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Feasibility Study on the Use of Seismic Methods in Detecting Monumental Tombs Buried in Tumuli

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ABSTRACT A tumulus is a monumental construction erected to cover a tomb. In this paper, we examine the feasibility of the seismic method in detecting buried tombs without destroying the tumulus. In the proposed seismic method, a number of refraction profiles are employed. First, we conduct a seismic refraction survey in order to map the subsurface in the vicinity of the tumulus. Then, we choose the optimum parameters of the seismic refraction survey which is employed for locating the tomb. In this survey, the geophones are spread along a circular profile on the periphery of the tumulus, while the shot is located at its top. Time delays observed on the arrivals of the head waves reveal the position of the tomb. The delays are not caused by the monument itself, but they reflect the position of the ramp which was dug in the undisturbed soil for constructing the tomb.

In this paper, we present three case studies from Northern Greece. The feasibility of the proposed seismic method was first established at an already explored tumulus near Toumpa village. The efficiency of the new tool was verified on the second case study, where the tomb in Messiano village tumulus was detected by the proposed seismic refraction technique. This method was also applied in order to search for a second tomb in the Pella tumulus.

Key words: tombs; tumuli; seismic refraction

Introduction

In archaeological geophysics the tombs buried inside tumuli comprise significant exploration goals, because they usually contain important findings. Tumuli are artificially erected small hills which cover monumental tombs. Since the tumuli are themselves monuments of past human activity, they deserve to be preserved. A lot of effort has been put in to find ways to locate the tombs without destroying the tumulus.

In most of the reported case studies (Orlando *et al.*, 1987; Tsokas *et al.*, 1994), resitivity surveys have been conducted successfully in flat areas. As far as the search in tumuli is concerned, Katevski (1986) and Petkov *et al.* (1989) employed the resistivity method and conducted circular profiles following the topographic contours of the tumulus. However, the reported detections refer to structures buried at a small depth compared to their dimensions. Seismic, electromagnetic and ground penetrating radar surveys were conducted by Utecht (1988) and Utecht *et al.* (1993) in a tumulus in South East Asia Minor with objectives to map the stratigraphy of the construction and to locate a monument under the artificial cover. They achieved only the first goal. Tsokas and Rocca (1987) employed the geoelectric sounding method arranged on a rectangular grid established on a

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tumulus in Northern Greece. They did not locate any tomb, but they pinpointed the edge of the ancient pit.

In this paper, we examine the potential of seismic methods in detecting tombs inside a tumulus. A tumulus would have been constructed in stages. At first a pit was dug and a ramp was made at one edge of the pit for carrying the masonry into the pit which was used to build the tomb. Tombs are usually small but carefully finished monumental constructions. After the funeral procedures, the tomb was sealed and the tumulus was erected covering everything. The loose material of the tumulus infillment is likely to have different physical properties from the undisturbed environment. However, the material of the tumulus is highly inhomogeneous. It has, usually, high clay content which presumably limits the penetration of any electrical or electromagnetic technique. In most known explored tumuli the tomb is located away from the centre of the tumulus, thus minimizing the chance of finding it by excavating from a random point toward the centre of the tumulus.

In the seismic methods, information about the subsurface is deduced from the times that the seismic waves take to travel from the shot location to the geophones. The tomb inside the tumulus distorts the seismic wavefield and delays the seismic waves that travel through it. Here, we look for significant delays on the first arrivals which are related to the presence of the tomb.

Our first attempts have been focussed on testing the seismic method in an explored tumulus near Toumpa village (Figures 1 and 2). Delays of the arrival times for seismic waves (head waves) that arrive first at the geophones have been observed. Ray-tracing helped in the interpretation of the data from Toumpa village as well as in the design of the seismic survey conducted in the unexplored tumulus near Messiano village. By placing the source at the centre of the tumulus and the receivers on the periphery of a circle, the radius of which is larger than the critical distance, we managed to locate the tomb. Modelling using a finite difference algorithm that describes the propagation of acoustic waves in 3D heterogeneous media has been utilized for the interpretation of the Messiano tumulus field data.

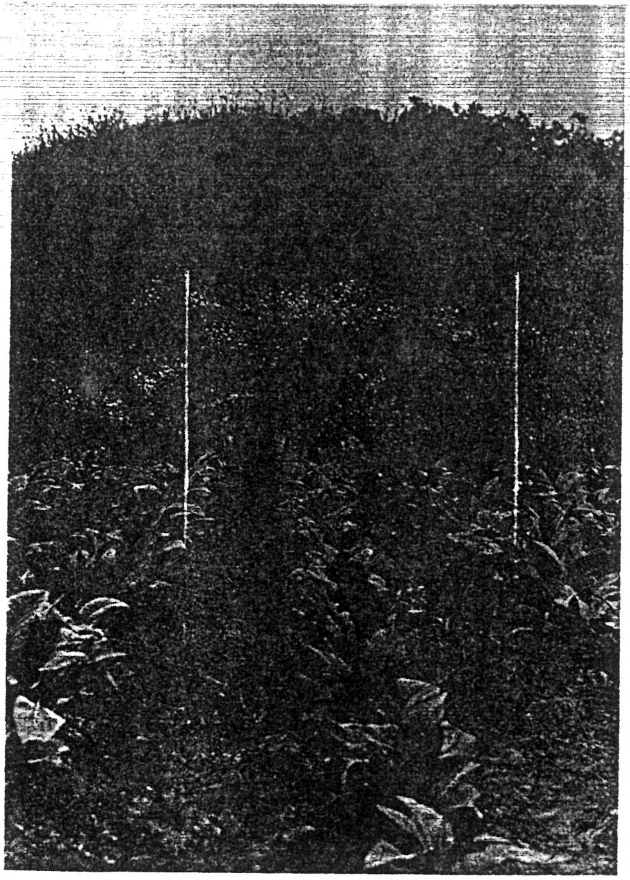


Figure 1. Photographs of the tumulus and the upper part of the monumental tomb near Toumpa village.

High resolution seismic methods can be employed for locating tombs. For exploration at shallow depths, where the tomb is located, the seismic reflection method may face difficulties mainly due to ground roll. Ground roll is the most common type of noise which often deteriorates the quality of shallow reflections (Steeples and Miller, 1990). We can map the subsurface employing the seismic tomography method (Kilty and Lange, 1990). For locating tombs with dimensions of the order of metres, the seismograms must contain sufficient energy at frequencies higher than 500 Hz. Tests for examining the applicability of the high resolution seismic methods for detecting buried tombs are not included in this paper.

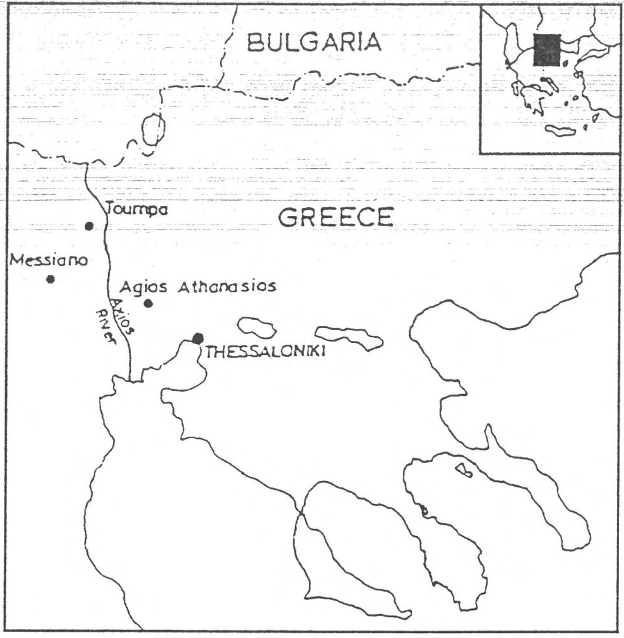


Figure 2. Map of the tumuli sites. The tumuli surveyed in this paper are close to Toumpa, Pella and Messiano in N. Greece.

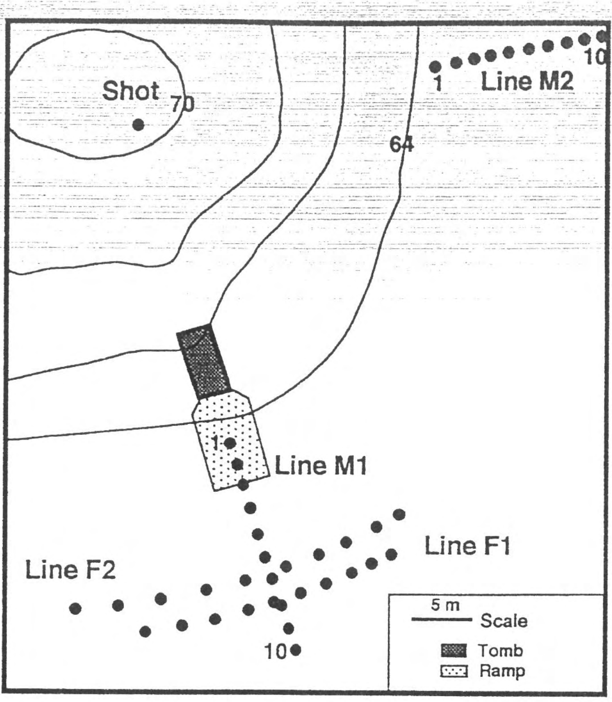


Figure 3. Geometry of the seismic survey in Toumpa village tumulus.

Feasibility study on Toumpa village tumulus

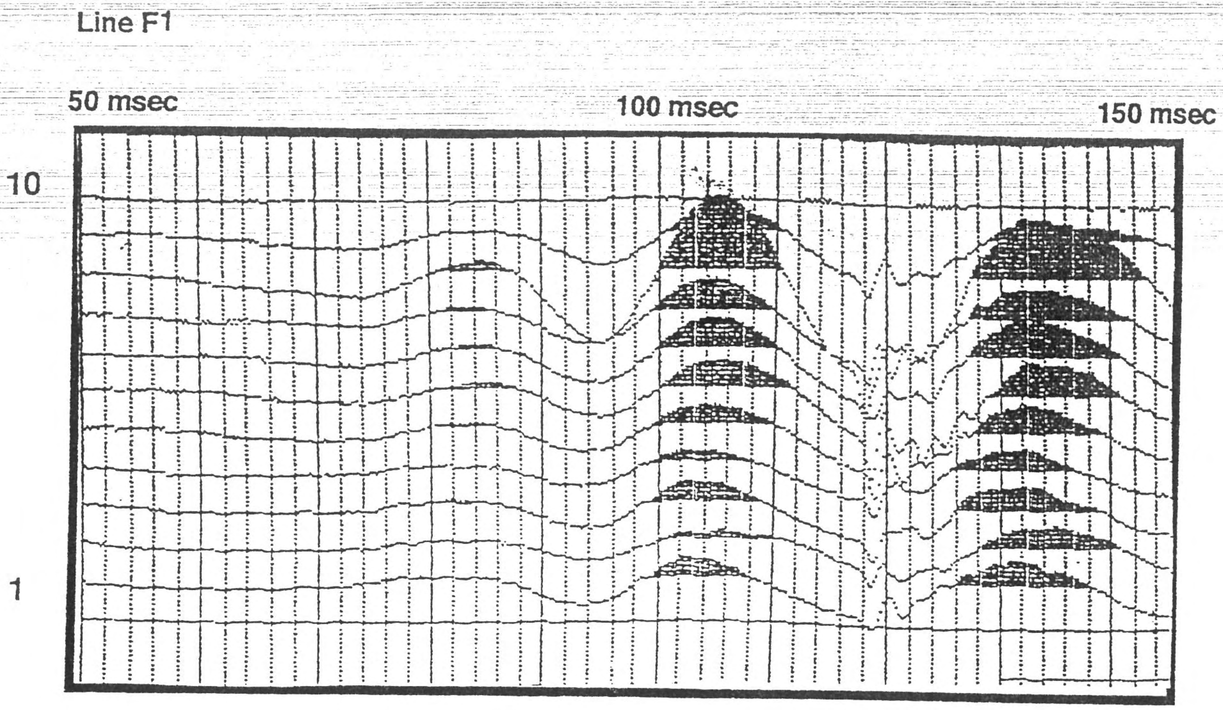
An explored tumulus located near the Toumpa village in Northern Greece (Figure 2) has been chosen for examining how feasible the seismic method is for the detection of tombs. Excavations prior to the geophysical investigations revealed the monument shown in Figure 1. We performed a seismic refraction survey by laying the geophones on two short lines (M1 and M2) along the radial direction and on another two lines (F1 and F2) at the periphery of the tumulus (Figure 3). The shot was located at the centre of the tumulus and seismic waves were generated using a sledge hammer.

The spacing of the geophones on lines F1 and F2 was 2 m and 3 m respectively. We were unable to observe changes (Figure 4) on the first arrivals, since all the recorded waves arriving first at the geophones travel through the tomb. This experiment failed to locate the tomb, because lines F1 and F2 were not long enough for recording waves that do not travel through the tomb.

From small refraction profiles in the vicinity of the tumulus, we determined the velocity of the uppermost layer in the undisturbed earth. It was 400 m s^{-1}, while the underlying halfspace showed a velocity of 1300 m s^{-1}. The thickness of the first layer was 6.4 m.

Next, we placed the source and the geophones on the radial direction along lines M1, which crossed the axis of the monument, and M2, located away from the tomb (Figure 3). The distance between the first geophones and the shot was 26.5 m and the geophone spacing was 1.5 m. The seismograms are shown in Figure 5. From the traveltime curves (Figure 6(a)) we note that the first breaks for line M1 are delayed compared to the ones for line M2. The time differences between the first breaks recorded from the geophones located at the same radial distance are 9 to 16 ms representing a more than 20% change. From ray-tracing, we deduce that the first breaks on line M1 correspond to the head waves which travel along the ramp (Figure 6(b)).

The Toumpa village geophysical survey showed that surveying on the radial direction with the seismic refraction method is useful in locating monumental tombs. However, the seismic methods with this geophone array is



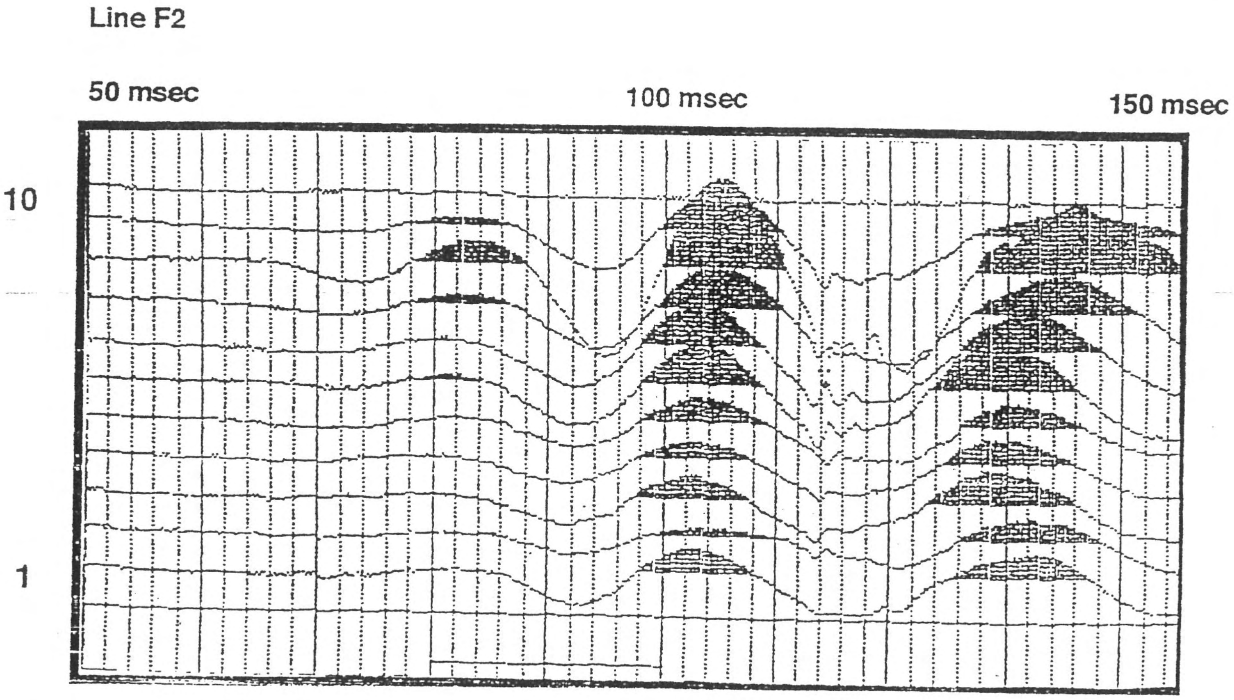


Figure 4. Seismograms recorded from refraction profiles F1, F2.

impractial because in an unexplored tumulus it requires a large number of profiles. The radial receiver geometry can be applied on selected locations for verification purposes.

Messiano tumulus geophysical survey

In order to design properly the geophysical survey in the tumulus near Messiano village (Tsokas *et al.*, 1995), we conducted an initial

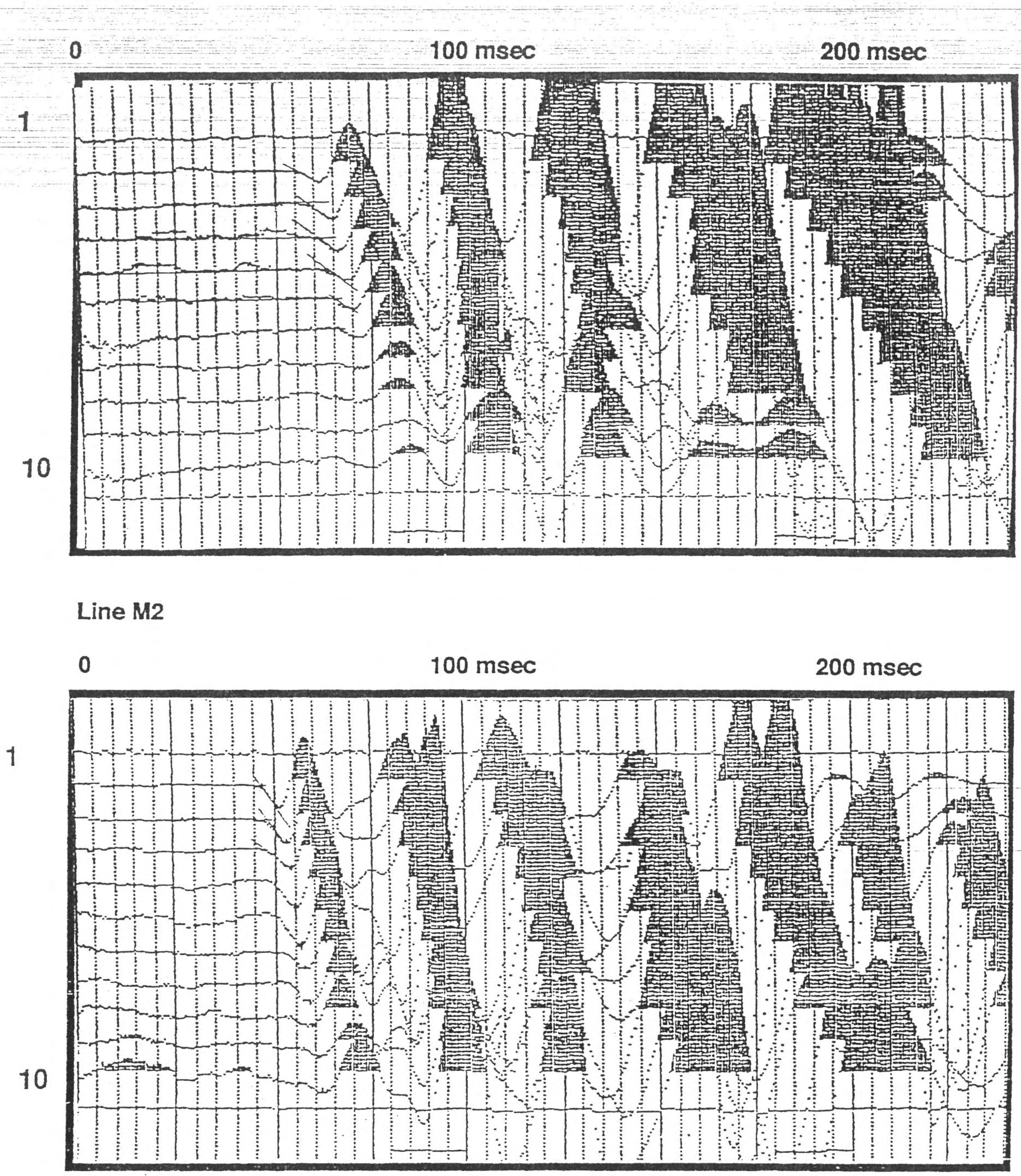


Figure 5. Seismosgrams recorded from refraction profiles M1, M2.

refraction survey for the evaluation of the seismic velocities and layer thicknesses of the substratum. A two-layer structure was found, with velocities 500 and 1280 m s^{-1}. The thickness of the first layer was 2 m. The choice of the geophone array and the seismic survey parameters was based on the experience gained from the Toumpa village geophysical survey as well as on modelling of seismic wave propagation. Ray-tracing for the tumulus model shows pronounced delays on the travel times of the head waves from the interface between the 500

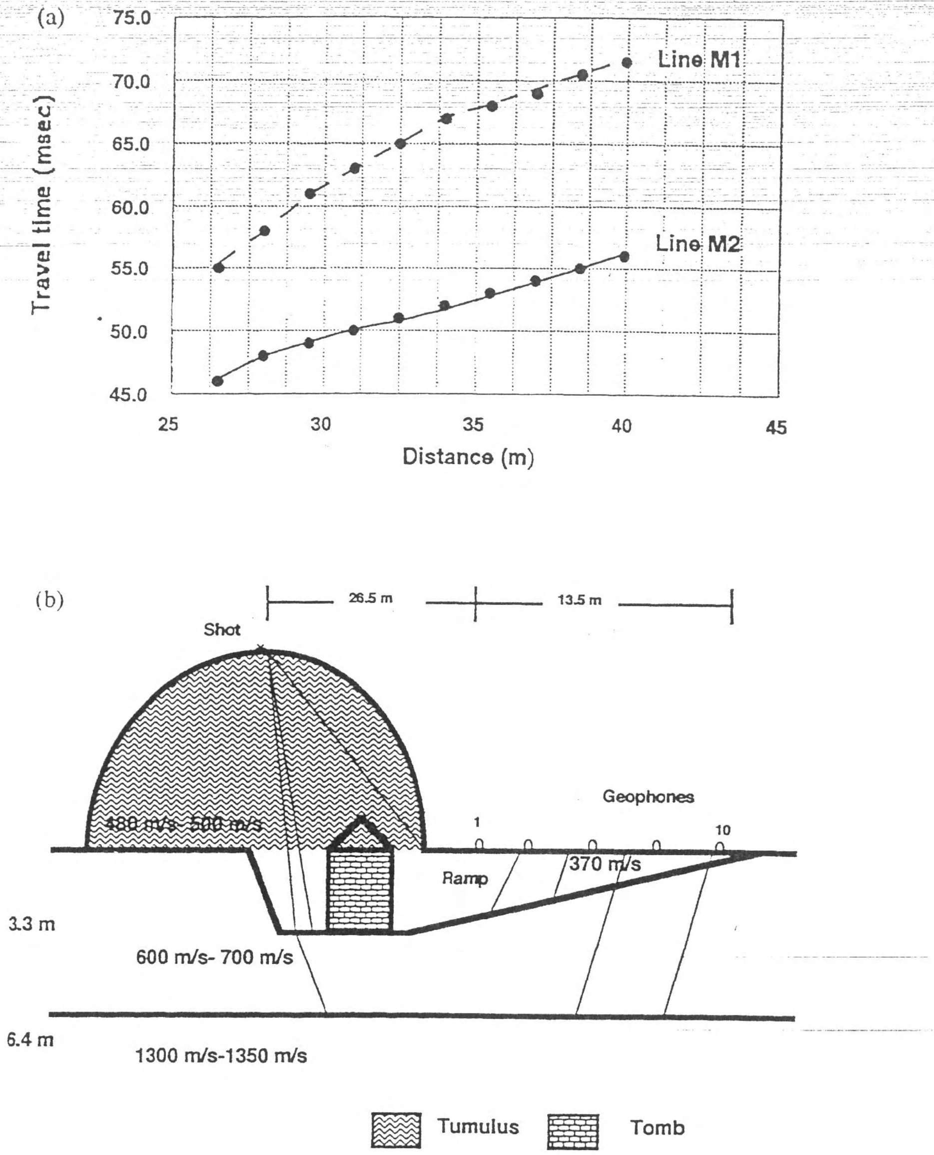


Figure 6. Ray-tracing for the tumulus model (b) was performed in order to calculate the travel times of the direct and head waves for receivers on the radial direction which are depicted by the dashed curve in (a). The continuous curve on the travel time diagram corresponds to waves propagating in the undisturbed region of the tumulus (away from the tomb). The dots correspond to the field data.

m s^{-1} layer and the 1280 m s^{-1} layer (interface #1). Therefore, by placing the geophones at the periphery of the tumulus the radius of which was greater than the critical distance, we ensured that the head waves from interface #1 arrived first at the geophones. The shot point was placed at the centre of the tumulus. The geophone spacing was 1m and the radius of the circle, where the geophones are located, was 46 m.

In the first arrival time versus geophone position diagram (Figure 7), more than 25% delays are observed around the geophone #80. The observed anomaly around geophone #80 was attributed to the existence of the monument. The excavation, conducted by the archeologist Dr. P. Chrisostomou, revealed the monument of Figure 8 around geophone #80.

Verification of Messiano tumulus model with 3D forward modelling

Forward modelling is a versatile tool for inter-

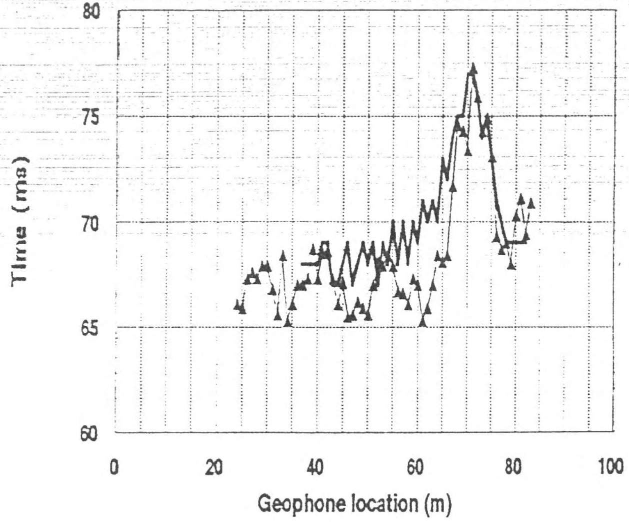


Figure 7. Comparison of the field and synthetic travel times for geophones #22 to #84. Symbols correspond to the field data and the solid curve, to the synthetic data (Tsokas et al., 1995).

preting seismic data. Recent advances in computing based on vector computation and the subdivision of the computational sequence into parallel components allow the application of forward modelling in realistic cases. Here, we perform a numerical simulation of the wave propagation based on a 3D finite difference forward modelling algorithm (Vafidis *et al.*, 1995) for the model shown in Figure 9. The purpose of performing this wave propagation simulation was to verify the validity of the proposed seismic technique in detecting tombs.

The model of the tumulus including the tomb and the ramp is shown in plane and sectional view (Figure 9). The size of the tomb and the ramp have been measured after excavation. The velocities were obtained from the initial refraction survey. The tumulus was a huge construction covering a monumental tomb of 10 × 5 × 5.5 m^3 and a large ramp as shown in Figure 8.

In the wave propagation simulation, we employed a 3D finite difference algorithm because the experiment at Messiano is three-dimensional, i.e. the shot is placed at a different level from the geophones and the geophones define a surface not a straight line. Modelling has been performed on a portion of the field data around geophone #80. The computed and the observed travel times are shown in Figure 7. The two sets of arrival times show a remarkable agreement confirming, thus the validity of the initial interpretation.

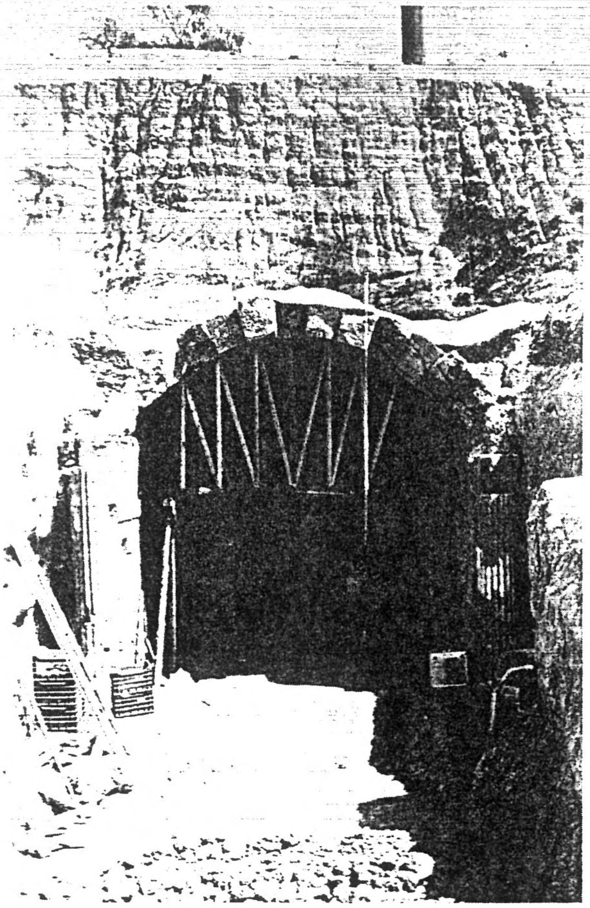


Figure 8. Photograph of the tomb revealed by the seismic method.

The recorded anomaly depends mostly on the size and the orientation of the ramp, rather than the tomb itself. The delays caused by the monumental tomb on the head waves are expected to be smaller compared to the ones caused by the ramp. The order of magnitude of these delays is the same as the sampling interval (0.2 ms) and it is very hard to observe them.

Numerical simulation of the wave propagation for Messiano tumulus also verified the ability of the seismic refraction method in detecting tombs. Forward modelling can be used not only after the experiment for verification purposes, but also prior to the survey for design purposes.

Case study of the Pella tumulus

The plan view of the circular receiver array at the Pella tumulus is depicted in Figure 10. The arrival times of the head waves generated by a source located on the top of the tumulus are shown in Figure 11. The geophone spacing was set to 1 m. The anomaly at azimuthal location 130 can be attributed to the ensemble of a tomb and a ramp. Also, a wide anomaly is present at location 50 through 90 which is probably due to a pit.

Conclusions

A tool for detecting tombs is proposed. This method detects the location of the ramp rather than the monumental tomb itself which is usually small. The method consists of the following steps. First, a refraction profile must be generated near the tumulus. Forward modelling is performed in order to choose the geophone array parameters of the seismic survey which is subsequently conducted on the tumulus. Next, the seismic refraction method is employed by placing the shot at the centre and the geophones at the periphery of the tumulus. The recorded first arrivals give information regarding the location of the tomb. The potential location of the tomb is finally verified by performing refraction profiles along the radial direction.

The seismic refraction surveys presented in this study demonstrate the simplicity of the field procedures and interpretation as well as the efficiency of the seismic method in detecting

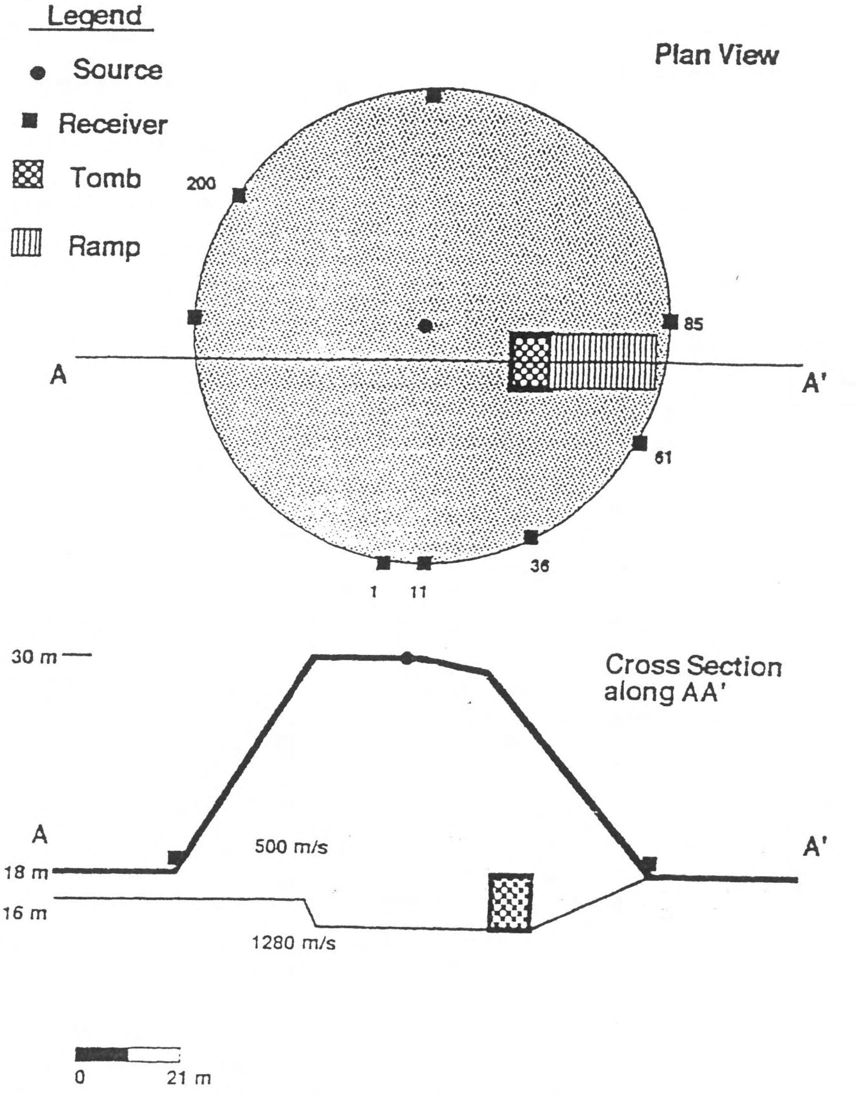


Figure 9. Plan view and cross section of the velocity model employed in 3D seismic modelling.

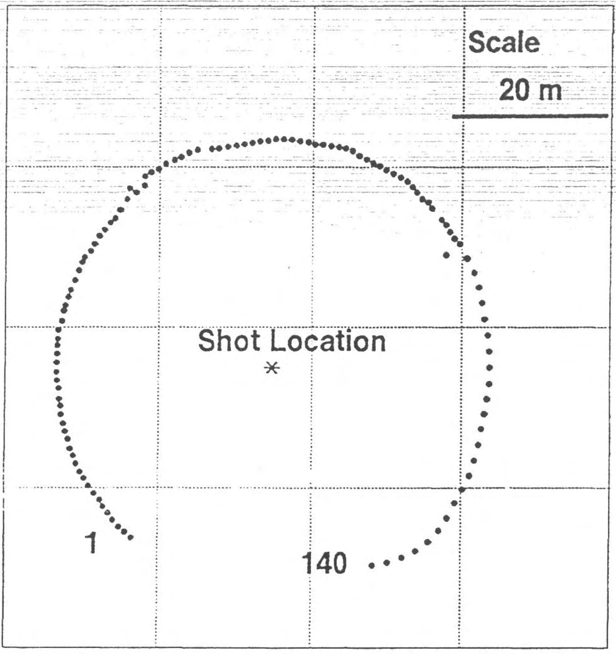


Figure 10. Geometry of the seismic survey in Pella tumulus. The dots denote geophone locations.

tombs covered by tumuli. The benefit of this technique is that selective excavation can be carried out, leaving the rest of the tumulus undisturbed.

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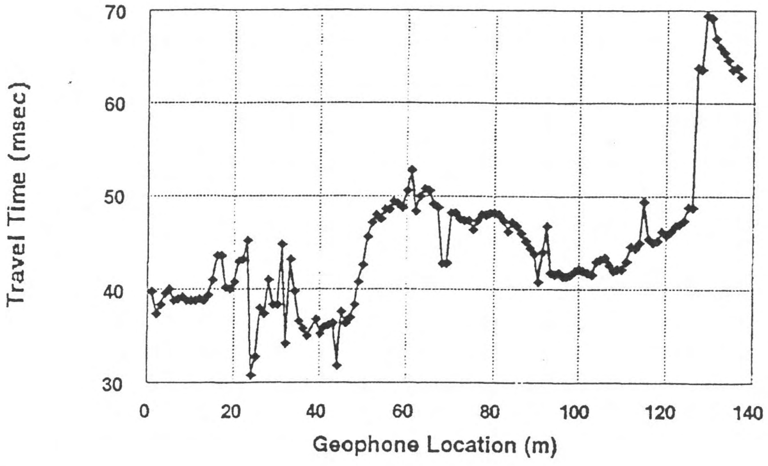

Figure 11. Travel time curve from the seismic survey in Pella tumulus.

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