of line IKRP2 profile (Fig. 9). It is easily seen that the area over 120 m has lower values of P-wave velocity. Figure 10 shows the velocity graph of the previous processing. Although the velocity variation is clear in this section, it is difficult to decide if the low velocity zone is limited inside the upper layer without additional information.

Seismic line IKRP4 (Figure 11) also indicates a small deterioration in the upper part of the first layer. The estimated velocities by the previous processing are presented by red lettering. The agreement between the two processing methods as far as the P-wave velocity is concerned, was very good. However the new processing succeeded to specify better the area with the lower velocities.

CONCLUSIONS

The reprocessing of the data leads to obtain new information about the velocity field derived from the seismic refraction survey. It also provides an idea about the quality of the previous inverse modelling results. The former techniques could not estimate the velocity values in the deeper part of the upper layer since they could not handle models with a gradient increase in the velocity field.

The reprocessing of the data is worth trying since new information can be derived from the former seismic refraction experiments having extensive ray-coverage. In Greece, there are many datasets i.e. important engineering seismic surveys and crustal investigations. This work shows that the reinterpretation of these datasets would be very useful.

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